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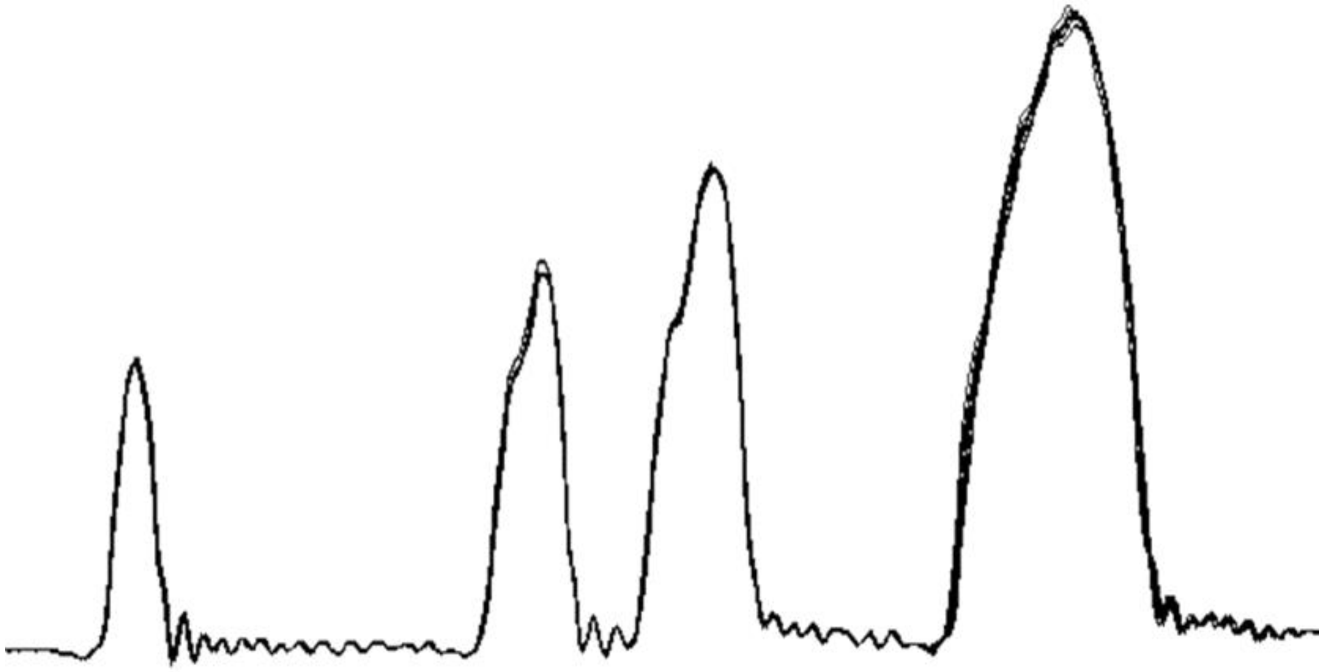

Diesel Combustion Control with Digital Rate Shaping

Master's thesis in Automotive Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

MASTER'S THESIS IN AUTOMOTIVE ENGINEERING

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Cover:
A triple pilot injection pattern from IAV software.

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Abstract

Due to the impact of the transport industry on the environment, stringent emission norms are being pushed for implementation. The real challenges for OEM's are to keep up with the regulations. The transition to complete electric future is still distant, and the existing diesel engines must survive for at least 5-10 years. Therefore, OEM's must achieve the legislative requirements with fuel consumption benefits using the available technology. One of the techniques available is diesel combustion control with digital rate shaping. Therefore, the thesis will investigate this method with triple pilot injection strategy and study the improvements in terms of fuel efficiency and emissions.

The work is carried out in two different parts; first, the Injector capabilities were tested in FIE (Fuel Injection Equipment) test rig at different load points with shorter and longer dwell times for different fuel quantities at different rail pressures. The aim was to investigate for injector performance in terms of minimum possible dwell time, fuel quantity, repeatability, and robustness of the injector. Results show inconsistent injector performance.

Second, the combustion is studied in a single-cylinder test rig. The test was investigated for one specific load point. The Injector capabilities and boundary conditions for triple pilot injection were again tested. Based on the Rate of heat release curve, each parameter, i.e. dwell time, fuel quantities and rail pressures were manually varied. Next, design of experiments (DoE) was set up using ETAS ASCMO. Running the DoE point in single-cylinder test rig, a combustion model was created from this data. Dwell time, fuel quantities and rail pressure as input parameters different response curves were created to see effects of these parameters on emissions, bsfc and combustion noise. These curves are then used to define a calibration strategy. Optimisations performed in the software are verified in the single-cylinder test rig.

The optimised injection strategy was validated in Gen IV Volvo multi-cylinder production engine. The results replicate the inconsistent performance of injector seen in FIE test rig and do not justify the supplier claim. However, based on the trend a description about how to efficiently balance the calibration to achieve lowest engine-out emissions, combustion noise and achieve efficiency through model-based calibration is proposed.

Keyword: Triple pilot injection; Digital rate shaping; Injection strategy; Engine calibration; Model-based calibration; FIE.

Contents

Acknowledgements

This thesis was carried out at Volvo car corporation (VCC) and could not have been possible without the support of many people. We are grateful to **Johan Zackrisson**, Manager diesel combustion control for providing us with this thesis and made sure that we got all the support needed for the project.

We wish to present our special thanks to our industrial supervisor **Thomas Vikamn**, who has continuously guided and encouraged us throughout the thesis. The questions and discussions had with him has elevated our understanding deeper and gave us a direction for our work.

The large part of the modelling and validation of the work was carried out at a single-cylinder rig at VCC. Our work could have been jeopardized due to unavailability of a technician during the period. As the saviour of the moment, **Joop Somhorst**, an expert in diesel combustion and a Volvo Industrial PhD student with his ongoing work at the rig shared his eagerness to help us out. **Michael Denny** PhD, who's expertise and experience on this subject of triple pilot strategy provided us with credible and invaluable material which helped us to plan the work. We express our sincere gratitude towards both of them for their help with planning the tests and continuous feedback, without their passionate participation and involvement, the work could not have been successfully conducted.

We would also like to express the gratitude to our examiner **Lucien Koopmans**, head of combustion division at Chalmers University of technology for giving us his encouragement and valuable comments on the thesis.

Finally, we would like to thank all the technicians and supportive colleagues at VCC whose assistance and resources facilitated in accomplishing our goal. This achievement would not have been possible without them.

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Akshay Yalmuri Krishnamurthy, Sachit Kumar

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Acronyms

VCC	Volvo Car Corporation
NEDC	New European Driving Cycle
WLTP	World Harmonic Test Procedure
RDE	Real Driving Emissions
DRS	Digital Rate Shaping
ECU	Electronic Control Unit
FIE	Fuel Injection Equipment
DoE	Design of Experiments
CN	Cetane Number
FAME	Fatty Acid Methyl Ester
ROHR	Rate of Heat Release
EGR	Exhaust Gas Recirculation
RMSE	Root Mean Square Error
SSR	Sum of Squared Residuals
MFB	Mass Fraction Burned
BSFC	Brake-Specific Fuel Consumption
QP2	Quantity of Pilot 2
QP3	Quantity of Pilot 3
QPre	Quantity of Pilot just before Main
QMain	Quantity of Main Injection
MBC	Model-based calibration
THC	Total hydrocarbons
LP	Low pass filter [axis in plots]
Int	Integrated ROHR [axis in plots]
INJ	Injection signal [axis in plots]
dQ	Rate of heat release [axis in plots]
PCYL	Cylinder pressure [axis in plots]
PLIN	Rail pressure [axis in plots]

1 Introduction

1.1 Background

Global warming is a growing concern, which jeopardises the environment and human health. Some of its effects can already be felt in the many parts of the world, with extreme weather conditions and an increase in health disease due to emissions. The world is focusing on fighting global climate challenges, and there is a strong need to reduce these emissions. The emissions from the transport sector contributed to 23% of global Greenhouse gases in 2016 [1]. Thus, more stringent emissions regulations on the vehicles are being implemented by regulatory authorities. European Emission regulations were introduced in 1992 to reduce tailpipe emissions, with the latest implementation of Euro 6 regulations in 2015, the pollutants have been reduced by 96% since its first introduction. The successive levels of Euro 6 (6b, 6c & 6d-temp) were introduced culminating in Euro 6d.

Euro 6b onwards New European Driving Cycle (NEDC) has been replaced with World Harmonic Test Procedure (WLTP) for laboratory testing. Euro 6d has more stringent regulation to meet with the introduction of Real Driving Emissions (RDE) in addition to legislative test cycles. The regulatory authorities aim at reducing the difference between legislated and real driving emissions by considering the conformity factor. The vehicles meeting with a conformity factor of 2.1 is certified as Euro 6d-temp. In future, it will be challenging for manufacturers to meet Euro 6d which includes conformity factor of 1.

Figure 1.1 – Deaths due to air pollution [2]

Volvo Cars have focused on technological improvements and innovation in making substantial contributions to climate change mitigation in the automotive sector. The current generation 3 diesel engines meet the new euro 6d-temp regulations. There is always a need to develop more fuel-efficient and clean emission engines. The Company is looking to develop more productive and sustainable solutions to reduce engine emissions in future. Hence, the next milestones will be to meet Euro 6d regulations which might be implemented in the near future. This topic explores the possibility of reducing emissions and improving the fuel efficiency of these diesel engines.

1.2 Aim

Digital rate shaping (DRS) in combustion control is an approach of controlling the fuel injection, which helps to achieve better fuel efficiency, low exhaust gas emissions and low noise in Diesel engines. The objective of this Master's thesis is to evaluate fuel efficiency, exhaust emissions and combustion noise using DRS for a 3^{rd} generation Volvo Diesel engines with solenoid based injectors and thus develop a good response model for these aspects which characterises the system trade-off.

Additionally, we define the hardware requirement such as needed separation time, flow rate, common rail pressure; injection shot precision and robustness. Also, state software functionality to handle the proposed injection pattern and DRS.

1.3 Limitations

It is out of the scope of this project to investigate the mechanical noise produced by the engine and other hardware aspects corresponding to ECU, fuel pump, common rail system, piston design and cylinder geometry as they are fixed. This thesis will also not focus on the piezo type injector, and this will be part of the future scope.

1.4 Specification of issues under investigation

The expected question that this thesis will answer are:

- What kind of separation time between injections is possible to run?
- How many numbers of injections possible (pilot, main)?
- Minimum and maximum quantities that can be injected in each pilot?
- What are the limitations of generation 3 injector?
- What is the effect of this on fuel efficiency, exhaust gas emissions and combustion noise?
- Is the system capable of running the triple pilot injections?

2 Fuel Injection

The main purpose of the fuel injection system maybe is to deliver the fuel to the cylinders, but how, when and how much fuel is injected into the cylinders is more critical as it affects the fuel efficiency, emissions, noise of the engine [3].

2.1 Types of fuel injection

There are different types of fuel Injection:

- Single-point or throttle body injection
- Port or multipoint fuel injection
- Sequential fuel injection
- Direct injection

Our concentration is on the direct injection type where the fuel is injected directly into the combustion chambers. This type is more common in diesel engines [4].

2.2 Common rail fuel injection

The merits of a common rail fuel injection system have been recognised since the development of diesel engines. Common rail fuel injection systems are used in most of the light-duty vehicle Diesel engines because of the advantages it has. Some of the significant advantages would be [5]

- Fuel pressure in the injection system is independent of engine speed and load conditions
- Introducing pilot injections is much easier with common rail fuel injection. It is important as introducing pilot injections show decreased emissions and engine noise which is what this thesis is about
- Less strain on the engine shaft as power and average torque requirements of the common rail fuel injection system is similar all the time

2.3 Types of injectors

The injector is one of the significant parts of an injection system. It is designed to achieve high accuracy in fuel injection quantities and the start of ignition timing. The common rail diesel injection systems use the following injector designs.

- Servo controlled electrohydraulic injectors
    - Solenoid injectors
    - Piezoelectric injectors
- Servo controlled electrohydraulic injectors incorporating pressure amplification
- Direct-acting injectors.

The work carried is based on solenoid injectors, which has the state-of-the-art technology to deliver accurate and robust injections.

2.4 Multiple injection strategy

Multiple injection strategy can be defined as multiple small injections in a small quantity of fuel before the main injection event and these small injections are called as pre injections or pilot injections. If the injection events occur after the main injection, they are called as post injections.

The idea of using pilot injections to reduce combustion noise has been there since the 1930s [6]. Pilots injections are a critical part of how the combustion propagates since each small pilot act as a source of fire for subsequent injections to achieve smooth combustion. In the current production engines, many companies are using up to 5 injections per cycle, i.e. 2 pilots + 1 main + 2 post injections to reduce combustion noise, emissions and increase performance.

The literature [7][8] says that using triple pilot has more advantages and that the emissions, combustion noise can be reduced, and performance can be further increased. In our thesis, we have investigated on triple pilot strategy. We would not be considering post injections for the research.

2.4.1 Triple pilot injection definition

The start of pilot injection is always determined from the start of the main injection. When the ECU transmits a signal for fuel injection it sends the main injection timing and based on this, a small built-in computer on the injector reverse calculates the timing for pilot injection.

The supplier defines an injection interval (TINT) as the distance between the Least square line drawn at Max QP3 and QP2 (tangential red line) at zero injection rate. This line must pass through two points, 45% of Max QP3 and 20% of Max QP3 shown in Figure 2.1. Similarly, for QP2. Based on this definition FIE test rig software is coded to identify the fuel quantity for each injection. These methods of measuring have been agreed between the supplier and Volvo.

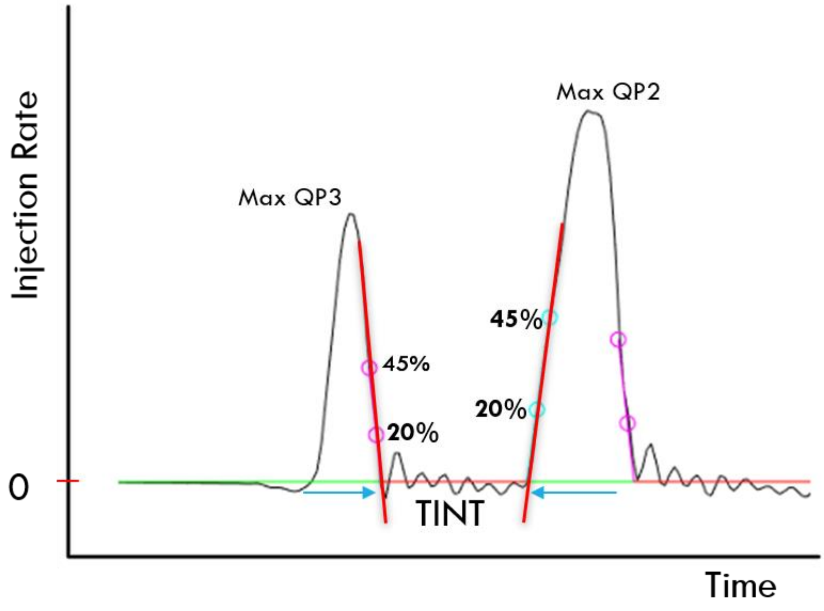


Figure 2.1 - Definition for injection interval

Figure 2.2 shows the different terms used in the triple pilot system. It is an injection rate plot of triple pilot injection. There are three pilot injections and one main injection.

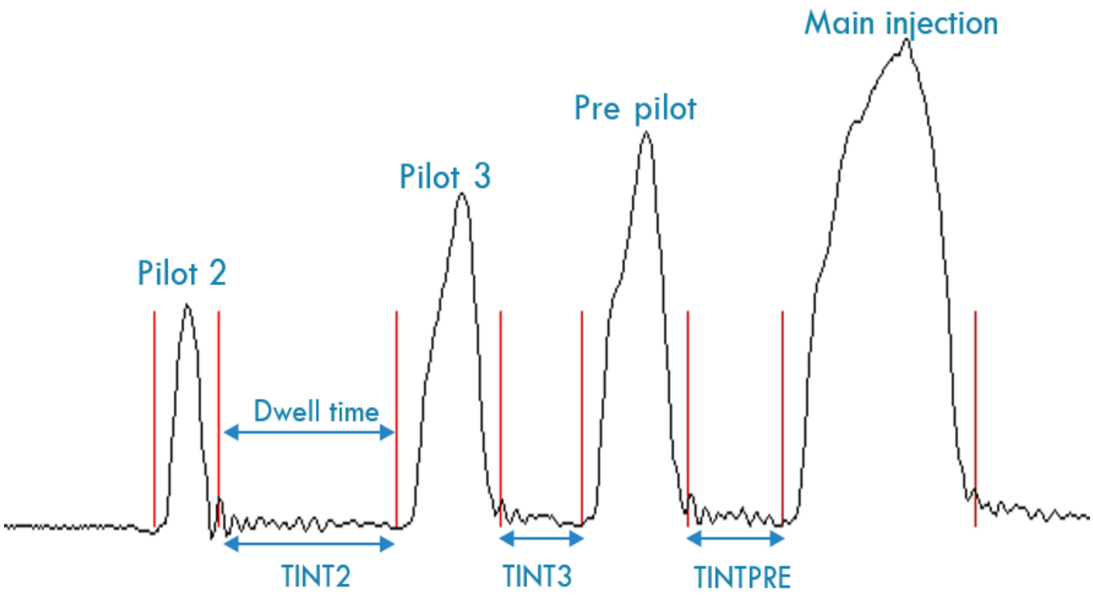


Figure 2.2 - Triple pilot injection definitions

- Pilot 2: This is the first injection which is usually very small. The fuel quantity of this pilot is termed as QP2
- TINT2: This is the separation end of pilot 2 injection and beginning of pilot 3 injection
- Pilot 3: This is the second pilot that is injected, and the quantity of it is usually more than the Pilot 2 quantity
- TINT3: This is the separation between the end of pilot 3 injection and the beginning of Pre pilot injection
- Pre-Pilot: This is the injection that happens before the main injection, hence the name ‘pre-pilot’. The quantity of it is usually more than the quantity of Pilot 3 and less than the quantity of the main injection.
- TINTPRE: This is the separation between the end of the pre-pilot injection and the beginning of the main injection.
- Main injection: This is the main injection where most of the fuel is injected in one shot.

3 Methodology

The primary objective of this thesis is to investigate the improvements in fuel efficiency, emissions, and combustion noise with digital rate shaping. The complete process is divided into two parts – Fuel injector experiment (FIE) test rig and single cylinder test rig. In the first step, the fuel injector operating boundary is investigated in FIE test rig and in the next step these results will be used in a single-cylinder test rig to set up the design of experiments (DoE). The measurement points will be used to build a combustion model, which will be used to find the optimal Injection strategy to achieve the target variables for this thesis.

A reference injection strategy was used based on the earlier research and experiments done on triple pilot injections internally at Volvo. The input parameters of this thesis work were swept around these reference values. The output values from this base strategy will be used as limits and not a comparison since it will be illogical to draw a comparison between multiple cylinder engine and single cylinder.

3.1 Selection of load points

The Load points for the test was selected based on the most run regions during the WLTP cycle and RDE Cycle. Following three points are selected

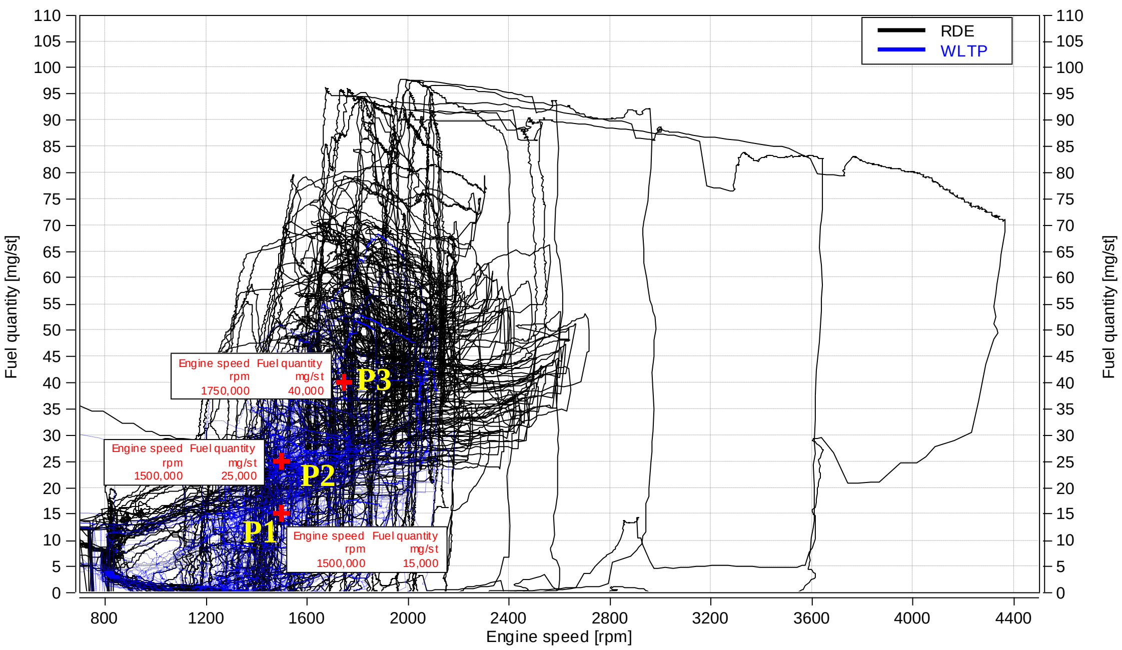


Figure 3.1 - Operating points

The Operating points, as shown in Figure 3.1, were chosen from the existing Gen 3 engine with double pilot injection strategy. The load point P2 is prioritised then P1 and P3 in this order. It is observed that during the engine certification test that load point P2 and P1 is most used in the WLTP cycle and P3 in RDE cycle. Thus, it is critical to understand the possible improvements with digital rate shaping for these load points. Further in the single-cylinder tests, due to time constraints only load point P2 data was collected and analysed.

3.2 Experimental setup

3.2.1 FIE test rig – IAV

The IAV injection analyser is the instrument for simultaneously measuring the fuel flow rate and mass of fuel injected with high-pressure injection system. The setup involves a closed fuel-filled tube which works based on the principle of measuring the dynamic rise in pressure in the tube in response to fuel injected in the system. The fuel injection data is recorded, which could also be ascertained in real-time. The instrument allows for direct shot-shot measurement of injection rates, injection masses, and fuel volume with very good accuracy. The schematic of the instrument is shown in Figure 3.2.

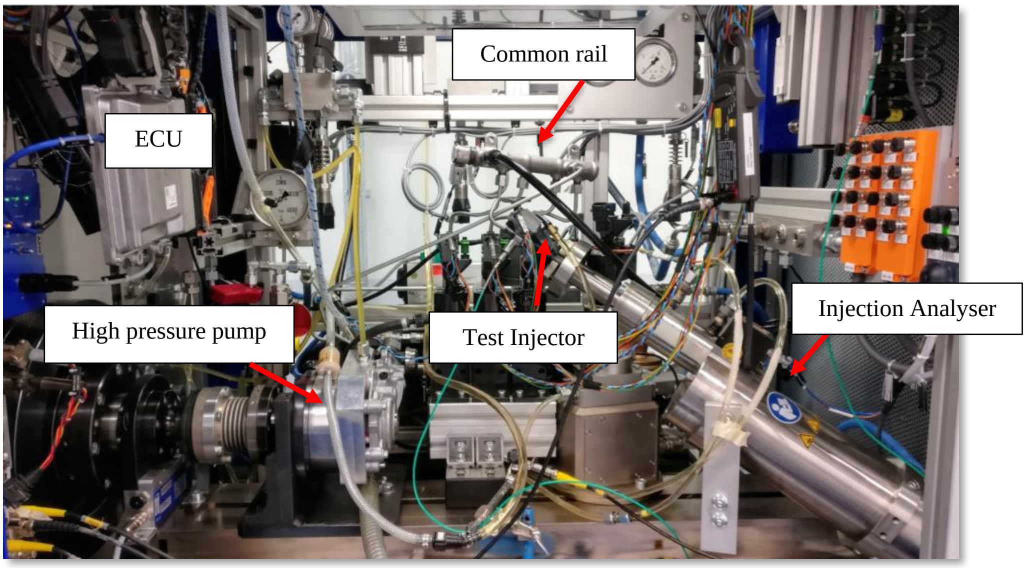


Figure 3.2 - Schematic of the FIE test rig

3.2.1.1 Test Plan

Based on the literature studies and internal Volvo triple pilot studies, a series of experiments were planned for capturing the data and understand the effect of pilot quantity by varying TINT2, TINT3, TINTPre. Based on the literature [9], the test was planned in such a way that pilot quantities were increased in ascending order as it has shown an improvement in terms of combustion noise and emissions.

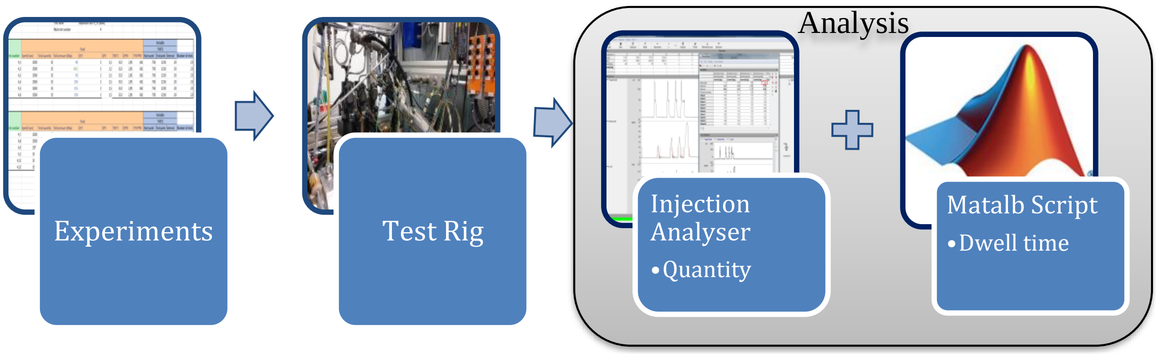


Figure 3.3 - Workflow for FIE test rig

Experiment

A semi-nominal fuel injector was used for this experiment which enables minimum separation of 100µs between the pilot injections. This injector was previously used only in FIE test rig. The ECU software and the injector used are based on production specification. The injector specification is given in Table 3.1. The fuel injection parameters were measured according to methods agreed between the supplier and Volvo Car Corporation.

Table 3.1 - Fuel injector specification

Description	Specification
Fuel injector type	Solenoid
Min hydraulic separation	100 µs
Max rail pressure	2500 bar
Min fuel injection	$1mm^3$

Experimental parameters

Test experiments were planned between the ranges, as shown in Table 3.2. FIE testing was performed for different injection quantity and hydraulic separation for a sweep in rail pressure. The fuel quantity was varied in most case in growing order (QP2<QP3<QPRE) [9]. However, there was a limitation from the supplier, regarding injection of pilot quantities because it produces inaccuracy in subsequent injection. The limit was defined up to 5mg/stroke.

Table 3.2 - Varied experimental parameters

Speed (rpm)	Fuel Quantity (mg/str)	Rail pressure (MPa)	TINT2 (µs)	TINT3 (µs)	TINPRE (µs)
1500	15 mg	85-150	60-500	80-500	60-500
1500	25 mg	60-180	60-500	80-500	60-500
1750	40 mg	80 - 215	60-500	80-500	60-500

The experiment was carried for each case with averaging of 10 strokes per cycle with contestant backpressure of 60bar to simulate the engine conditions.

Measurement tools

- Injection analyser

Energising dwell time is defined as the time interval between the end of the previous injection energising signal and start of next energising signal. Hydraulic dwell time is defined as the time between the end of previous fuel injection and the start of next fuel injection. There is a time delay in the actual injection signal in the injector and the start of hydraulic injection which is seen in the energising and hydraulic time plots in Figure 3.4. This is a limitation of the system.

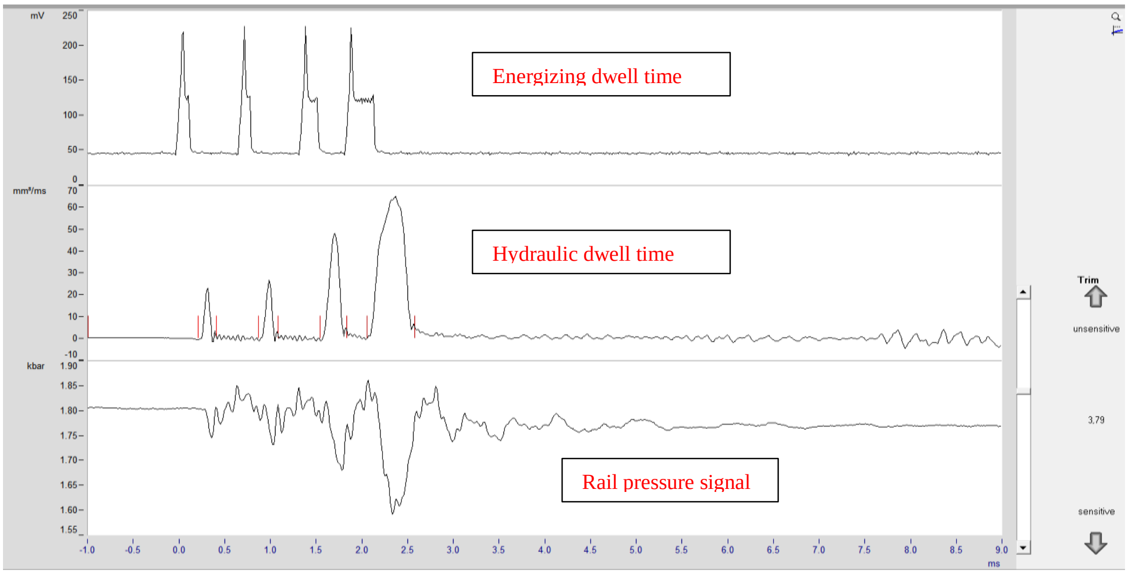


Figure 3.4 - Measurement of fuel quantity in Injection analyser

The fuel quantities are measured using Injection analyser software. It is calculated from the average of 10 strokes. The injection quantity is calculated through the limits, i.e. the intersection of injection rate with time on the x-axis. The red lines as shown in Figure 3.4 in 'hydraulic dwell time section' represents the limits for the detection. The sensitivity with which the device can detect the injection events can be selected from the slider function in the lower right corner of Figure 3.4. It is usually set to value 1. The slider controls the noise in the injection measurement. If the sensitivity is too high, then the injection analyser software captures the unwanted noise as injections. If sensitivity is low, then the actual injection is not detected. Based on the previous experiences it is set to 1.42 for this thesis work. The supplier updates the software to capture the correct injection quantity and interval based on its definition.

- MATLAB

Volvo developed a MATLAB script to calculate the separation by the definition given by the supplier, hydraulic dwell time is examined from the average of 10 strokes.

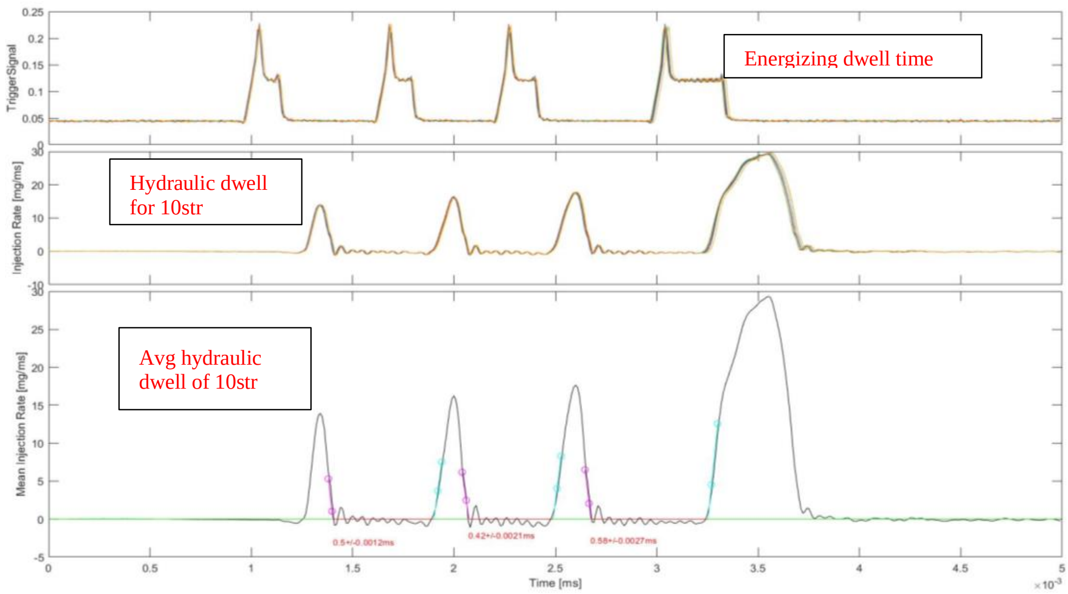


Figure 3.5 - Measurement of dwell time from a MATLAB script

3.2.2 Single-cylinder test setup

This single-cylinder engine replicates the current Volvo generation 3 multi-cylinder engine. The same fuel injector from the FIE test rig is used in this experiment. Due to defective smoke meter, soot data is not captured and will not be part of the analysis.

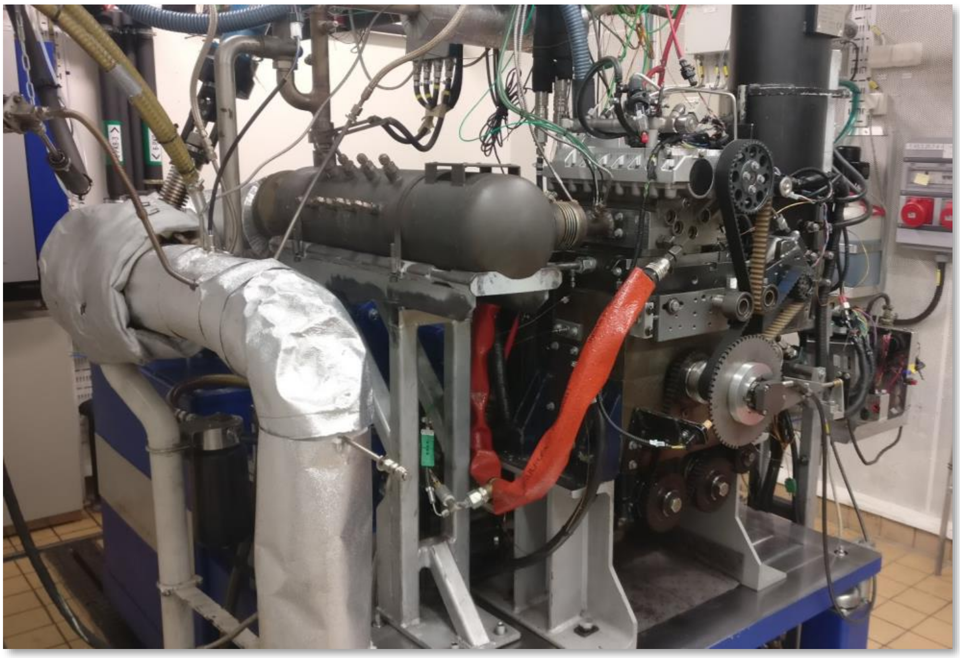


Figure 3.6 - Single cylinder engine in the test rig

The engine was controlled from three software interface – INCA, AVL PUMA, Indicom. AVL puma was required to initialise the ignition ON condition, and INCA would communicate between Puma and engine ECU. Indicom was used to visualise the recorded data like Rate of heat release (ROHR). The automatic test plan was fed into AVL puma based on the planned DoE to run the engine without manual supervision. The technical specification of the engine is given in Table 3.3.

Table 3.3 - Engine hardware specification

Single Cylinder Engine	**AVL 5812**
Displaced Volume	492 cc
Stroke	93.2 mm
Bore	82.0 mm
Compression ratio	15.5
Bowl type	Stepped bowl
Number of valves	4
Swirl number (Honeycomb)	2.0 to 3.2
Nozzle hole number x diameter	8 x 0.125mm
Included spray angle	155 degrees
Fuel injection system	Common rail, 2500 bar

Injector actuator type	Solenoid
Fuel	Diesel CN 51, 10% FAME

3.2.2.1 Test Plan

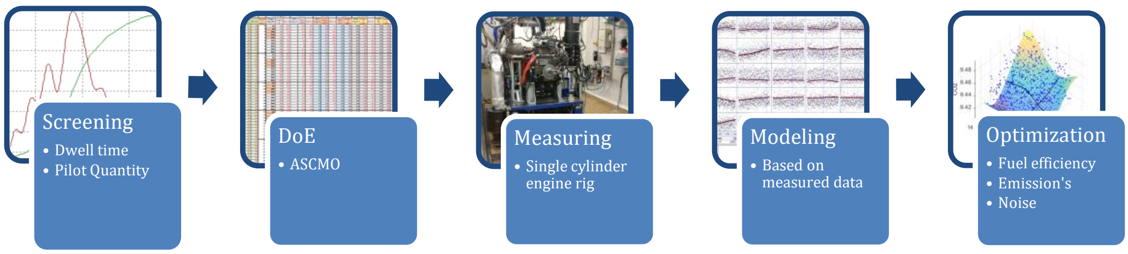


Figure 3.7 - Workflow for Single cylinder engine test rig

Screening

The screening was carried out again since results from the FIE test rig could not be used over to this test. The screening was performed based on visually inspecting the ROHR curve because it's not possible to detect the pilot quantity inside the cylinder and also cannot determine the exact hydraulic separation.

Using the existing triple pilot research data from Volvo multi-cylinder engine at P2, a new data was collected by sweeping around these settings. Torque, EGR, phasing (MBF), swirl position and boost pressure were fixed to baseline value and varied parameters are shown in table Table 3.5. Next step was to visually inspect the ROHR curve i.e. to check if pilots are growing together and how close a separation is possible before they grow together, based on this, minimum and maximum energising time was measured for different pilot quantities (QP2, QP3, QPRE) and rail pressure.

The baseline strategy settings for the load point P2 from existing triple pilot research at Volvo is shown in Table 3.4. However, due to limitation in achieving Qpre quantity the value was restricted to 4mg/str, since increasing the QPre quantity affected the stability of the main injection. Other parameters remained the same. This setting would be the baseline for comparing our optimization results from MBC.

Table 3.4 - Baseline settings

Rail Pressure (Mpa)	QP2 (mg/str)	QP3 (mg/str)	Qpre (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)	TINTPre (µs)
120	1	2	4	25	476	120	185

Also, the single-cylinder engine was sensitive to high hydrocarbons, which shuts off the engine immediately. This limited the screening of pilot quantity up to 5mg/stroke.

Modelling Tools

- ASCMO - Design of Experiments (DoE)

DoE is a systematic method to understand and study the different input parameters affecting the output of the experiment. There are different tools and different ways to setup DoE. In this project, ASCMO (static test planning) was used to set up the DoE, since the same tool is further used to build a model.

ASCMO – Advanced Simulation for Calibration, Modelling and Optimization is a modelling tool for understanding the input and output response of an unknown system based on the measuring data created from DoE [10]. The method used to create DoE for this project is a space-filling, which is created by evenly distributing the measuring points quasi-randomly between the ranges specified so that the system complexity is captured as arcuately as possible with minimum measurements.

To minimise the measuring data points and to check if the output variables fall in the physically meaningful range, DoE was created by adding constraints. For example, from the literature studies, better noise and emissions could be achieved by injecting pilot quantities in ascending order [9]. Therefore, the points could be excluded which do not agree with this condition. As shown in Figure 3.8, the blue dots are the data points. Once the constraint (QP2<QP3<QPre) is applied the lower right region points are removed to satisfy this condition.

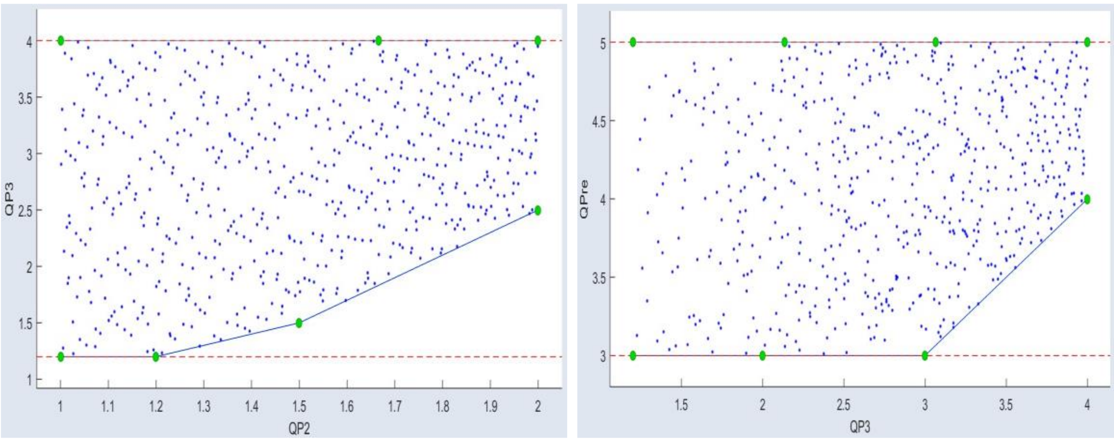


Figure 3.8 - DoE data points for pilot injection QP2, QP3 & QPre

During this work, only eight input parameters were varied between the range shown in Table 3.5. The parameter for MFD values was derived from internal Volvo material and literature study [11]. Rail pressure was swept between minimum and maximum from the existing triple pilot strategy. The injection settings like pilot quantity and dwell are derived based on the ROHR screening in the single-cylinder test rig. Other parameters like EGR, boost pressure, exhaust pressure, swirl position, phasing was fixed from their baseline values and a DoE is created with 600 measuring points.

Table 3.5 - DoE input parameters

S.No	Input parameter	Minimum	Maximum
1.	Mass fraction burned 50%	7.0	11.0
2.	Rail pressure (MPa)	100	140
3.	TINT 2 (millisec)	0.3	0.9
4.	QP2 (mg/str)	1.0	2.0
5.	TINT 3 (millisec)	0.12	0.5
6.	QP3 (mg/str)	1.2	4.0
7.	TINT PRE (millisec)	0.12	0.5
8.	QPRE (mg/str)	3.0	5.0
9.	EGR (in terms of CO2)	2.7%	
10.	Swirls position	65%	
11.	Boost Pressure	165 kPa	
12.	Torque	29.5Nm	

- ASCMO - Model-Based calibration (MBC)

Due to the increasingly complex systems like ECUs, the calibration process involves many challenges, for example, limitation with the availability of test object, an increase in the number of variants, a rise in the development cost, continues changing legislation all of these factors demand model-based calibration method. Thus, an MBC approach narrows down the amount of calibration work.

Based on the DoE, all the output data is collected from the single-cylinder engine to build a rough model.

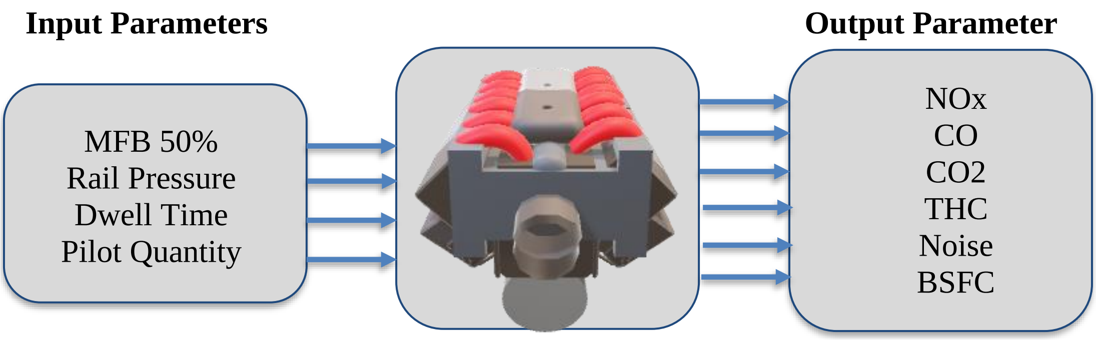


Figure 3.9 - Input and output parameters

One of the critical steps after importing the data would be training the model. The model will be less useful if trained with incorrect or varied data. Therefore, the trained data need to be visually accessed for an outlier in the measurement data. The outlier is defined as the incorrect or imperfect measured data points which are absurd [10]. These points can be visually picked up as shown in Figure 3.10. Outliers determine the quality of the model, if not detected it will create a poor response model.

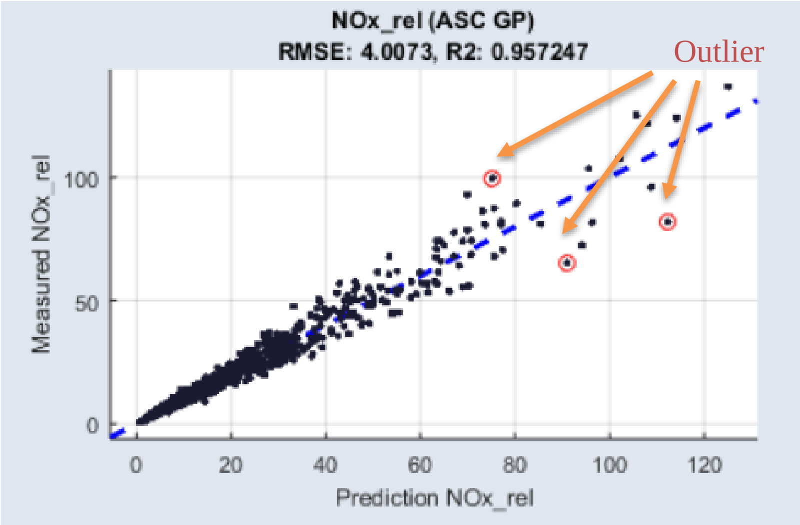


Figure 3.10 - Outlier in the measured data

ASCMO (static modelling and optimisation toolbox) was used to build response models. Model-based calibration in this project. ASCMO uses gaussian regression process to generate the response model from the measured data points. The measured data of 600 points are imported into ASCMO (static modelling and optimisation) for generating the response curves shown in Figure 3.11.

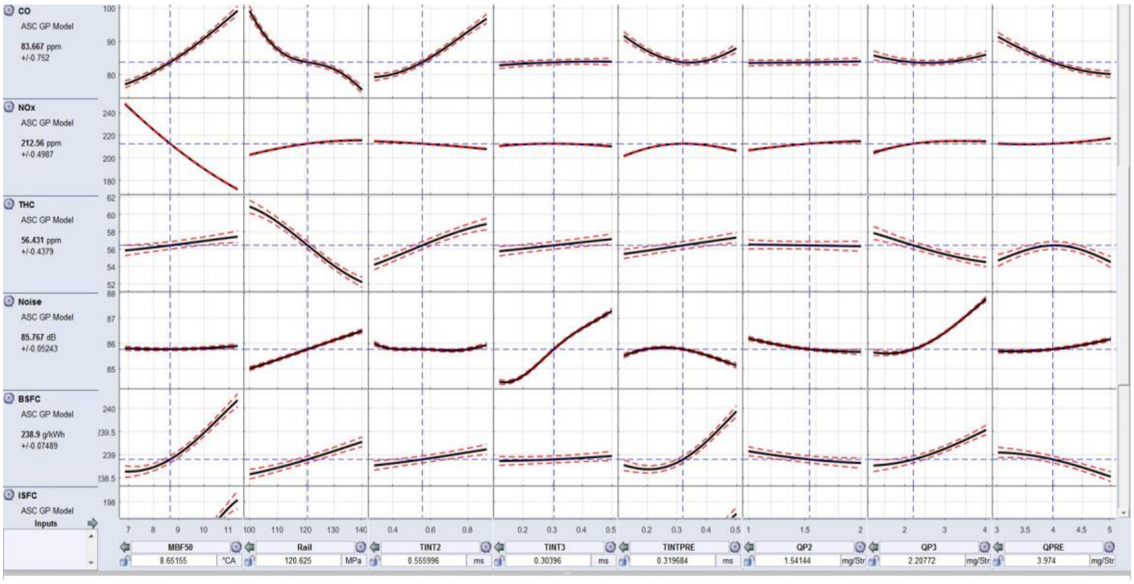


Figure 3.11 - Response model

Response models give a relation between inputs and outputs. As seen in Figure 3.11 Y-axis defines output (in this case - bsfc, noise, Nox, CO2) and X-axis defines input parameters (in this case - rail pressure, pilot quantity, dwell time). The black lines indicate model prediction, red lines show model accuracy range.

According to the ETAS ASCMO manual [10], the model quality is indicated by two variables described below –

- RMSE (Root mean square error) - which defines a residual standard of deviation of the model and is determined by the below formula:

$$RMSE = \sqrt{\frac{SSR}{n}}$$

Where *n* is the number of measuring data and SSR is the sum of squared residuals given by

$$SSR = \sum_{i=1}^{n}(X_{i,predicted} - X_{i,measured})^2$$

- R2 – which is known as the coefficient of determination. The significant variable among the two is R2, which determines the relationship between two variables, in this case, it is between predicted and measured. Its expressed in percentage. ETAS ASCMO manual defines the range for examining the model quality as below [10].

  0 < R2 < 0.5 – The model is not suitable for reliable prediction

  0.6 < R2 < 0.8 – The model is suitable for qualitative prediction

  0.9 < R2 < 1 – The model is good and is suitable for quantitative prediction

If a line is good fit i.e. the squares of the residual error is less then R2, which indicates that a lot of variation in the y-axis (predicted) is described by x-axis (measured).

The scope of the thesis prioritises on optimizing the variables as listed below –

1. Fuel consumption – BSFC (g/kWh)
2. Emissions
3. Combustion noise (dB)

After the model is created, each the output parameter is optimised individually to understand effects on each other (outputs) by setting specific target value within the model validity range and leaving the weight column same for all. Later, learning from the individual optimisation and according to thesis priority, a trade-off is optimised by specifying weights as shown in Figure 3.12. The optimization, in this case, was without any set target value.

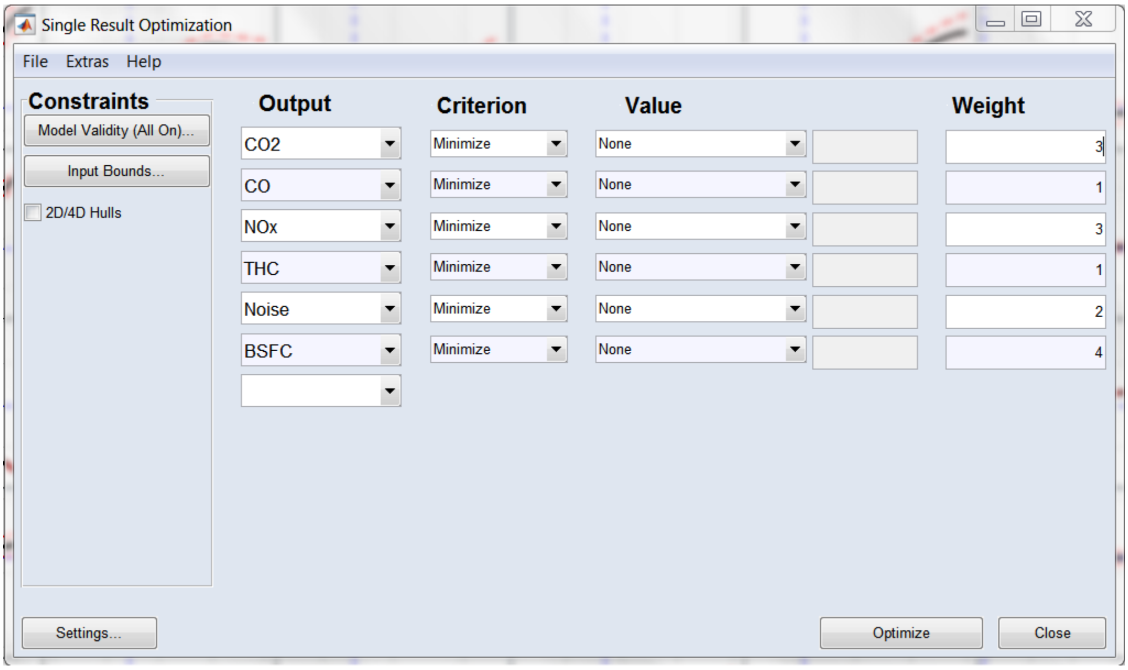


Figure 3.12 - Optimization window in ASCMO

Models were validity by running the single-cylinder test rig with these optimised settings.

Lastly, due to the short time, few tests in multi-cylinder rig were performed with the same optimisation as single-cylinder settings to replicate the improvements seen earlier. Also, verify the suppliers claim of achieving a minimum separation of 100µs.

4 Results

4.1 FIE test rig results

Tests were done in the FIE test rig for three different load points with different separation intervals and different pilot quantities. Results of load point P2 are elaborated in this section since the single-cylinder test rig results were obtained only for this point. Load points P1 and P2 are further documented in the Appendix of this report.

4.1.1 Load point P2 - 1500rpm and 25mg

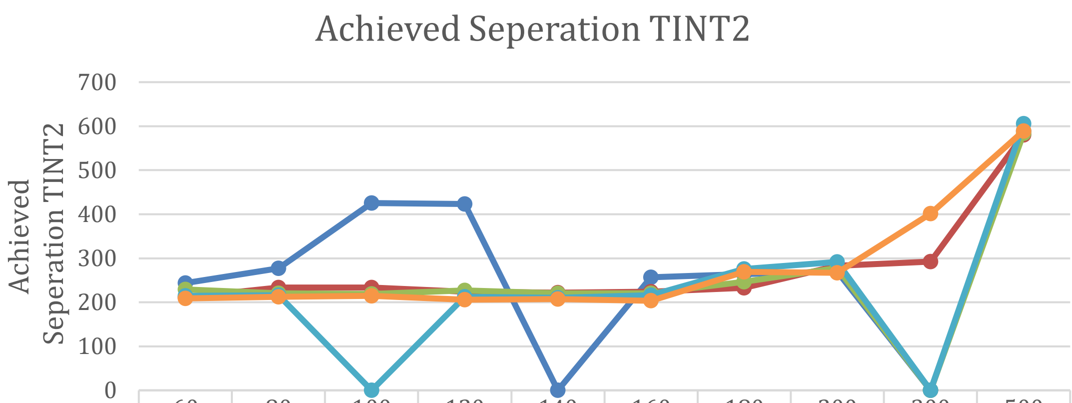
4.1.1.1 Tests were done varying TINT2

In this test, all the parameters are fixed except the TINT2 separation. The values that are fixed are as shown in Table 4.1.

Table 4.1 - Values of fixed parameters with TINT2 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT3 (µs)	TINTPre (µs)
1	1,95	5,85	16	25	115	185

- **TINT2 separation**



	60	80	100	120	140	160	180	200	300	500
60	244	277	425	423	0	257	264	270	0	589
119	211	233	233	224	222	224	233	283	293	581
129	229	220	219	227	221	221	247	278	0	584
149	215	216	0	213	210	216	276	291	0	606
180	209	212	215	206	207	203	269	267	401	589

Figure 4.1 - Requested TINT2 separation vs Achieved TINT2 separation at different rail pressures (60, 119, 129, 149, 180 MPa)

The plot in Figure 4.1 shows the requested TINT2 separation vs achieved TINT2 separation. At 60 MPa rail pressure, the results are a little strange, it can be said that 60 MPa rail pressure is too low for this load point. 119 MPa is the actual rail pressure for this load point in the current Gen3 Volvo engine.
There is a lot of variation between the requested and achieved TINT2 separation.

There are a few readings which show zero value, these are the ones that are not detected on the Injection analyser software or from the MATLAB script that we used, this happens when the injection quantity is too small, but this is happening at random points.

- **Quantities of each injection**

Achieved fuel quantity of all injections (QP2, QP3, QPRE, QMain) are plotted against requested TINT2 separation at five different rail pressures (60, 119, 129, 149, 180 MPa) shown in Figure 4.2. The requested fuel quantity of each injection can be seen in Table 4.1.

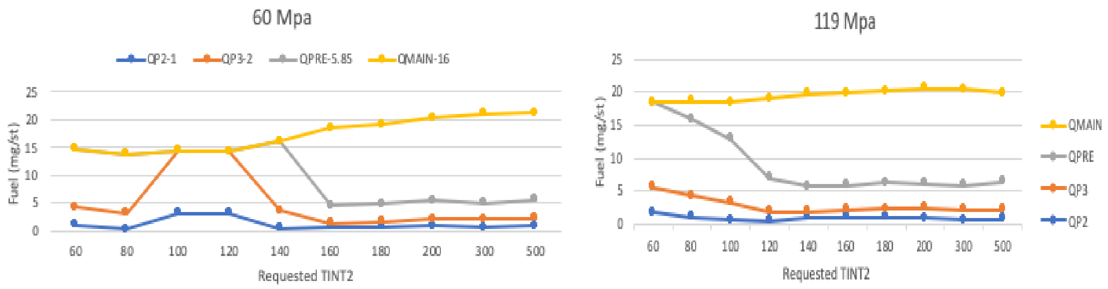


Figure 4.2 - Achieved fuel quantity of each injection vs requested TINT2 separation at 60MPa and 119MPa rail pressure

The Achieved QMain quantity does not deviate much from the requested quantity as the fuel quantity requested is more. In 60MPa plot, QP3 and QPRE are drastically increased after TINT2 separation of 80µs. It is again because 60MPa rail pressure is too low for this load point.

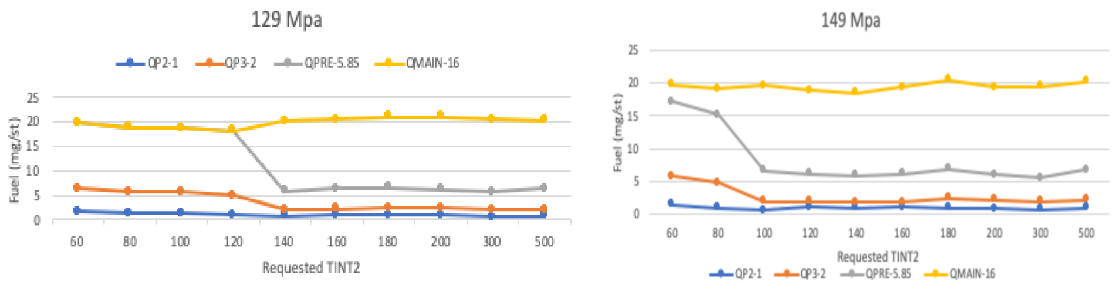


Figure 4.3 - Achieved fuel quantity of each injection vs requested TINT2 separation at 129MPa and 149MPa rail pressure

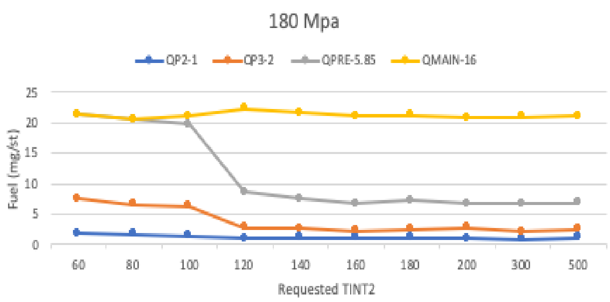


Figure 4.4 - Achieved fuel quantity of each injection vs requested TINT2 separation at 180MPa

At all rail pressures, QPRE quantity is a bit unstable, the achieved quantity varies from 5-20mg/stroke when the requested quantity is 5.85mg/stroke.

4.1.1.2 Tests were done varying TINT2 (Quantities doubled)

This is a test done varying TINT2 and fixing the other parameters as shown in Table 4.2. This is the same test as seen in section 4.1.1.1. In this test QP2 and QP3 pilot quantities are doubled, the total fuel quantity is still 25mg/stroke.

Table 4.2 - Values of fixed parameters with TINT2 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT3 (µs)	TINTPre (µs)
2	3,9	5,85	13	25	115	185

- **TINT2 separation**

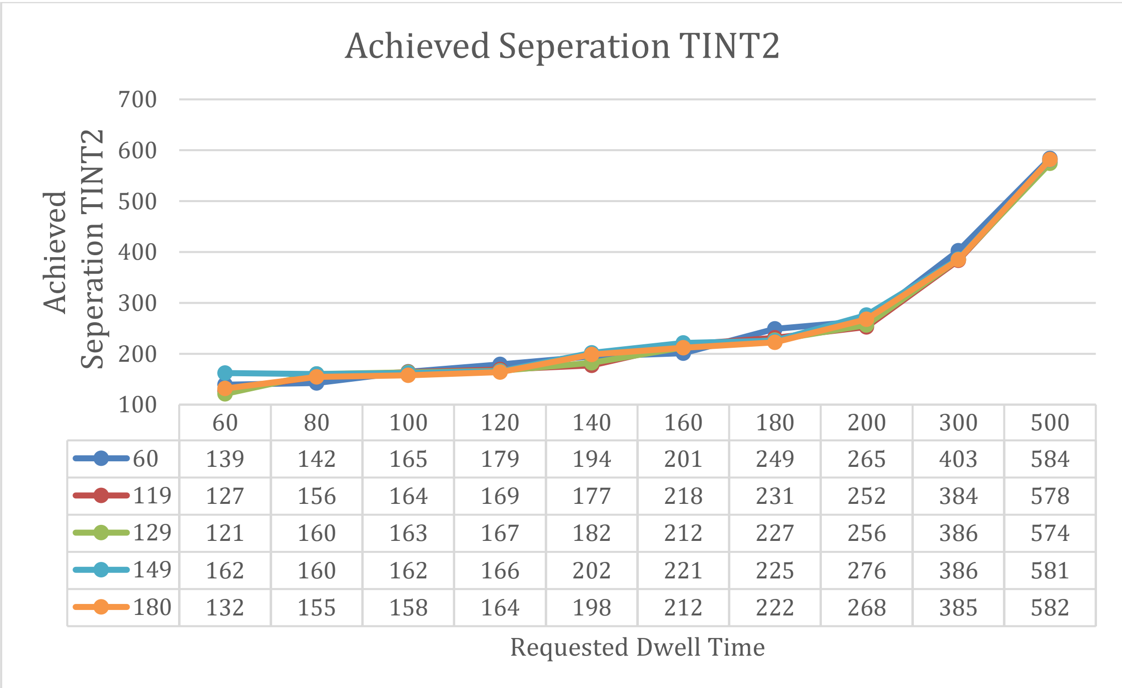


Figure 4.5 - Requested TINT2 separation vs Achieved TINT2 separation at different rail pressures (60, 119, 129, 149, 180 MPa)

The plot in Figure 4.5 shows the requested TINT2 separation vs achieved TINT2 separation. All separations are detected by the MATLAB script like the previous test. 119 MPa is the actual rail pressure for this load point in the current Gen3 Volvo engine. There is a lot of variation between the requested and achieved TINT2 separation.

- **Quantities of each injection**

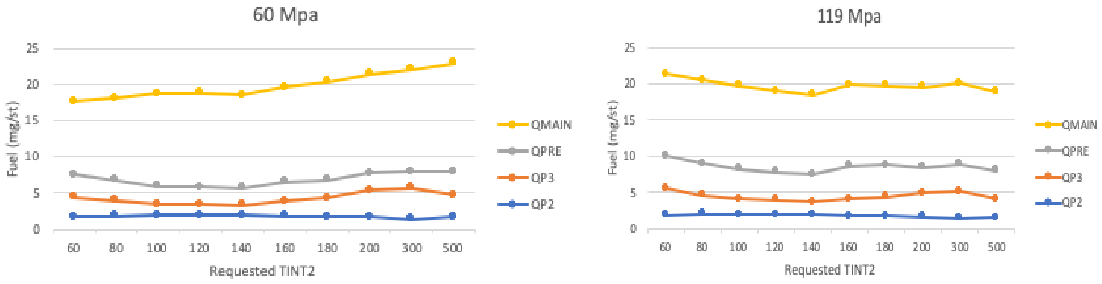


Figure 4.6- Achieved fuel quantity of each injection vs requested TINT2 separation at 60MPa and 119MPa rail pressure

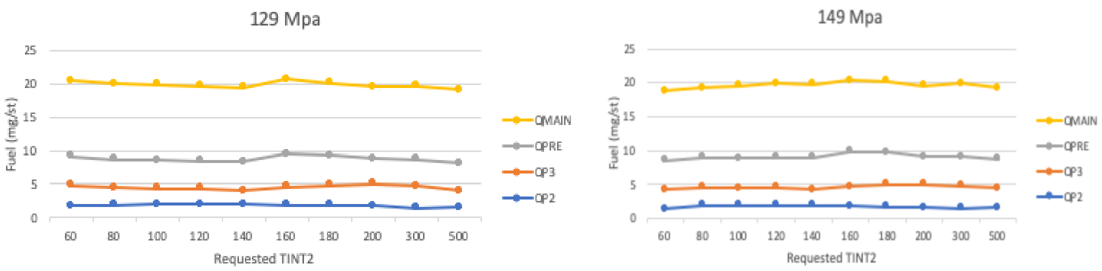


Figure 4.7- Achieved fuel quantity of each injection vs requested TINT2 separation at 129MPa and 149MPa rail pressure

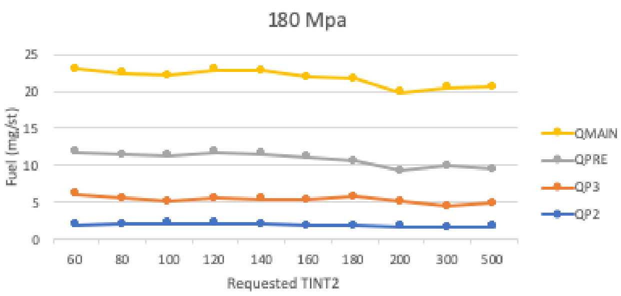


Figure 4.8 - Achieved fuel quantity of each injection vs requested TINT2 separation at 180MPa

At all five different rail pressures, the trend of all injections does not vary much. There is still a difference between the requested quantities and achieved quantities.

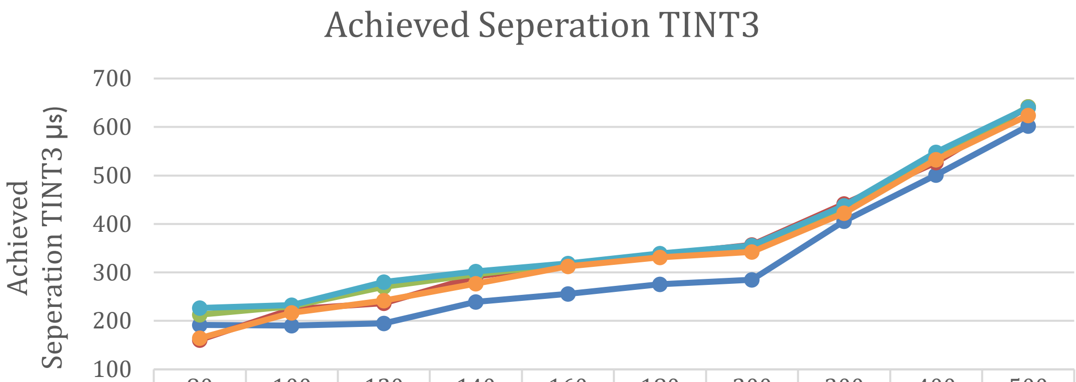
4.1.1.3 Tests were done varying TINT3

In this test, all the parameters are fixed except the TINT3 separation. The values of the fixed parameters are as shown in Table 4.3.

Table 4.3 - Values of fixed parameters with TINT3 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINTPre (µs)
1	1,95	5,85	16	25	476	185

- **TINT3 separation**



	80	100	120	140	160	180	200	300	400	500
60	192	190	195	240	256	275	285	406	501	602
119	161	224	236	291	317	337	357	441	527	642
129	213	230	270	296	317	338	354	436	533	642
149	227	233	280	302	318	339	356	438	548	640
180	164	217	242	277	313	331	343	422	533	624

Requested Dwell Time (µs)

Figure 4.9 - Requested TINT3 separation vs Achieved TINT3 separation at different rail pressures (60, 119, 129, 149, 180 MPa)

The plot in Figure 4.9 shows the requested TINT3 separation vs achieved TINT3 separation. All separations are detected by the software. 119 MPa is the actual rail pressure for this load point in the current Gen3 Volvo engine.
There is a lot of variation between the requested and achieved TINT3 separation.

- **Quantities of each injection**

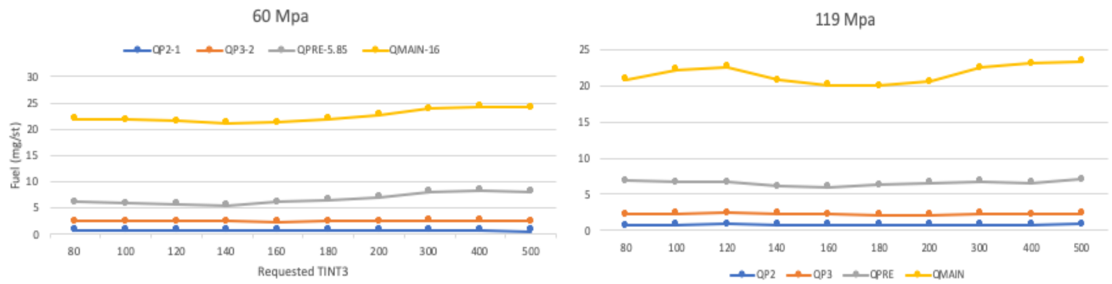


Figure 4.10 - Achieved fuel quantity of each injection vs requested TINT3 separation at 60MPa and 119MPa rail pressure

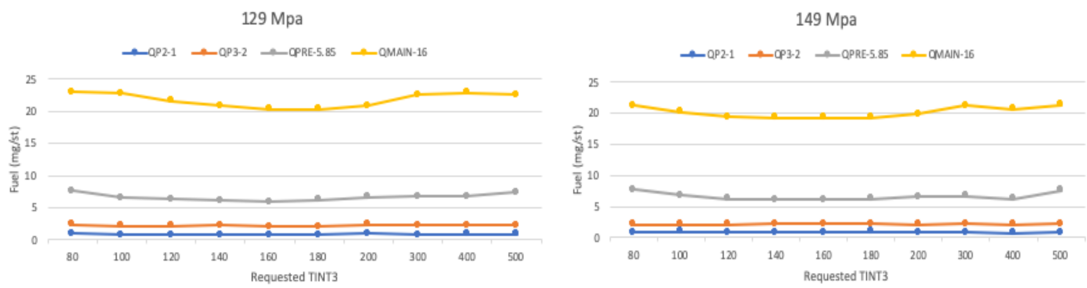


Figure 4.11 - Achieved fuel quantity of each injection vs requested TINT3 separation at 129MPa and 149MPa rail pressure

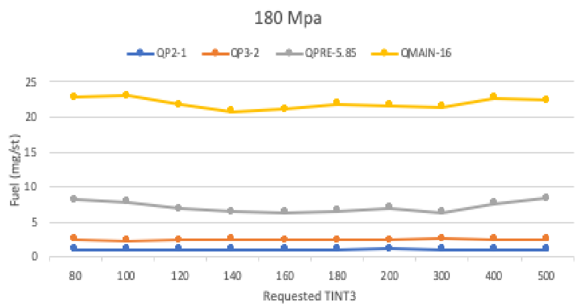


Figure 4.12 - Achieved fuel quantity of each injection vs requested TINT3 separation at 180MPa

At all 5 different rail pressures, the trend of all injections does not vary much. There is still a difference between the requested quantities and achieved quantities.

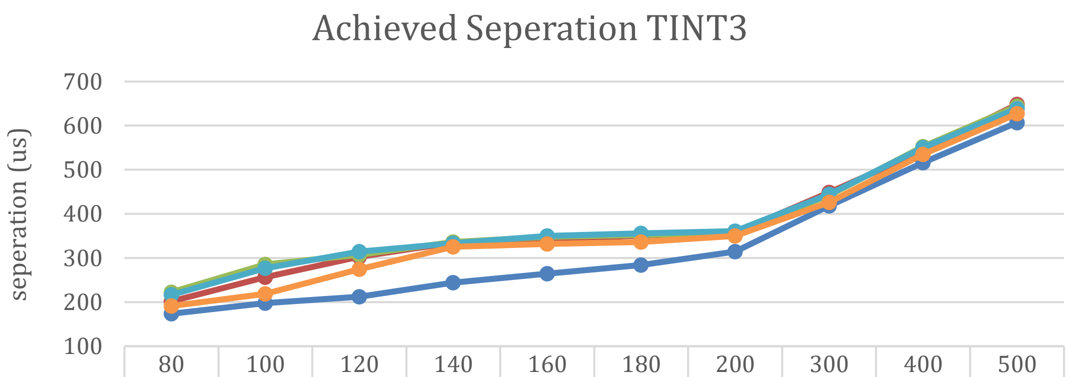
4.1.1.4 Tests were done varying TINT3 (Quantities doubled)

This is a test done varying TINT3 and fixing the other parameters as shown in Table 4.4. This is the same test as seen in section 4.1.1.3 QP3 pilot quantity is doubled, the total fuel quantity is still 25mg/stroke.

Table 4.4 - Values of fixed parameters with TINT3 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINTPre (µs)
1	3,9	5,85	14	25	476	185

- **TINT3 separation**



	80	100	120	140	160	180	200	300	400	500
60	174	198	213	244	264	284	314	419	516	607
119	202	257	303	335	342	351	357	449	543	648
129	222	285	307	336	348	352	357	442	552	644
149	216	277	314	333	350	356	361	445	551	639
180	191	219	274	325	332	336	350	426	535	627

Requested Dwell Time

Figure 4.13 - Requested TINT3 separation vs Achieved TINT3 separation at different rail pressures (60, 119, 129, 149, 180 MPa)

The plot in Figure 4.13 shows requested TINT3 separation vs achieved TINT3 separation. All separations are detected by the software. 119 MPa is the actual rail pressure for this load point in the current Gen3 Volvo engine.
There is a lot of variation between the requested and achieved TINT3 separation.

- **Quantities of each injection**

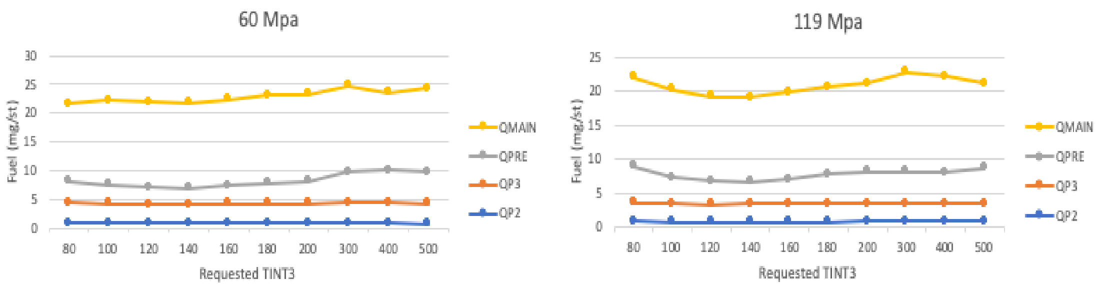


Figure 4.14 - Achieved fuel quantity of each injection vs requested TINT3 separation at 60MPa and 119MPa rail pressure

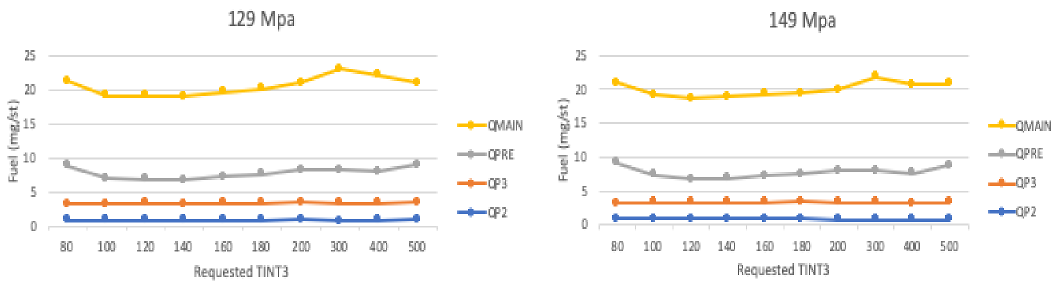


Figure 4.15- Achieved fuel quantity of each injection vs requested TINT3 separation at 129MPa and 149MPa rail pressure

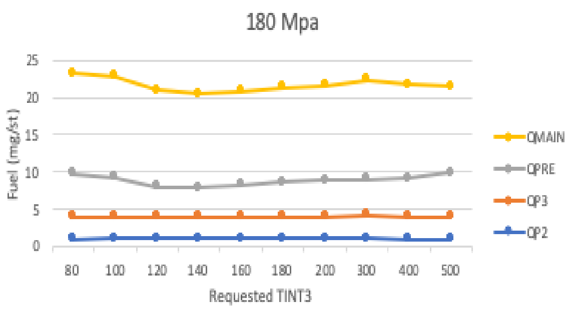


Figure 4.16- Achieved fuel quantity of each injection vs requested TINT3 separation at 180MPa

At all 5 different rail pressures, the trend of all injections does not vary much. There is still a difference between the requested quantities and achieved quantities.

4.1.1.5 Tests were done varying TINTPRE

In this test, all the parameters are fixed except the TINT2 separation. The values of the fixed parameters are as shown in Table 4.5.

Table 4.5 - Values of fixed parameters with TINTPRE as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)
1	1,95	5,85	16	25	476	115

- **TINTPRE separation**

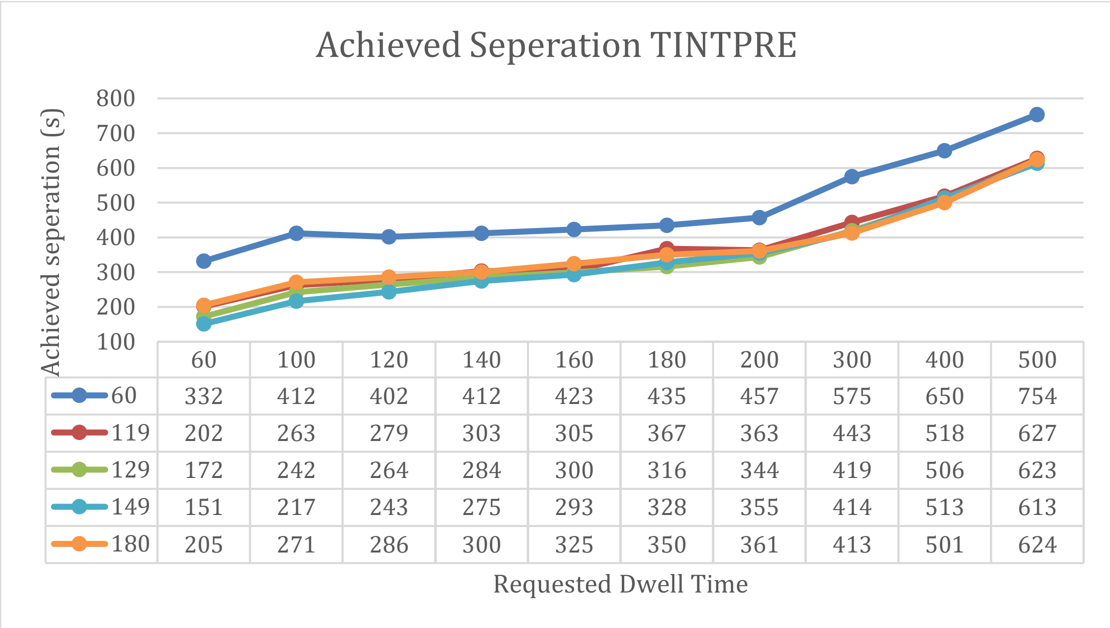


Figure 4.17- Requested TINTPRE separation vs Achieved TINTPRE separation at different rail pressures (60, 119, 129, 149, 180 MPa)

The plot in Figure 4.17 shows requested TINTPRE separation vs achieved TINTPRE separation. All separations are detected by the software. 119 MPa is the actual rail pressure for this load point in the current Gen3 Volvo engine.
There is a lot of variation between the requested and achieved TINTPRE separation.

- **Quantities of each injection**

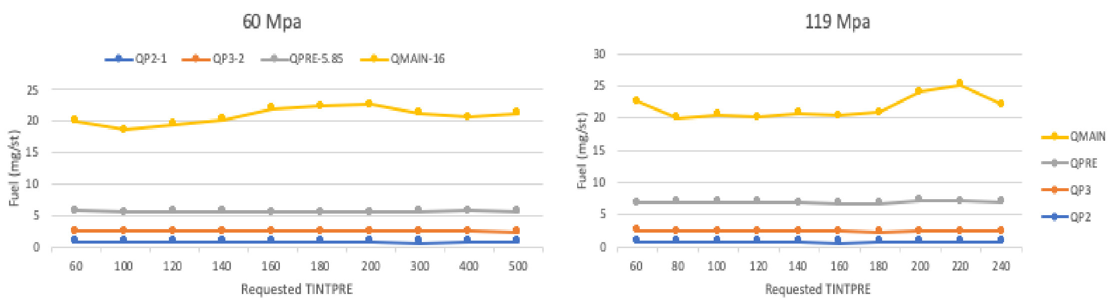


Figure 4.18 - Achieved fuel quantity of each injection vs requested TINTPRE separation at 60MPa and 119MPa rail pressure

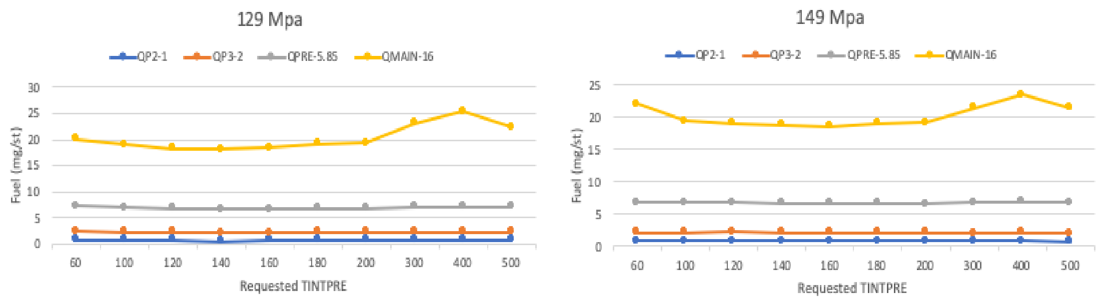


Figure 4.19 - Achieved fuel quantity of each injection vs requested TINTPRE separation at 129MPa and 149MPa rail pressure

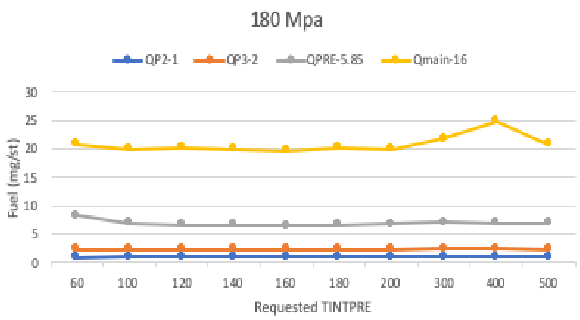


Figure 4.20 - Achieved fuel quantity of each injection vs requested TINTPRE separation at 180MPa

At all 5 different rail pressures, the trend of all injections does not vary much. There is still a difference between the requested quantities and achieved quantities.

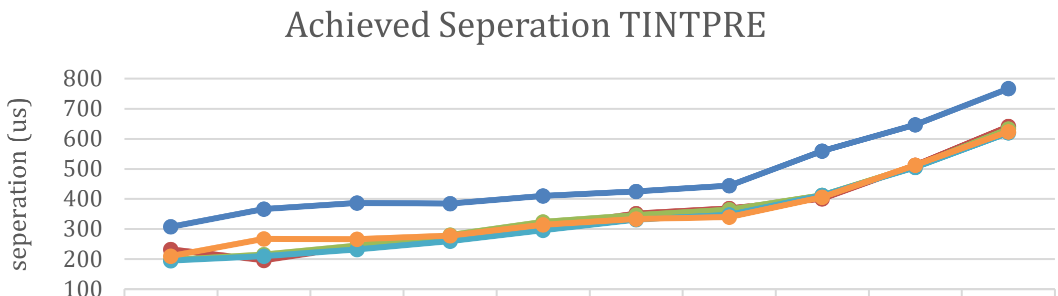
4.1.1.6 Tests were done varying TINTPRE (Quantities doubled)

This is a test done varying TINTPRE and fixing the other parameters as shown in Table 4.6. This is the same test as seen in section 4.1.1.5 but QP2 and QP3 pilot quantities are doubled, the total fuel quantity is still 25mg/stroke.

Table 4.6 - Values of fixed parameters with TINTPRE as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)
2	3,9	5,85	13	25	476	115

- **TINTPRE separation**



	60	100	120	140	160	180	200	300	400	500
60	307	367	386	385	410	425	444	559	647	766
119	232	196	243	270	307	351	368	401	512	641
129	197	215	245	280	324	346	365	412	509	632
149	195	210	232	260	295	331	347	412	505	619
180	210	267	266	278	314	334	339	406	513	624

Requested Dweel Time

Figure 4.21 - Requested TINTPRE separation vs Achieved TINTPRE separation at different rail pressures (60, 119, 129, 149, 180 MPa)

The plot in Figure 4.21 shows requested TINTPRE separation vs achieved TINTPRE separation. All separations are detected by the software. 119 MPa is the actual rail pressure for this load point in the current Gen3 Volvo engine.
There is a lot of variation between the requested and achieved TINTPRE separation.

- **Quantities of each injection**

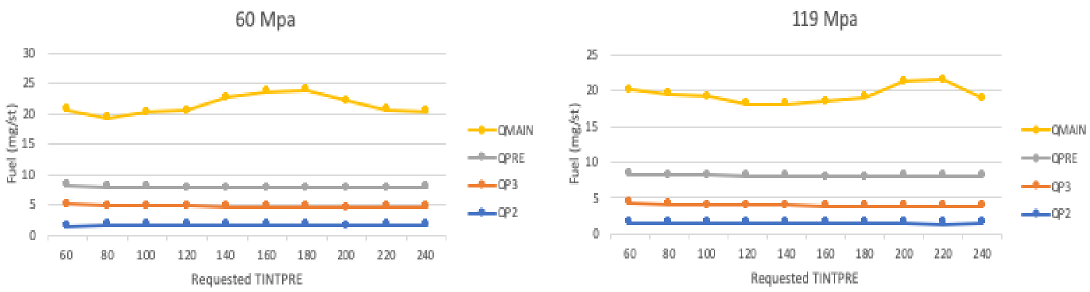


Figure 4.22 - Achieved fuel quantity of each injection vs requested TINTPRE separation at 60MPa and 119MPa rail pressure

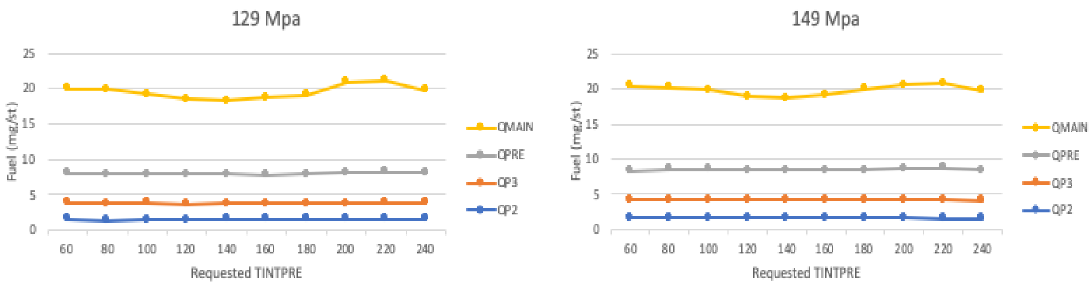


Figure 4.23 - Achieved fuel quantity of each injection vs requested TINTPRE separation at 129MPa and 149MPa rail pressure

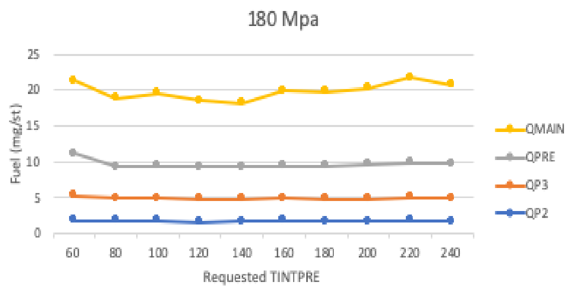


Figure 4.24 - Achieved fuel quantity of each injection vs requested TINTPRE separation at 180MPa

At all 5 different rail pressures, the trend of all injections does not vary much. There is still a difference between the requested quantities and achieved quantities.

4.1.2 Repeatability test- 1500rpm 15mg (load point P1)

Two different tests were conducted to check the repeatability and robustness of the injector performance at load point P1. During both the times, the values of the parameters were kept the same. After the first test, there was a gap of 3hours for the second test.

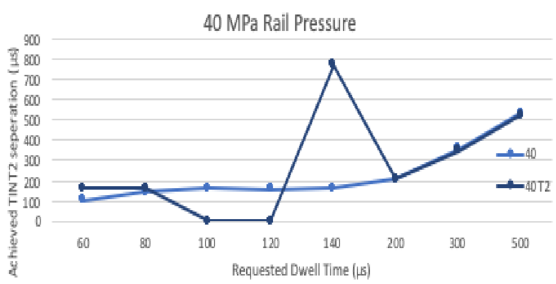
4.1.2.1 Tests were done varying TINT2

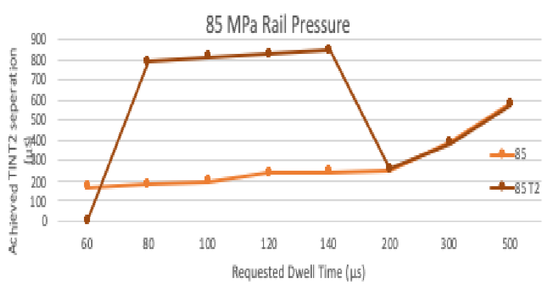
In this test, all the parameters are fixed except the TINT2 separation. TINT2 is varied between 60-500µs. The values of the fixed parameters are as shown in Table 4.7.

Table 4.7 - Values of fixed parameters with TINT2 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT3 (µs)	TINTPre (µs)
1	1,5	2,91	9,59	15	332	361

- **TINT2 separation**





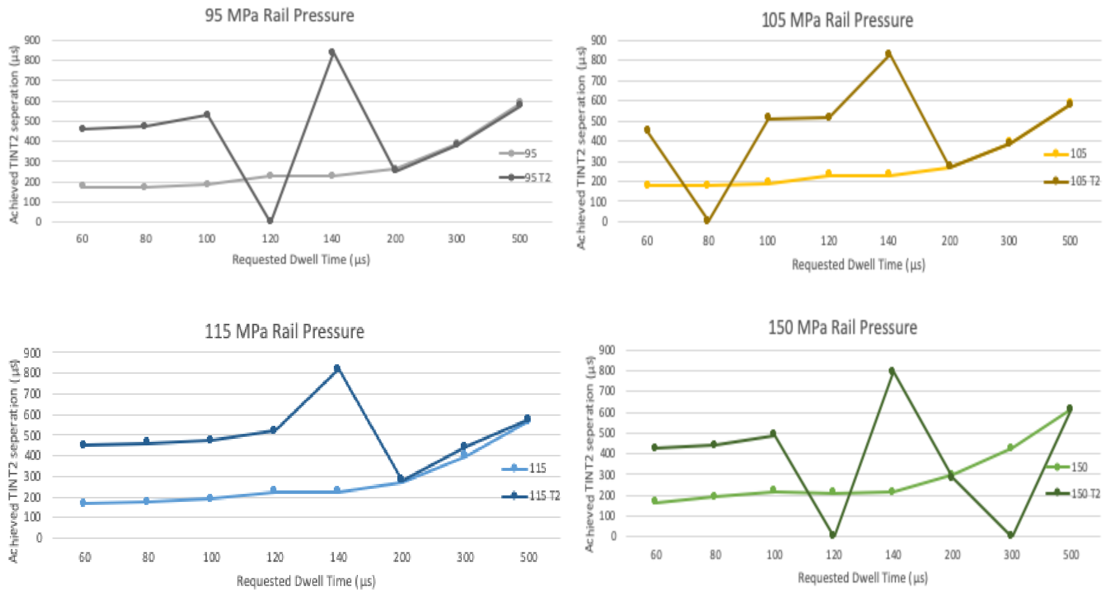
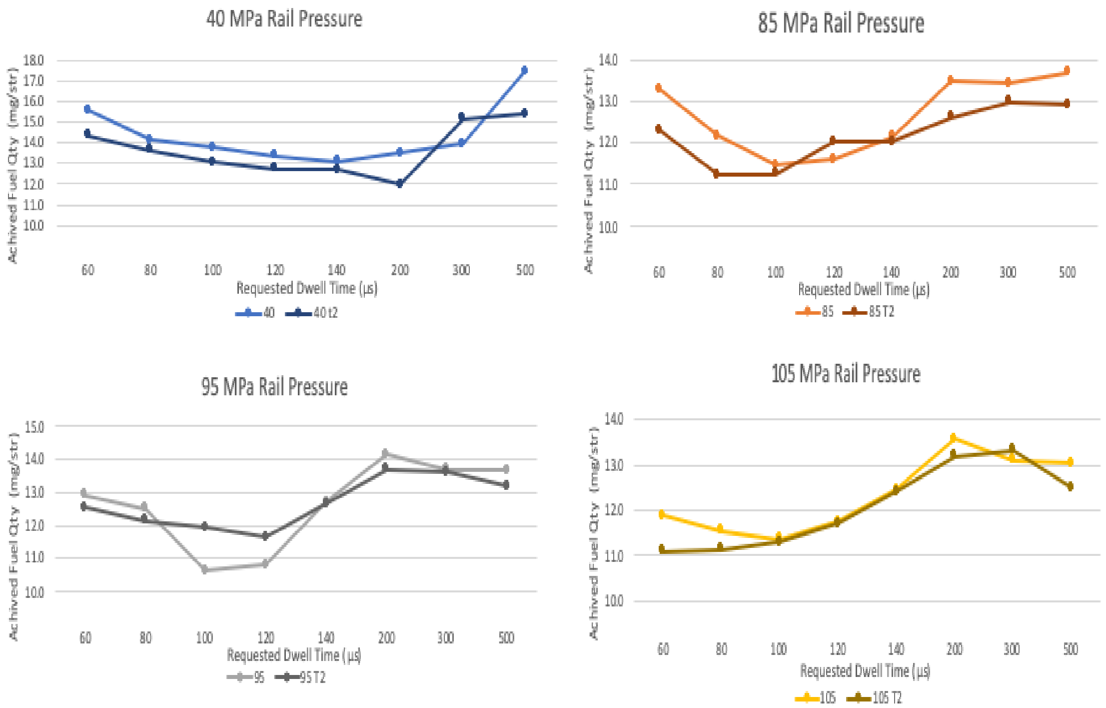


Figure 4.25 - Requested TINT2 separation vs Achieved TINT2 separation at different rail pressures (40, 85, 95, 105, 115, 150 MPa)

The plot in Figure 4.25 shows requested TINT2 separation vs achieved TINT2. It can be seen in the plots that there are a few values that are zero, these are the ones that are not detected by the Injection analyser software or the MATLAB script. The test name which ends with ‘T2’ (seen on the RHS of each plot) is the second test.

- **Total fuel quantity**



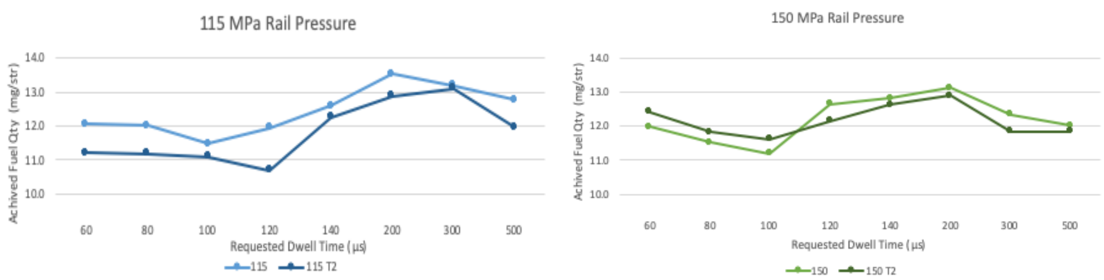


Figure 4.26 - Achieved total fuel quantity vs Requested TINT2 separation at different rail pressures (40, 85, 95, 105, 115, 150 MPa)

The total fuel quantity achieved vs the requested TINT2 separation is plotted for six different rail pressures. The test name which ends with 'T2' (seen at the bottom of each plot) is the second test. The requested total fuel quantity is 15 mg/stroke.

- **QP2 quantity**

Figure 4.27 - Achieved QP2 fuel quantity vs Requested TINT2 separation at different rail pressures (40, 85, 95, 105, 115, 150 MPa)

In Figure 4.27 QP2 quantity achieved vs the requested TINT2 separation is plotted for six different rail pressures. The test name which ends with 'T2' (seen at the bottom of each plot) is the second test. It can be seen here QP2 does not achieve consistent fuel at low rail pressure.

4.2 Modelling and validation

Based on the measurements from the single-cylinder rig, combustion models were created in ASCMO. The purpose of developing the models was to understand the complex relationships between parameters. This allows us in developing calibration map based on these model predictions. The quality of the model was determined by the coefficient of determination (R2). This determines how well the model can predict all the measured points. For example, in the case of CO, the model can predict only 77% of the variation in data, and 23% of the data is not predicted. The values are shown in Table 4.8.

Table 4.8 - Model quality

Model	RMSE	R2
CO	4.8882	0.82442
NOx	2.8457	0.98101
THC	3.8916	0.39134
Noise	0.12615	0.99012
BSFC	0.62475	0.49916

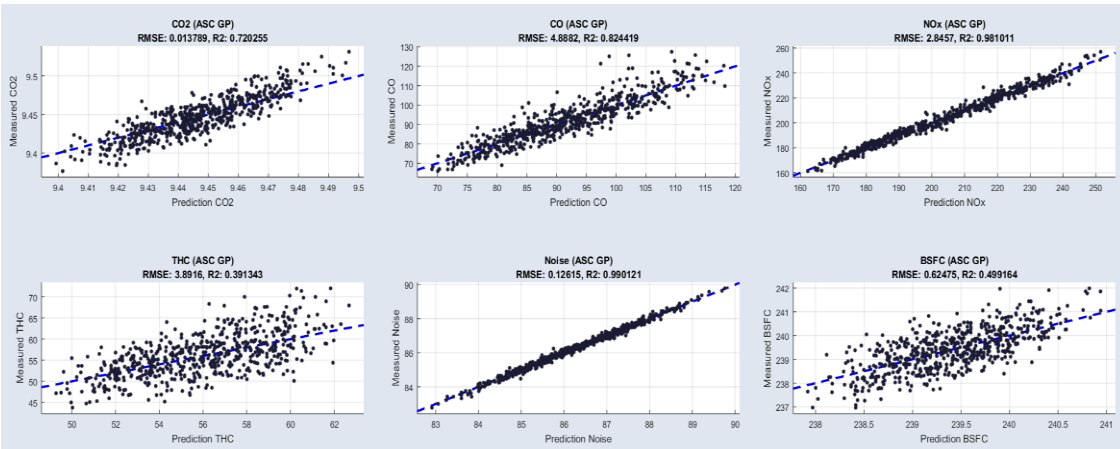


Figure 4.28 - Model quality

Individual optimizations were run for each output parameter, this was done to understand each parameter response on other output. For example, when NOx was optimised for minimum it is seen that bsfc would go up. This is bound to happen since the temperature is one of the factors for causing NOx. So, in this case, model's optimisation suggested a delay in MBF50 and lower rail pressure which would influence bsfc negatively.

Finally, a trade-off optimisation was created by considering these influential parameters. In this optimisation, NOx and noise were limited by target value and bsfc was set to 'minimum' and all outputs were prioritised by weights. These settings (dwell, quantity, and rail pressure) were tested in a single-cylinder test rig for checking the model validity. This is shown in Figure 4.29.

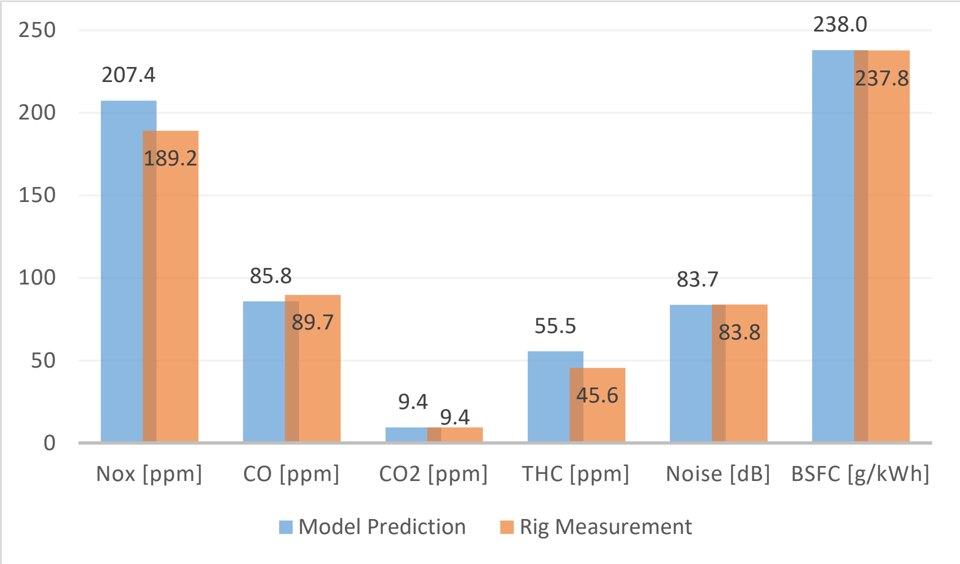


Figure 4.29 - Model validation results

The model has good accuracy for bsfc, noise models, notably bsfc which seems quite good considering the model quality, this could be due to a low RMSE value. NOx model shows the drift of 9%, which is fine since we use ppm for measuring. Maximum drift is noticed for THC model with 18% difference, this is expected and is due to THC model quality. Overall, the model is satisfactory from validation results and can be used to analyse the data quantitatively.

From the model's response curves, a relevant input parameter affecting the combustion is derived shown in
Table 4.9. NOx, BSFC, CO are most sensitive to MBF50%, but noise is very sensitive to TINT3. This table will be the most significant in determining how to calibrate the triple pilot injection input parameters to achieve the goal of fuel-efficient combustion.

From a calibration perspective, an efficient way to achieve good overall triple pilot strategy would be to fix the QP2 parameter for a definite value, as this holds very less relevance from the
Table 4.9 for any output parameter. Then based on the primary requirement, for example, to better optimise for the noise the critical input parameter affecting it would be pilot 3 (quantity and dwell). Hence these could be calibrated to achieve the results. Similarly, to achieve bsfc, phasing and TINTPre are critical.

Table 4.9 - Relevant parameters chart based on combustion modelling

Output parameter	**MFB 50**	**Rail pressure**	**QP2**	**QP3**	**QPRE**	**TINT2**	**TINT3**	**TINT PRE**
CO_2	+ + + +	+ + + +				+ +		+ + +
CO	+ + + +	+ + + +			+ +	+ + +		+ +
NOx	+ + + +							
THC								
NOISE		+ +		+ + + +			+ + + +	
BSFC	+ + + +	+ +		+ + +	+ + +			+ + + +

Representation –
+ + + + : highest relevant parameter
+ + + : Medium relevant parameter
+ + : Low relevant Parameter

4.3 Engine Results: Single-cylinder test rig

The experiment was conducted for only one load point. Based on the restriction with the availability of the test rig, the load point P2 was chosen as it presents a better understanding of the impacts of dwell time, fuel quantities compared to P1 and P3. Thus, the results further will be based on load point P2 (1500rpm at 25mg/str).

The response models' curve is used to predict the trend for all output parameter except THC. For the case of NOx, which is quite sensitive towards the MFB 50%. A higher the MBF value results in lower NOx, which can be attributed to combustion happening when the piston is moving towards BDC. Other input parameters do not affect NOx substantially. Similarly analysing all the output parameters, the model is optimised for and the settings achieved are shown in Table 4.10.

Table 4.10 - An MBC optimised trade-off settings

MFB 50%	Rail pressure (MPa)	QP2 (mg/str)	QP3 (mg/str)	QPRE (mg/str)	TINT2 (µs)	TINT3 (µs)	TINTPRE (µs)
8.63	110.73	1.57	2	4.81	370	147	204

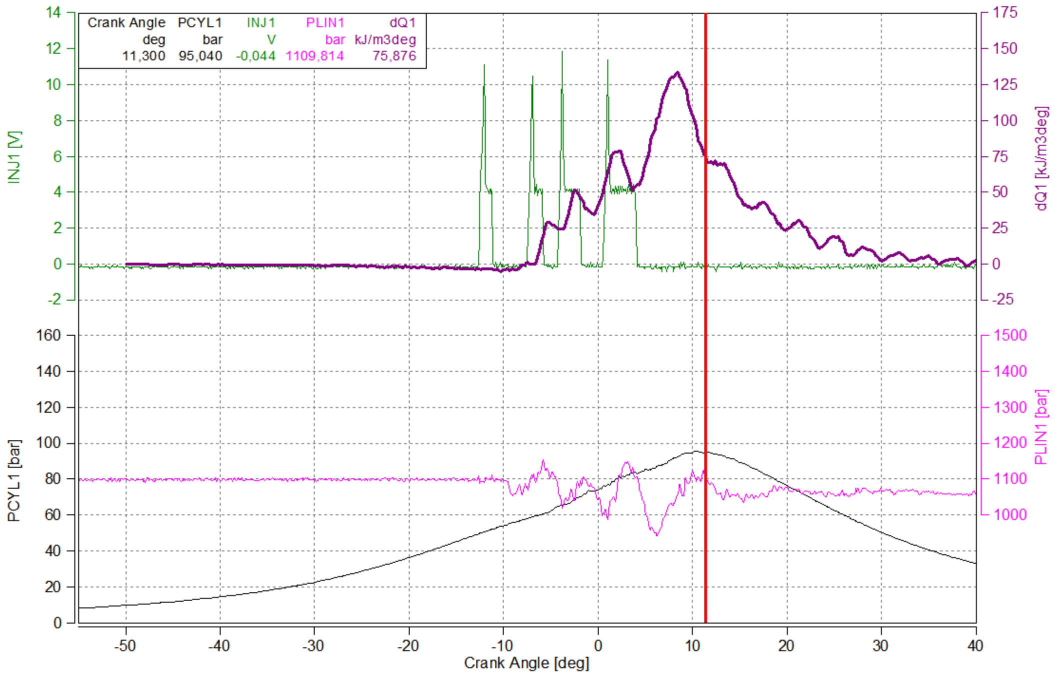


Figure 4.30 – Single cylinder results from MBC Optimisation trade-off settings

INJ [V] – Injector electrical signal

dQ [kJ/m^{3}deg] – Rate of heat release

PCYL [bar] – Cylinder pressure

PLIN [bar] – Rail pressure

In Figure 4.30, it can see there is a delay in an electrical signal generated and the actual injection happening, this is the same delay which was seen even in FIE test rig – energising dwell and hydraulic dwell. In the above plot, each peak in the ROHR curve (dQ axis) until the large peak represent combustion from each pilot and main. Adding each pilot quantity in ascending order and tuning the dwell time gives the time for good mixture and improves the flame propagation until the final peak from the main injection. Thus, achieving a smooth curve. Each fuel injection causes rail pressure oscillation, and which directly affects the subsequent injections. Thus separation (dwell) between the injection is also critical in achieving the good combustion.

Comparing the results to baseline triple pilot strategy the improvements are shown in Figure 4.31. It shows a considerable increase over baseline.

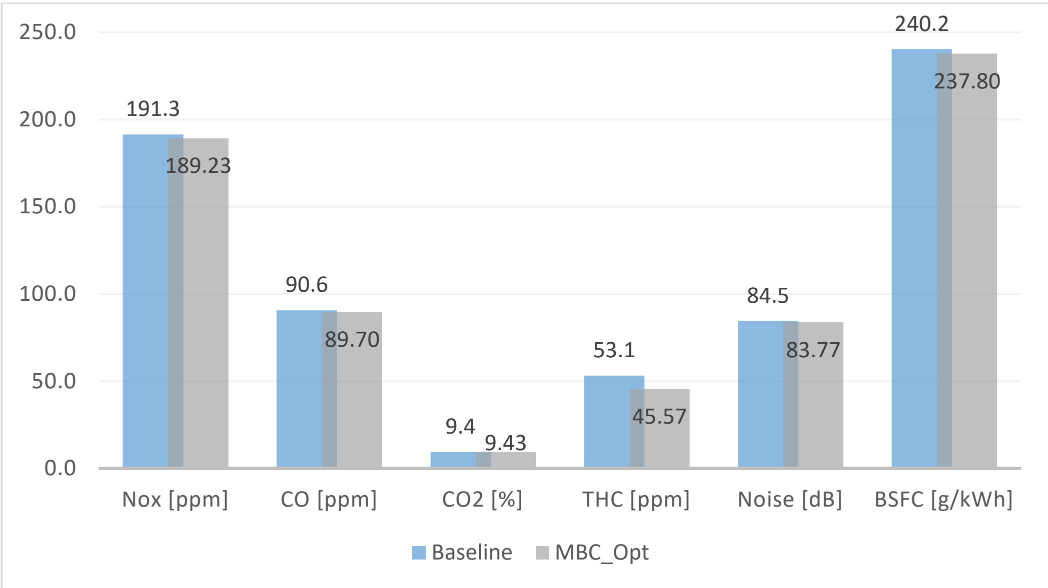


Figure 4.31 - Results comparing baseline vs MBC based optimised settings

Combustion noise, CO, and NOx have improved quite a lot but a considerable improvement can be seen for bsfc which is improved by 1% over the baseline, one thing to also notice is NOx has not been set at a specific value. As bsfc and NOx have an inverse relation, so if NOx is set to baseline value then the improvement in terms of bsfc could be more than 1%.

Repeatability of Single-cylinder engine

The injection settings shown in Table 4.11 was a repetition point included in 600 points DoE, which was run on different days. This was done to check the consistency of the injection and engine performance. The repetition point was included at every 50th point. In Figure 4.32 ROHR curves of 8 different days are overlapped on top of each other.

Table 4.11 - The repeatability point parameter

Rail Pressure (Mpa)	QP2 (mg/str)	QP3 (mg/str)	Qpre (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)	TINTPre (µs)
120	1	2	4	25	476	120	185

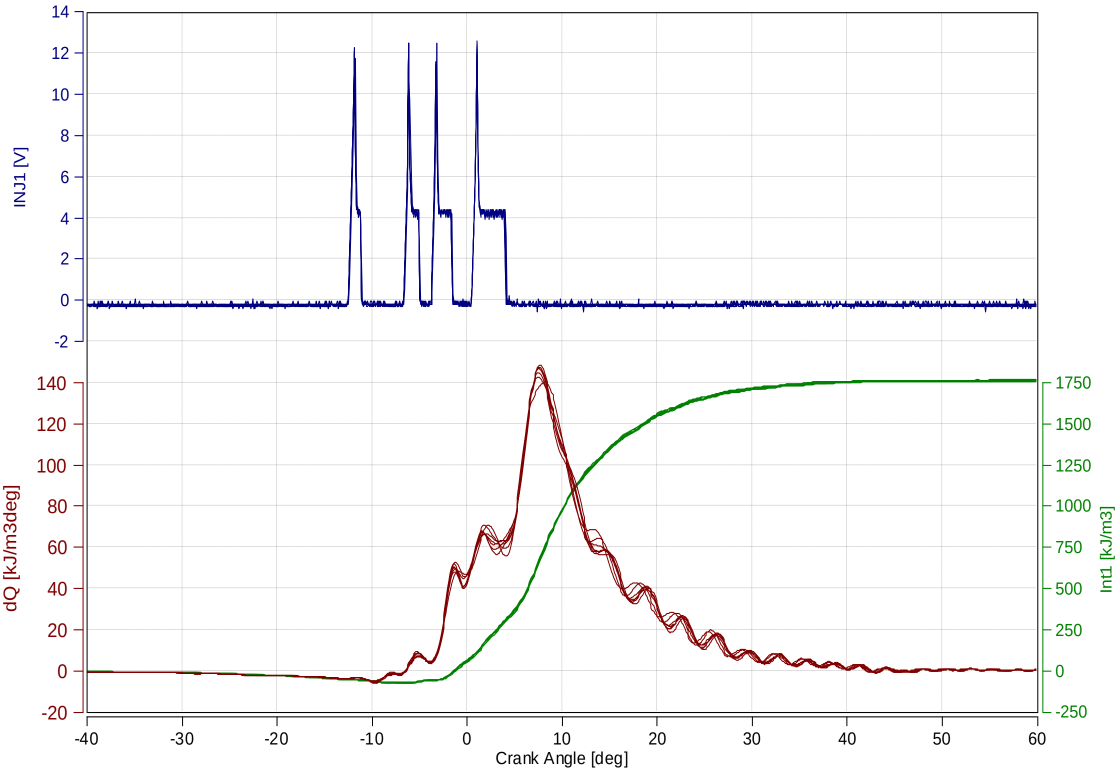


Figure 4.32 - Check for repeatability based on ROHR

It is quite evident from the above plot; the ROHR curve indicates a robust in achieving consistent fuel injection and separation.

4.4 Engine Results: Multi-cylinder test rig

The aim was to replicate the improvements seen in the single-cylinder to the production engine and understand the fuel injection pattern into the system. The focus in this section will be to understand the fuel injection pattern from both test rigs. Same optimisation settings were run in this test rig and nothing has been optimised for this engine. However, it must be noted that the injector model in ECU used is calibrated for a multi-cylinder engine and is different compared to the one used in the single-cylinder test rig. The settings used to run the test rig are the same as in Table 4.10.

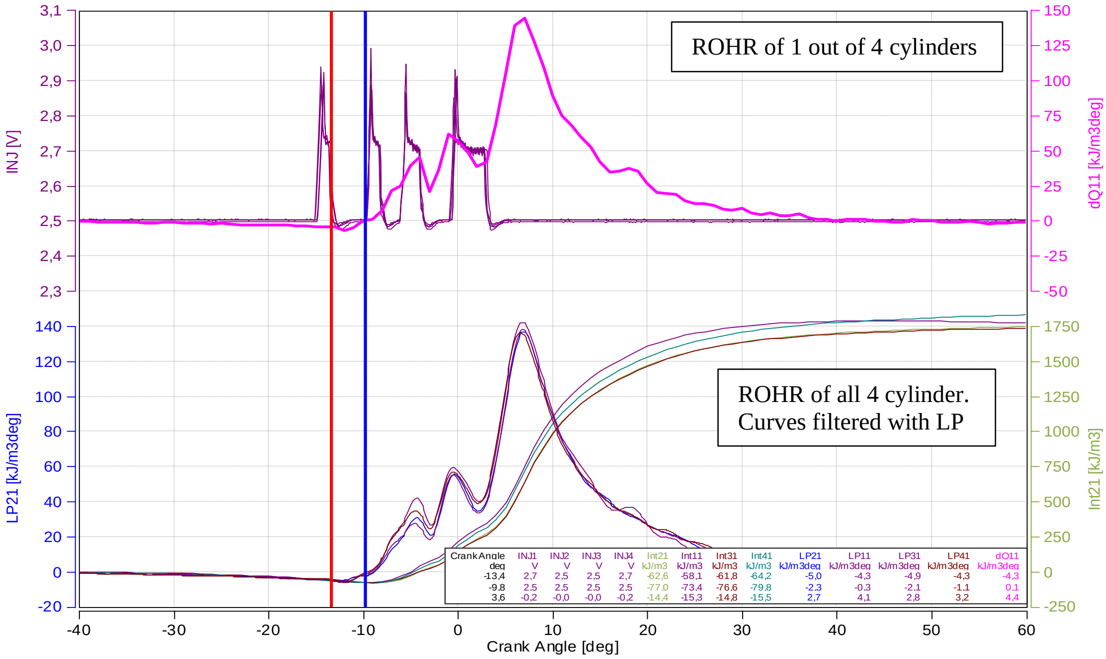


Figure 4.33 - Multi-cylinder ROHR from MBC optimised settings

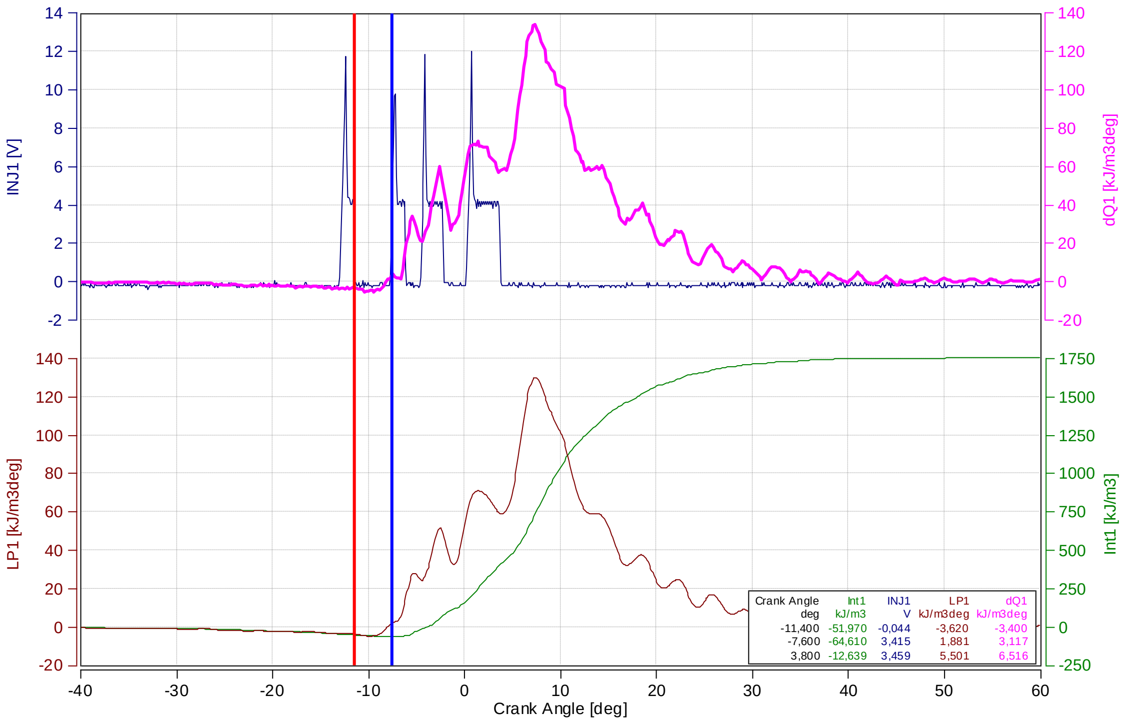


Figure 4.34 - Single cylinder ROHR from MBC optimised settings

From Figure 4.33, looking at ROHR curve for all 4 cylinders (smoothen ROHR curve with low pass filter), the pilot 2 seems to be fused with pilot 3 and then there is combustion. This is seen when looked at the single curve from 4 cylinders (unfiltered ROHR curve) there is a small noticeable bump at pilot 2 and smoothly mergers with pilot 3. For pilot 3 and pilot pre a clear separation is visible and there is combustion for these pilots. But after pilot pre, there is a large peak for the main injection, could be due to large separation. The achieved heat release for pilot pre is 750 kJ/m^3 and for single cylinder, it is more than 750 kJ/m^3. Overall ROHR curve does not ascend in smooth order.

This is not the case in a single-cylinder test rig, from Figure 4.34 ROHR curve (unfiltered curve - pink coloured) there is a clear peak for pilot 2 and pilot 3. The curve is gradually increasing, this difference could be due to either different calibration of a-Art or poor injector performance in achieving smaller separation in multi-cylinder setup. The issue with the ECU sending weak signal can be ignored since the energising dwell (electrical dwell) generated match for both the cases. This problem was discussed with the supplier since it was completely different from their claim of achieving minimum shorter separation of 100µs. Later, they suggested to try increasing the pilot 2 quantity and understand if this was due to separation.

Hence, the best case suitable for this investigation would be a noise ROHR curve, which ideally requires a shorter separation and smooth curve [8]. MBC model was optimised for noise and obtained settings are shown in Table 4.12. Two cases were run to understand the issue.

Table 4.12 - An MBC noise optimised settings

Rail Pressure (Mpa)	QP2 (mg/str)	QP3 (mg/str)	Qpre (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)	TINTPre (µs)
116	1.8	2.8	4.4	25	316	129	205

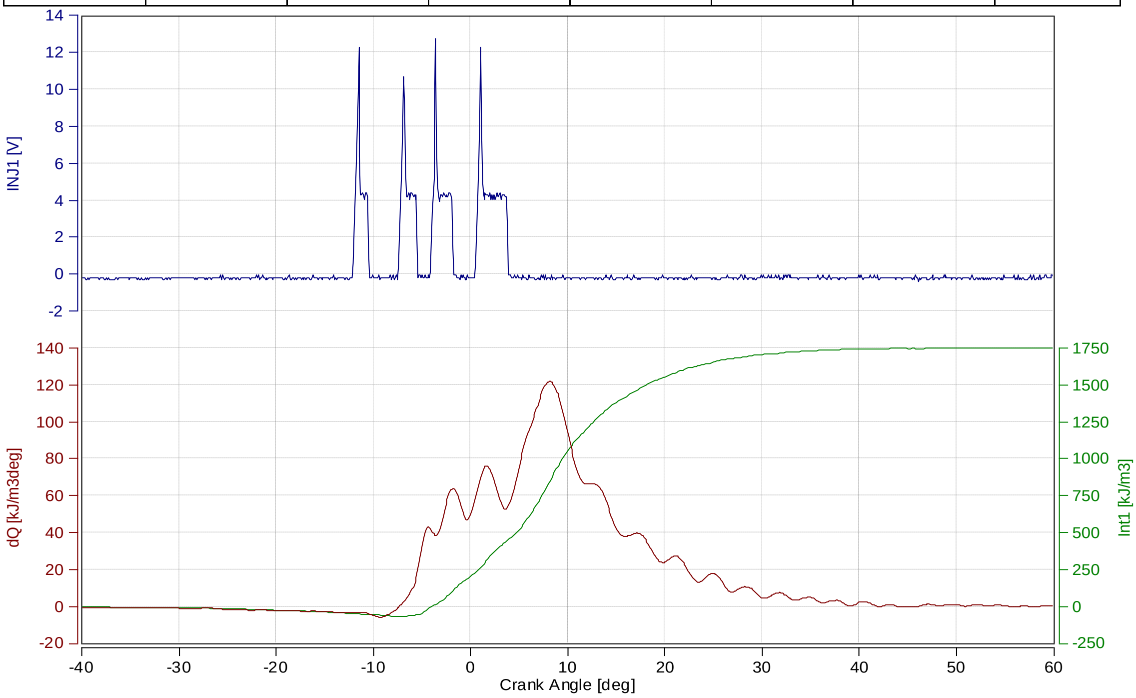


Figure 4.35 - Single cylinder ROHR from MBC noise optimised settings

Case 1: Normal MBC noise optimised settings

In this case, the above MBC noise settings were run in both test rigs and ROHR curve was plotted to see the achieved pilot performance. Studying Figure 4.36 with TINT2 separation of 316µs and QP2 quantity of 1.8 mg/str, there is pilot 2 injection into the system because it is not taking part in combustion there is no peak but instead, it fuses with pilot 3 injection. This is justified, as a higher ROHR peak for pilot 3 compared to pilot pre.

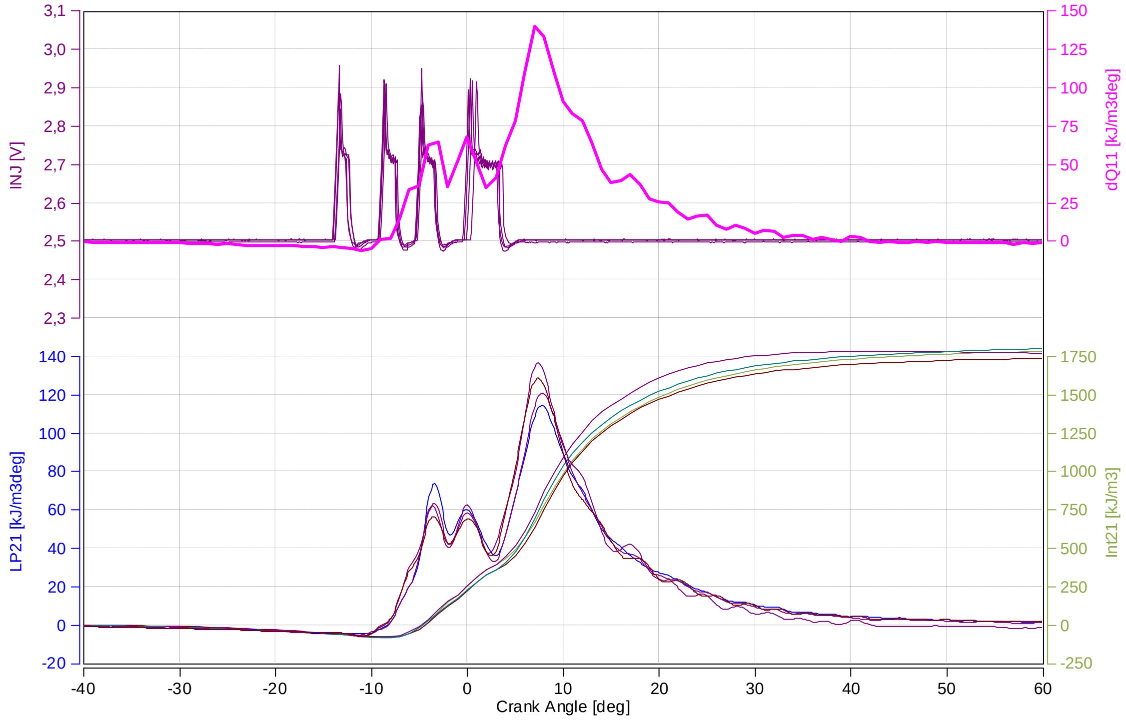


Figure 4.36 - Multi-cylinder ROHR from MBC noise optimised settings

For the same settings in the single-cylinder test rig, there are clear peaks visible for each pilot, refer Figure 4.35. The peaks from pilots are tighter and have a gradual smooth increase. The injector signal was also observed for any discrepancy, but this was dismissed as the timing of this signal based on the crank angle has not varied at all.

Case 2: Normal MBC noise optimised settings but only QP2 increased.

This test was only run in the multi-cylinder test rig since the separation issue was noticed in this rig. In the 2nd case, only QP2 quantity was increased manually, and other parameters were unchanged. The increment in QP2 was performed from 1.8mg/str until a clear indication of pilot 2 taking part in combustion was observed, this was noticed at 2.5mg/str.

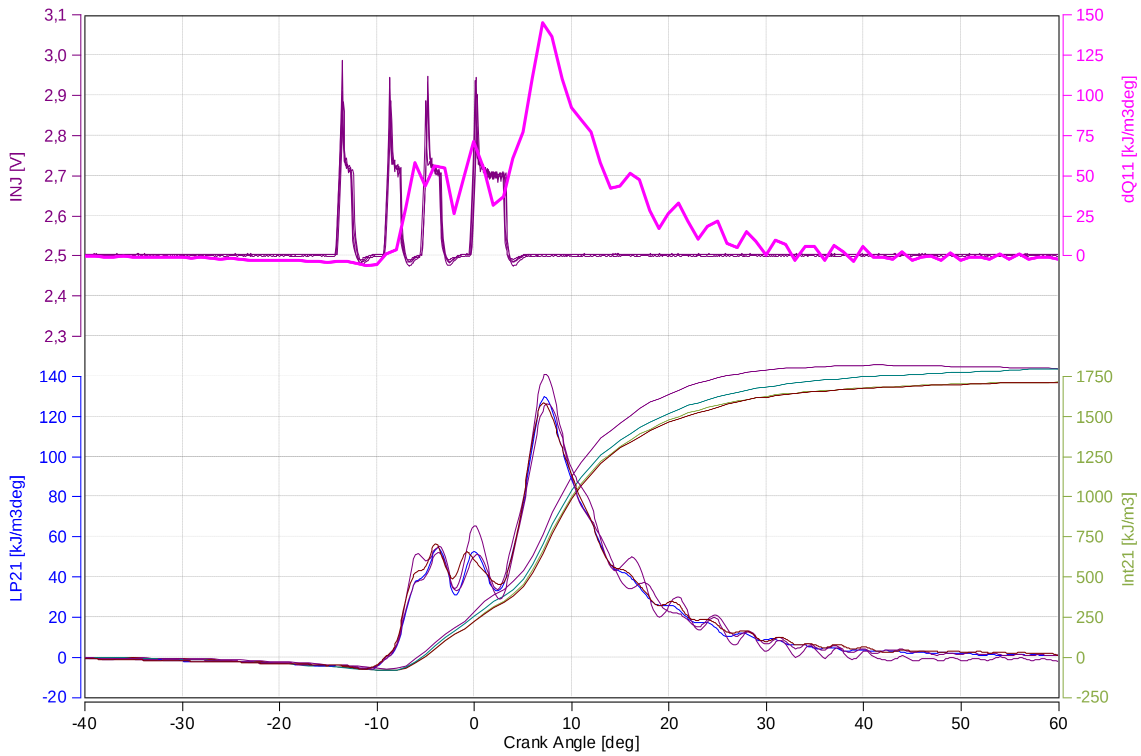


Figure 4.37 - Multi-cylinder results from MBC noise optimised settings with QP2 increase to 2.5mg/str

The pilot 2 is indicating a small bump in ROHR curve as seen in Figure 4.37, the quantity was not possible to increase further since this would affect the pilot 3 which was injected with 2.8mg/str. Increasing the QP3 quantity will again affect the pilot 2 and will cause the fusion issue and also directly influence the pilot pre.

Overall, this problem pertains to achieving separation/dwell at smaller quantities and to achieve the separation, the quantity of pilot must be increased and this conflicts with the supplier's restriction to not exceed the pilot quantity above 5mg/str. If we increase the pilots in ascending order for smoother combustion then the QPre will have to exceed the set limit, then it could affect the accuracy and stability of injection.

5 Conclusion and discussion

The current work was undertaken to improve diesel combustion through digital rate shaping by injecting pilots before the main injection. Thus, define the software settings for triple pilot strategy and way to calibrate it to improve fuel consumption and reducing the emissions. Following conclusions are drawn:

- **FIE test rig.**

This was the first stage of verifying the minimum possible hydraulic separation achievable. Since the results show a lot of variation in terms of quantities achieved and separation/dwell, therefore it could be said that the injector performance was not satisfactory. The achieved separation was completely deviating than requested separation, also it was difficult to quantify this deviation as no trend was observed due to irregular changes at different rail pressure and separation time. Even after many iterations of tuning software by the supplier to detect the pilot accurately has not been helpful. The pilot quantities especially pilot 2 would go undetected or deliver inaccurate quantity.

One of the variations which can cause this inaccuracy could be the pressure in fuel injection tube. It has been maintained at constant pressure for all the rail pressure tested in the rig. Whereas this is not the case in Engine rig, the pressure inside the cylinder varies based on the load point and may cause different fuel delivery due to the back pressure acting on the needle of the injector. This will impact the needle lift and fuel being delivered.

The repeatability results show highly unstable injector performance. Overall, the variation seen from the rig contradicts the supplier’s claim of achieving an accuracy of 1.25mg/str at 100µs separation for rail pressure 50-250MPa.

- **Engine test rig**

From a model-based calibration perspective, DRS for diesel combustion does show an overall improvement in terms of improved bsfc and reduced NOx compared to the baseline strategy. This has also been validated in the single-cylinder test rig. However, the hydraulic separations observed was based on ROHR curve and it is difficult to say if the separation achieved was exactly as requested.

The MBC shows that shorter separation produces better results in terms of fuel efficiency and reduced emissions. Finally, a relevance chart could be used to calibrate for the required optimisation. QP2 holds less relevance when calibrating the triple pilot strategy, thus can be set to a certain value for calibrating triple pilot strategy.

The results presented in the multi-cylinder test rig do not show the same improvements as in single cylinder since the separation was not accomplished. The results show similar results as seen in the FIE test rig. Inaccurate pilot quantities and separations intervals.

The inaccuracy in pilot injection quantity can affect combustion in multi-cylinder. For example, at cold start conditions, heating up the cylinder faster and maintaining emissions in RDE are critical. Based on the above results from FIE rig If the pre-pilot dwell time is not achieved as requested, and if it is close to main then it will amplify the main injection and can lead to higher combustion noise and increased soot. This will result in poor combustion. Hence the recommendation would be to have longer dwell time so that the pilot burns completely thereby spreading the combustion noise profile bit smoother.

From the Multi cylinder testing we can see that during higher loads the combustion happens so fast that the burning of three pilots might not happen fully. Therefore, this is also seen in ROHR curves where the pilot 2 is not taking part in combustion since it burns together with pilot 3 even though with pilot 2 has increased fuel. Hence the running with 2 pilots benifts both in terms of fuel and reduces the peak cylinder pressure.

The key findings from this work were not as expected and do not justify the supplier's claim. It is apparent that solenoid-based injector hardware is not capable of delivering accurate and robust shorter separation and smaller quantities which are critical for DRS technology.

6 Future Scope

As seen from this work DRS technology does show improvement with shorter intervals since the pilots act as flame propagation and this will reduce for the longer intervals. The injector is a critical part for attaining it, thus a recommendation would be to test the injector in FIE test rig with improved detection software in co-operation with the supplier.

Based on the MBC relevance chart, set up a new DoE, for example, set certain value for QP2 and create a new DoE thereby reducing the number of variables and complexity. It will be interesting to add EGR as variable into this DoE as this could influence the injection strategy, especially at low loads.

Carry out the tests directly in multi-cylinder rig as this will eliminate the probable issues when moved from single to multi-cylinder rig and could save time. Perform the tests with same injector models in ECU used in the single-cylinder rig. Optimising a steady-state on a multi-cylinders rig can be helpful when transient optimisation is carried out. Quantify the exact gain in fuel consumption by setting NOx to a certain value.

7 References

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8 Appendices

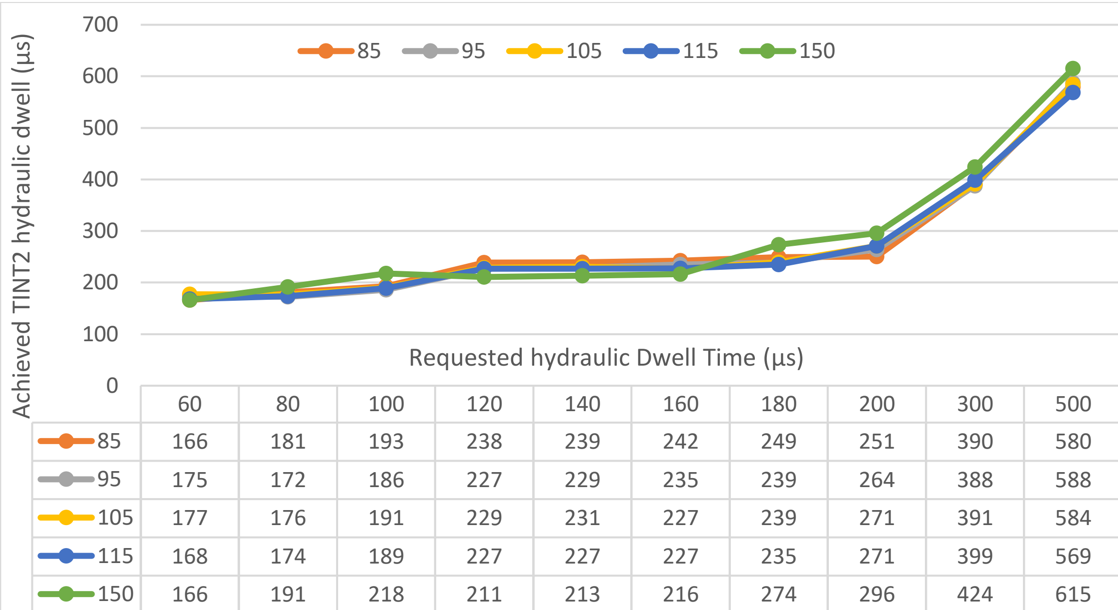
8.1 Load Point P1 – 1500 rpm and 15mg/str

8.1.1 Tests are done varying TINT2

Table 8.1 - Values of fixed parameters with TINT2 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT3 (µs)	TINTPre (µs)
1	1.5	2.91	9.59	15	332	361

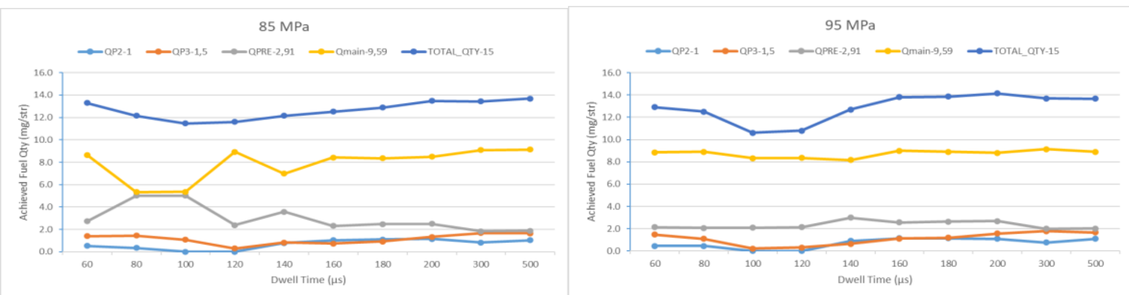
- **TINT2 Separation**



	60	80	100	120	140	160	180	200	300	500
85	166	181	193	238	239	242	249	251	390	580
95	175	172	186	227	229	235	239	264	388	588
105	177	176	191	229	231	227	239	271	391	584
115	168	174	189	227	227	227	235	271	399	569
150	166	191	218	211	213	216	274	296	424	615

Figure 8.1 - Requested TINT2 hydraulic dwell vs Achieved TINT2 dwell at different rail pressures (85, 95, 105, 115, 150 MPa)

- **Quantities of each injection**



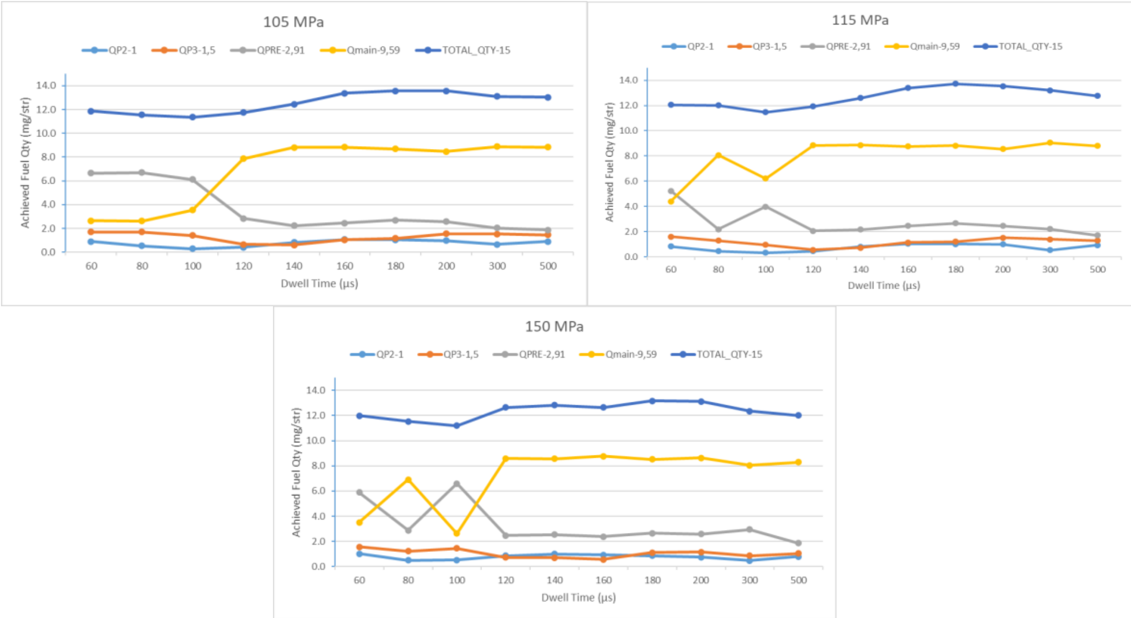


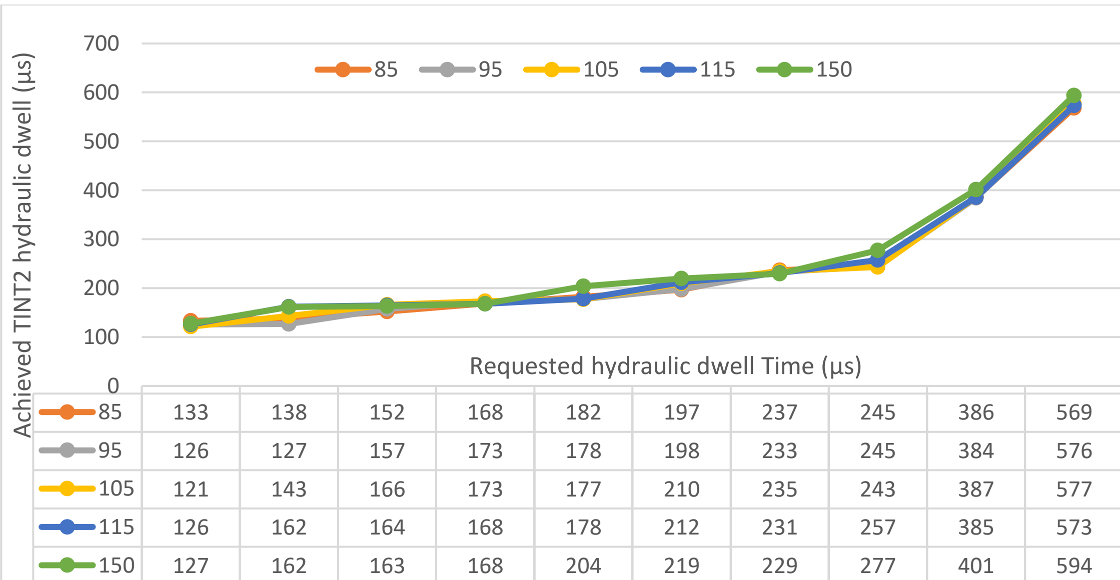
Figure 8.2 - Achieved fuel quantity of each injection vs requested TINT2 dwell at different rail pressure (85,95,105,115 & 150 MPa)

8.1.2 Tests are done varying TINT2 (Quantity doubled)

Table 8.2 - Values of fixed parameters with TINT2 as a variable parameter, only QP2 & QP3 doubled due to limitation in Total fuel quantity of 15mg/str

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT3 (µs)	TINTPre (µs)
2	3	2.91	7.09	15	332	361

- **TINT2 Separation**



85	133	138	152	168	182	197	237	245	386	569
95	126	127	157	173	178	198	233	245	384	576
105	121	143	166	173	177	210	235	243	387	577
115	126	162	164	168	178	212	231	257	385	573
150	127	162	163	168	204	219	229	277	401	594

Figure 8.3 - Requested TINT2 hydraulic dwell vs Achieved TINT2 dwell at different rail pressures (85, 95, 105, 115, 150 MPa) for pilot quantities doubled

- **Quantities of each injection**

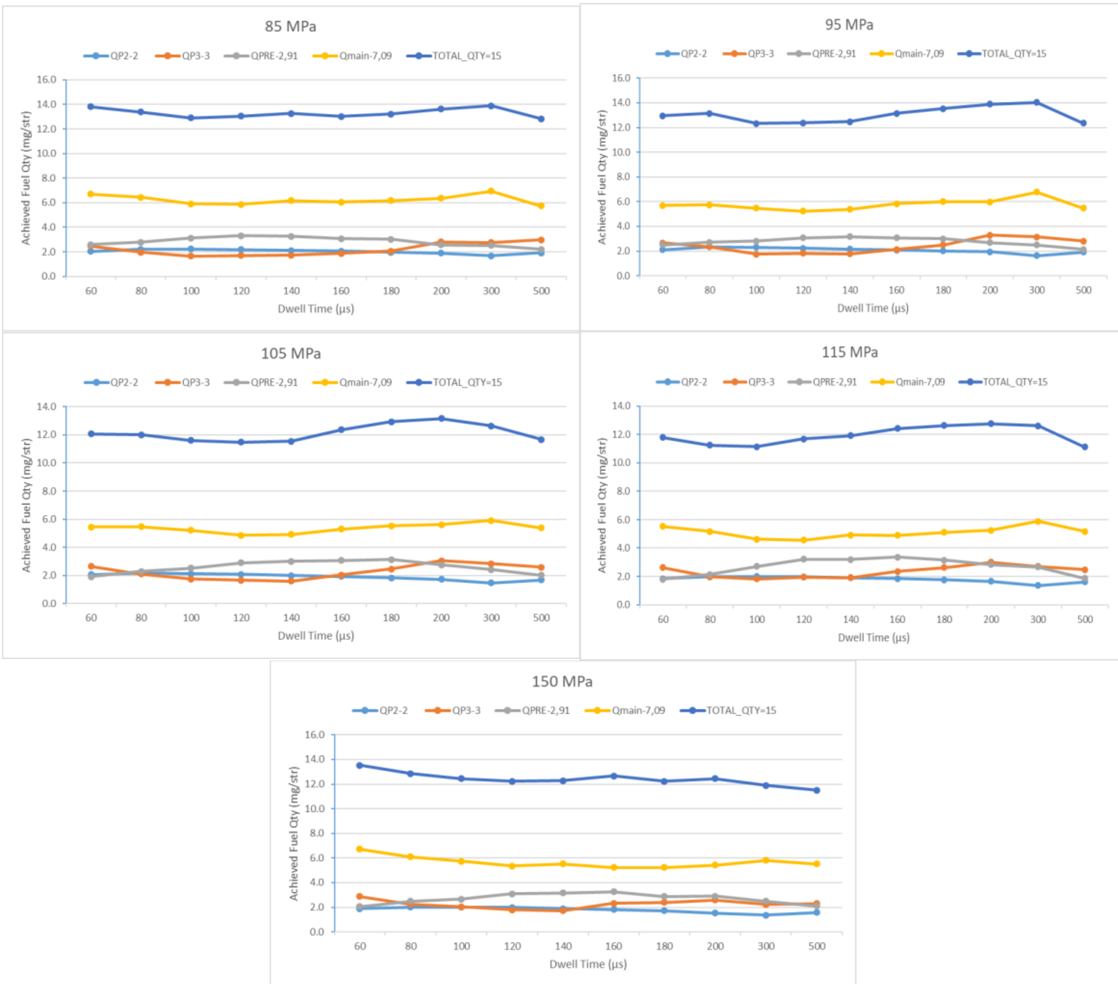


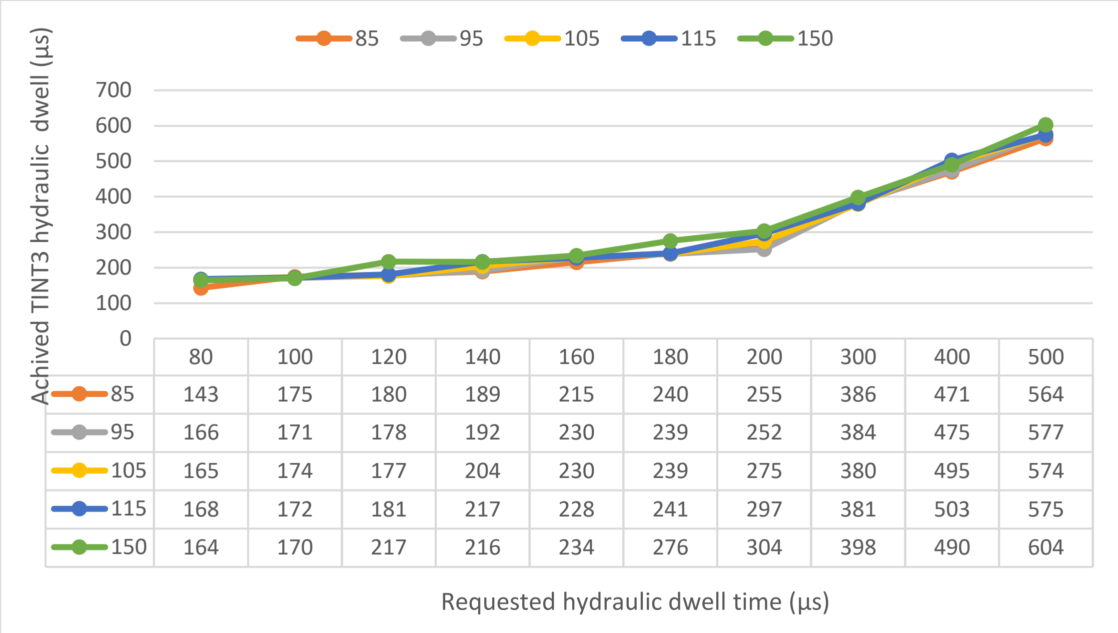
Figure 8.4 - Achieved fuel quantity of each injection vs requested TINT2 dwell at different rail pressure (85,95,105,115 & 150 MPa) for pilot quantities doubled

8.1.3 Tests are done varying TINT3

Table 8.3 - Values of fixed parameters with TINT3 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINTPre (µs)
1	1.5	2.91	9.59	15	763	361

- **TINT3 Separation**



	80	100	120	140	160	180	200	300	400	500
85	143	175	180	189	215	240	255	386	471	564
95	166	171	178	192	230	239	252	384	475	577
105	165	174	177	204	230	239	275	380	495	574
115	168	172	181	217	228	241	297	381	503	575
150	164	170	217	216	234	276	304	398	490	604

Figure 8.5 - Requested TINT3 hydraulic dwell vs Achieved TINT3 dwell at different rail pressures (85, 95, 105, 115, 150 MPa)

- **Quantities of each injection**

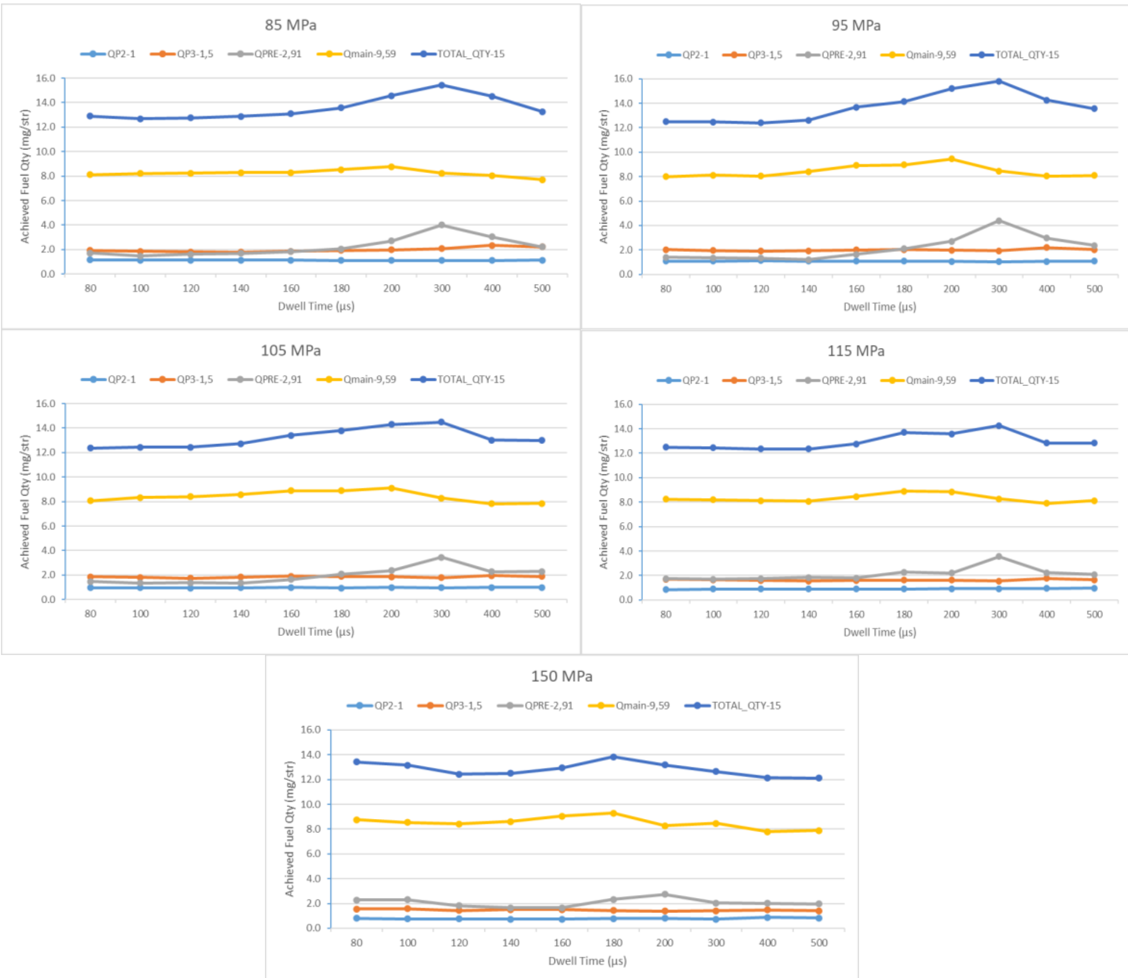


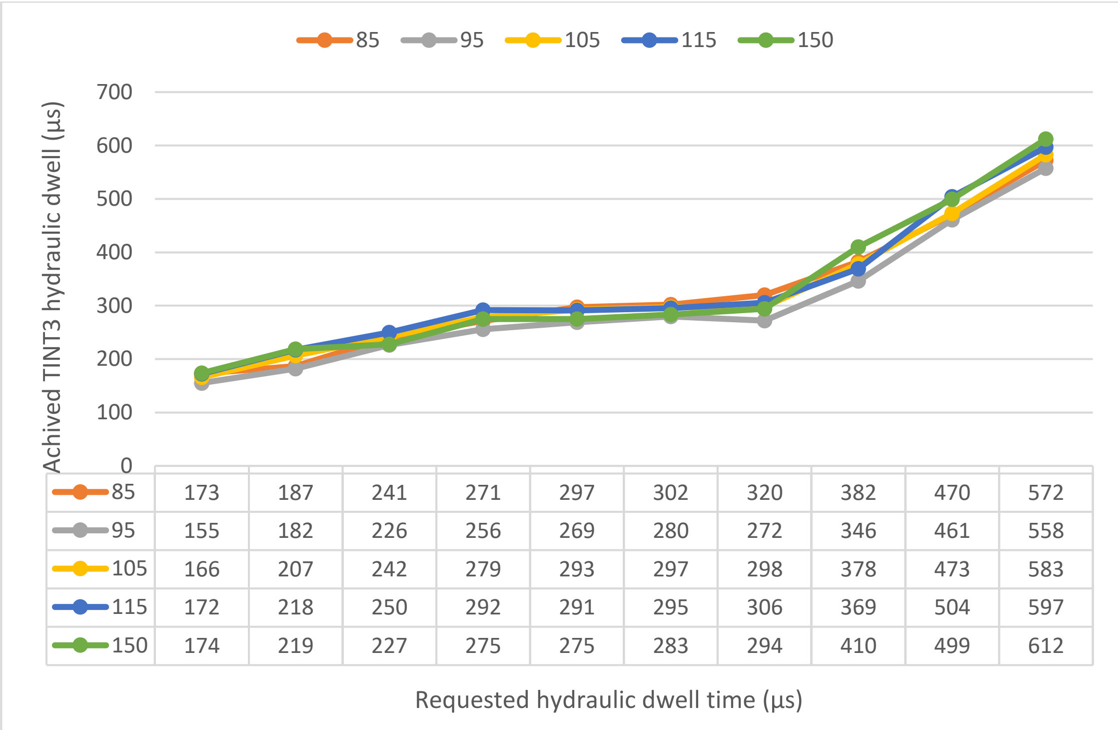
Figure 8.6 - Achieved fuel quantity of each injection vs requested TINT3 dwell at different rail pressure (85,95,105,115 & 150 MPa)

8.1.4 Tests are done varying TINT3 (Quantity doubled)

Table 8.4 - Values of fixed parameters with TINT3 as a variable parameter, only QP3 & QPRE doubled because QP2 is not affected by TINT3

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINTPre (µs)
1	3	5	6	15	768	361

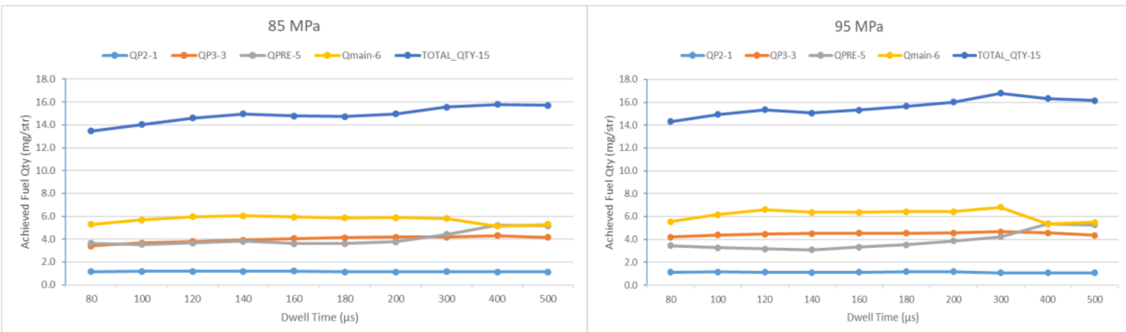
- **TINT3 Separation**



85	173	187	241	271	297	302	320	382	470	572
95	155	182	226	256	269	280	272	346	461	558
105	166	207	242	279	293	297	298	378	473	583
115	172	218	250	292	291	295	306	369	504	597
150	174	219	227	275	275	283	294	410	499	612

Figure 8.7 - Requested TINT3 hydraulic dwell vs Achieved TINT3 dwell at different rail pressures (85, 95, 105, 115, 150 MPa) for pilot quantities doubled

- **Quantities of each injection**



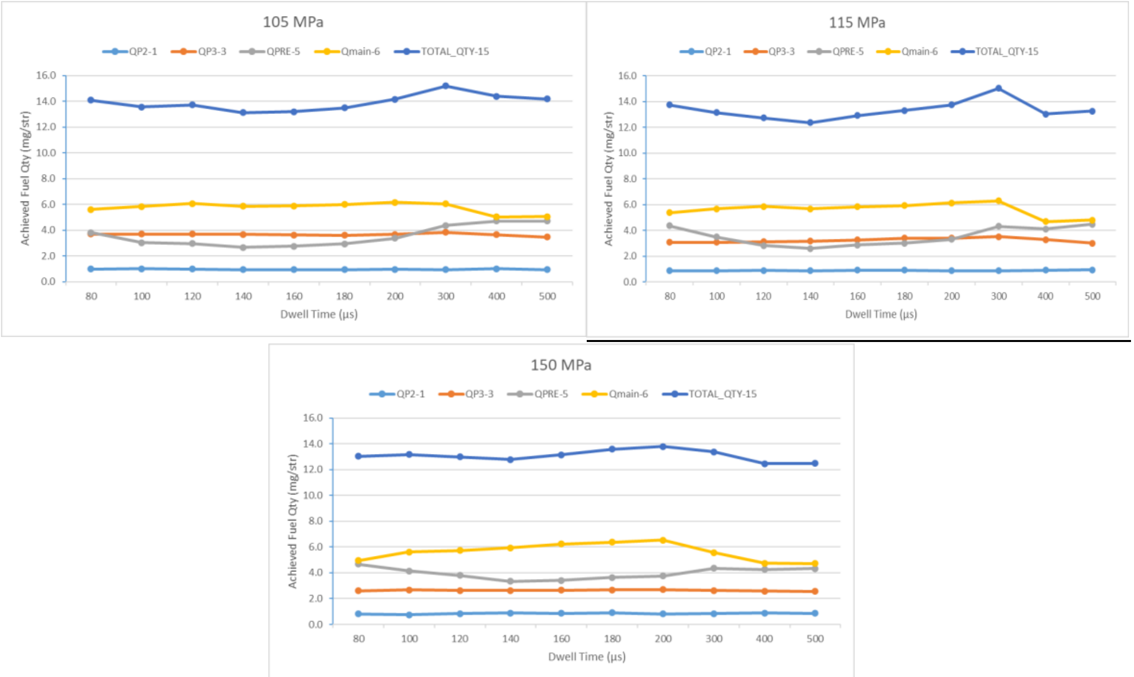


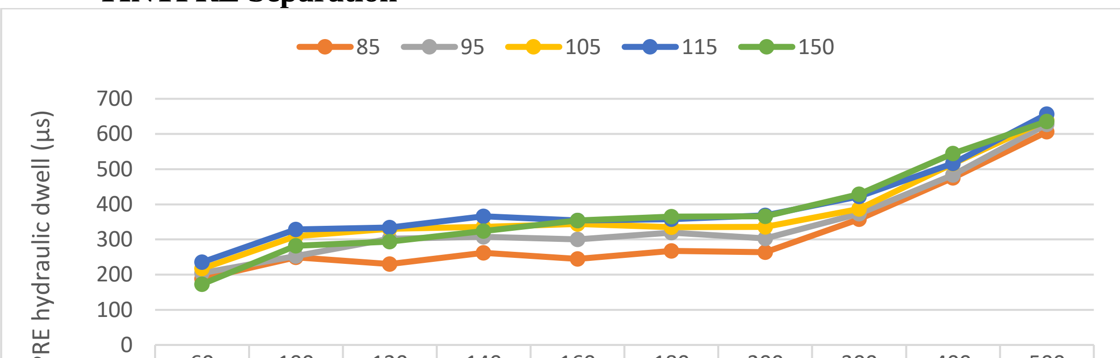
Figure 8.8 - Achieved fuel quantity of each injection vs requested TINT3 dwell at different rail pressure (85,95,105,115 & 150 MPa) for pilot quantities doubled

8.1.5 Tests are done varying TINTPRE

Table 8.5 - Values of fixed parameters with TINTPRE as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)
1	1.5	2.91	9.59	15	768	332

- **TINTPRE Separation**



	60	100	120	140	160	180	200	300	400	500
85	188	249	230	262	245	267	264	357	475	606
95	204	253	302	307	300	319	303	373	484	628
105	217	310	331	335	344	335	336	386	515	639
115	235	328	334	366	354	357	369	423	516	656
150	173	282	294	324	354	365	366	429	544	636

Figure 8.9 - Requested TINTPRE hydraulic dwell vs Achieved TINTPRE dwell at different rail pressures (85, 95, 105, 115, 150 MPa)

- **Quantities of each injection**

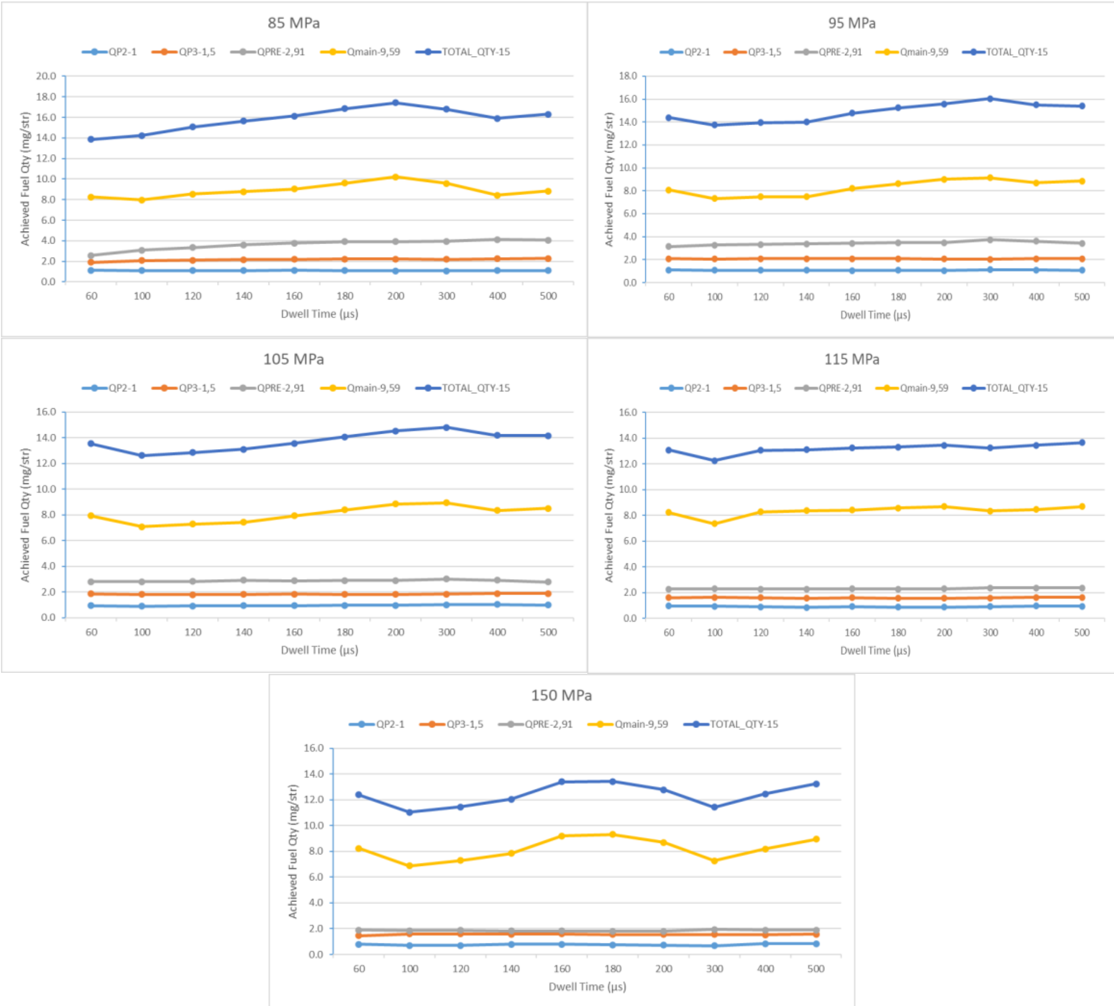


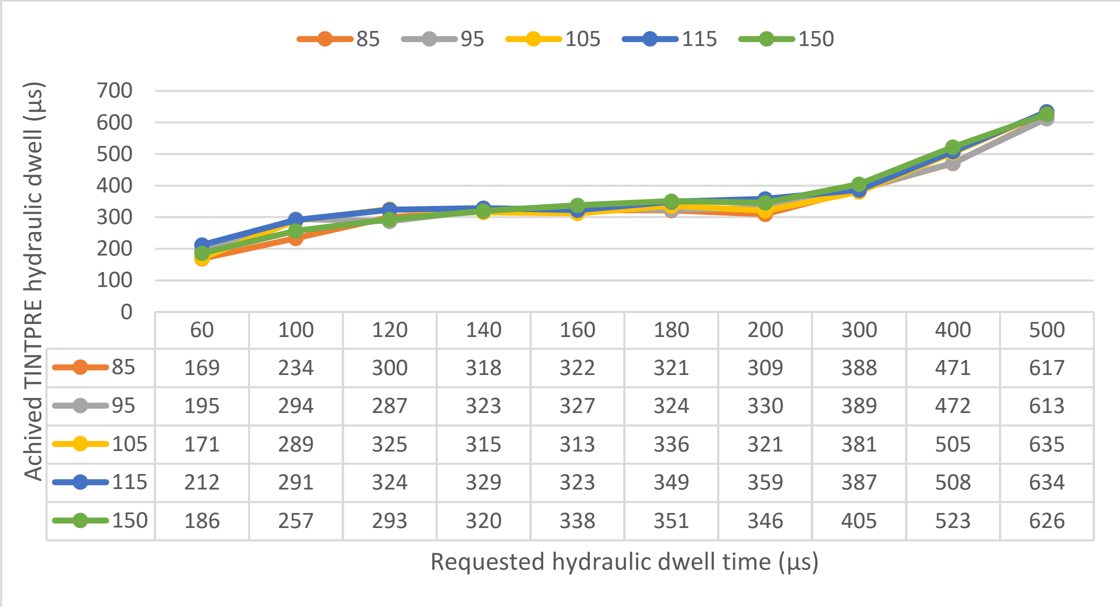
Figure 8.10 - Achieved fuel quantity of each injection vs requested TINTPRE dwell at different rail pressure (85,95,105,115 & 150 MPa)

8.1.6 Tests are done varying TINTPRE (Quantity doubled)

Table 8.6 - Values of fixed parameters with TINTPRE as a variable parameter, only QP2 & Q3 doubled

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)
2	3	2.91	7.09	15	768	332

- **TINTPRE Separation**



	60	100	120	140	160	180	200	300	400	500
85	169	234	300	318	322	321	309	388	471	617
95	195	294	287	323	327	324	330	389	472	613
105	171	289	325	315	313	336	321	381	505	635
115	212	291	324	329	323	349	359	387	508	634
150	186	257	293	320	338	351	346	405	523	626

Figure 8.11 - Requested TINTPRE hydraulic dwell vs Achieved TINTPRE dwell at different rail pressures (85, 95, 105, 115, 150 MPa) for pilot quantities doubled

- **Quantities of each injection**

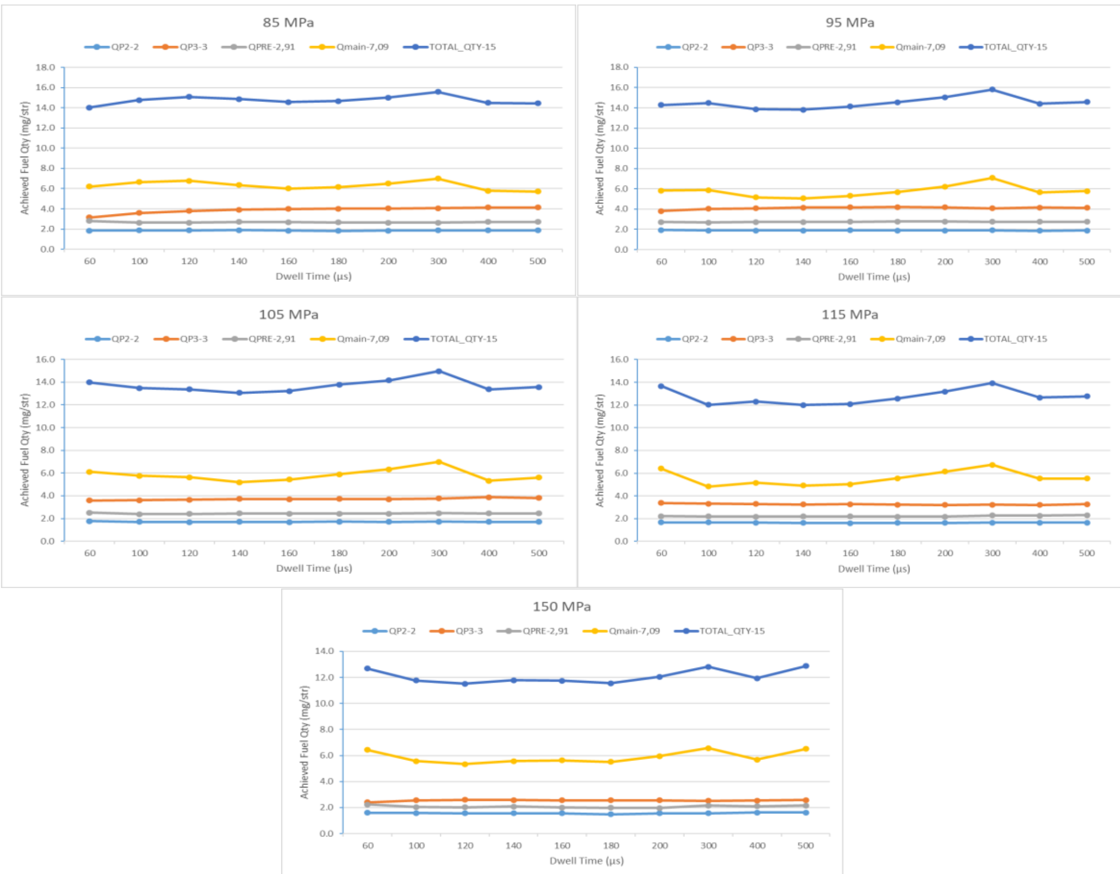


Figure 8.12 - Achieved fuel quantity of each injection vs requested TINTPRE dwell at different rail pressure (85,95,105,115 & 150 MPa) for pilot quantities doubled

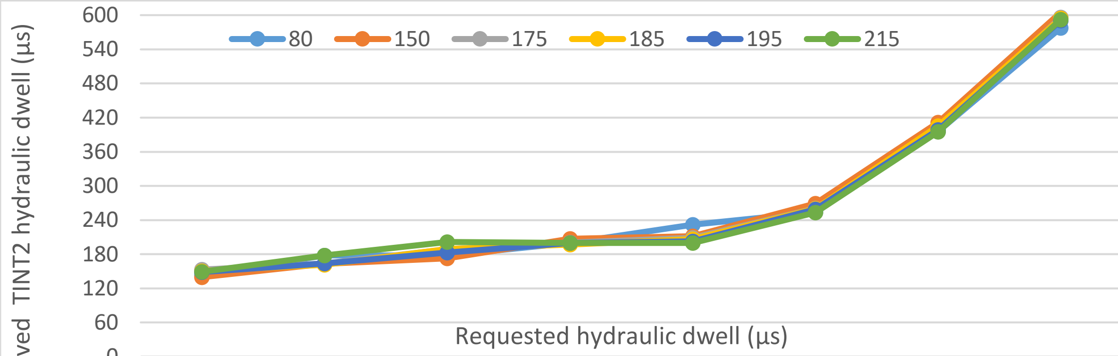
8.2 Load Point P3 – 1750 rpm and 40mg/str

8.2.1 Tests are done varying TINT2

Table 8.7 - Values of fixed parameters with TINT2 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT3 (µs)	TINTPre (µs)
1	2	5.73	31.27	40	114	115

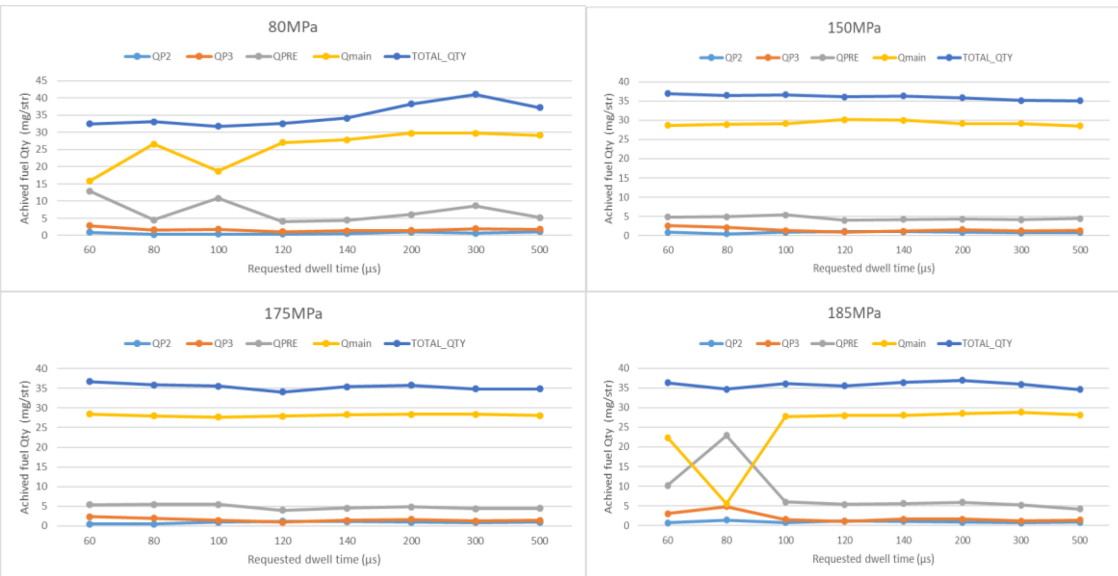
- **TINT2 Separation**



	60	80	100	120	140	200	300	500
80	143	178	178	200	232	254	396	578
150	140	163	173	207	212	269	412	605
175	153	164	189	201	209	261	397	596
185	151	162	189	197	207	260	405	594
195	149	164	183	200	203	259	398	591
215	149	178	201	200	200	253	395	592

Figure 8.13 - Requested TINT2 hydraulic dwell vs Achieved TINT2 dwell at different rail pressures (80, 150, 175, 185, 195 & 215 MPa)

- **Quantities of each injection**



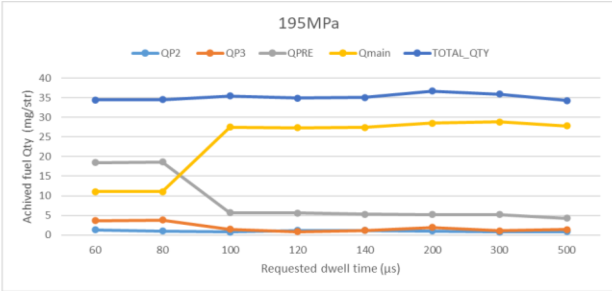


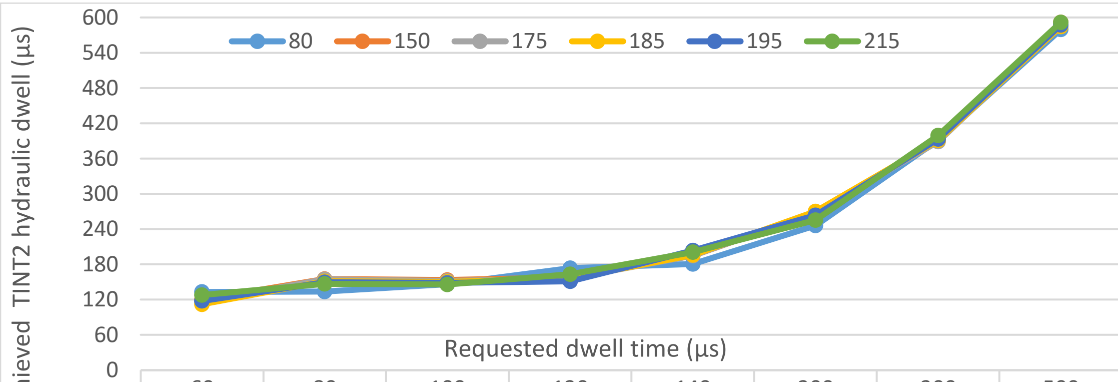
Figure 8.14 - Achieved fuel quantity of each injection vs requested TINT2 dwell at different rail pressure (80, 150, 175, 185 & 195 MPa)

8.2.2 Tests are done varying TINT2 (Quantity doubled)

Table 8.8 - Values of fixed parameters with TINT2 as a variable parameter, only QP2 & QP3 doubled

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT3 (µs)	TINTPre (µs)
2	3.92	5.73	28.35	40	114	115

- **TINT2 Separation**



	60	80	100	120	140	200	300	500
80	133	134	146	173	181	246	392	579
150	120	155	153	158	195	268	390	592
175	117	154	152	156	195	268	389	587
185	112	151	150	156	196	270	391	585
195	118	149	149	151	203	263	393	587
215	128	147	146	163	201	255	399	592

Figure 8.15 - Requested TINT2 hydraulic dwell vs Achieved TINT2 dwell at different rail pressures (80, 150, 175, 185, 195 & 215 MPa) for pilot quantities doubled

- **Quantities of each injection**

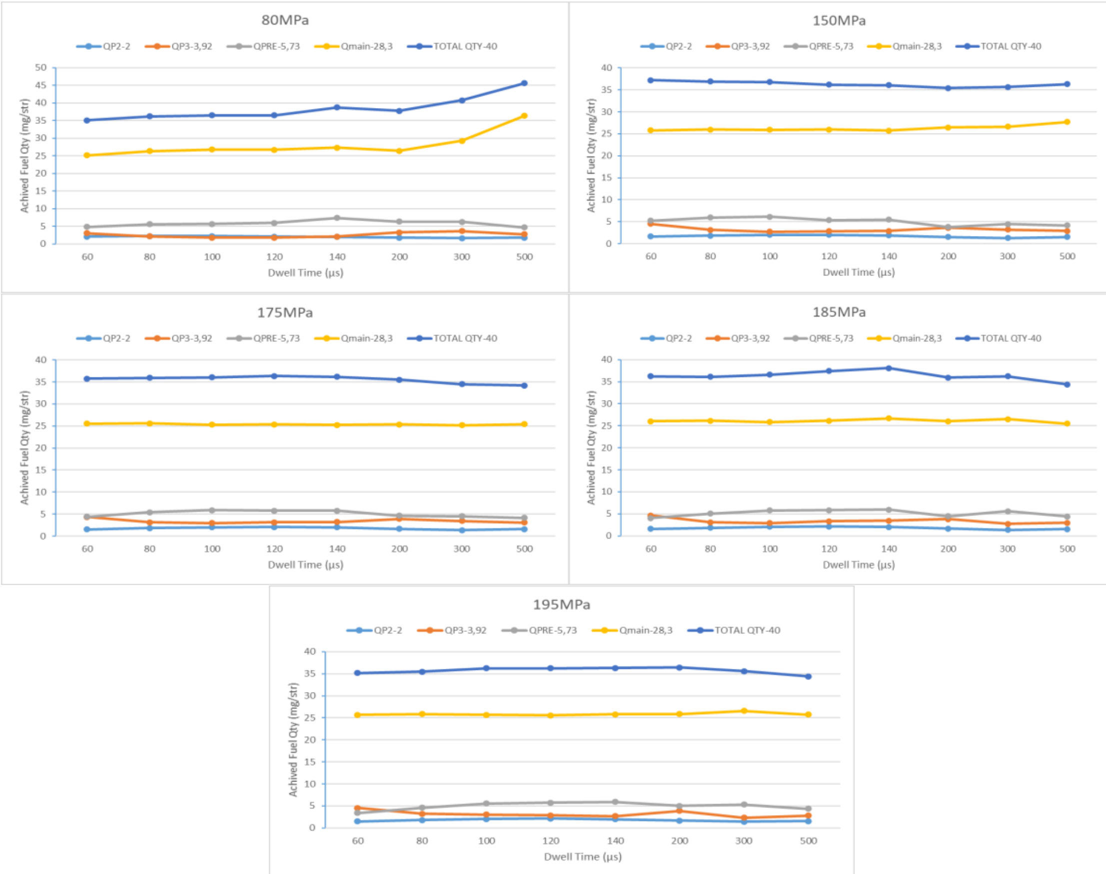


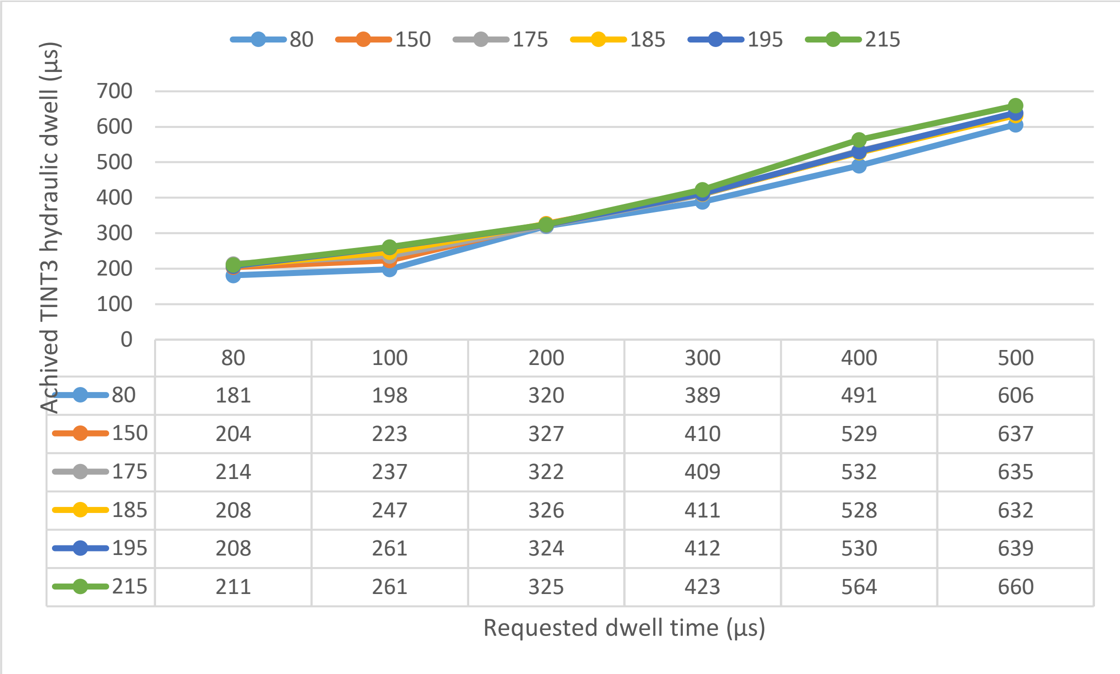
Figure 8.16 - Achieved fuel quantity of each injection vs requested TINT2 dwell at different rail pressure (80, 150, 175, 185 & 195 MPa) for pilot quantities doubled

8.2.3 Tests are done varying TINT3

Table 8.9 - Values of fixed parameters with TINT3 as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINTPre (µs)
1	1.96	5.73	31.2	40	371	115

- **TINT3 Separation**



	80	100	200	300	400	500
80	181	198	320	389	491	606
150	204	223	327	410	529	637
175	214	237	322	409	532	635
185	208	247	326	411	528	632
195	208	261	324	412	530	639
215	211	261	325	423	564	660

Figure 8.17 - Requested TINT3 hydraulic dwell vs Achieved TINT3 dwell at different rail pressures (80, 150, 175, 185, 195 & 215 MPa)

- **Quantities of each injection**

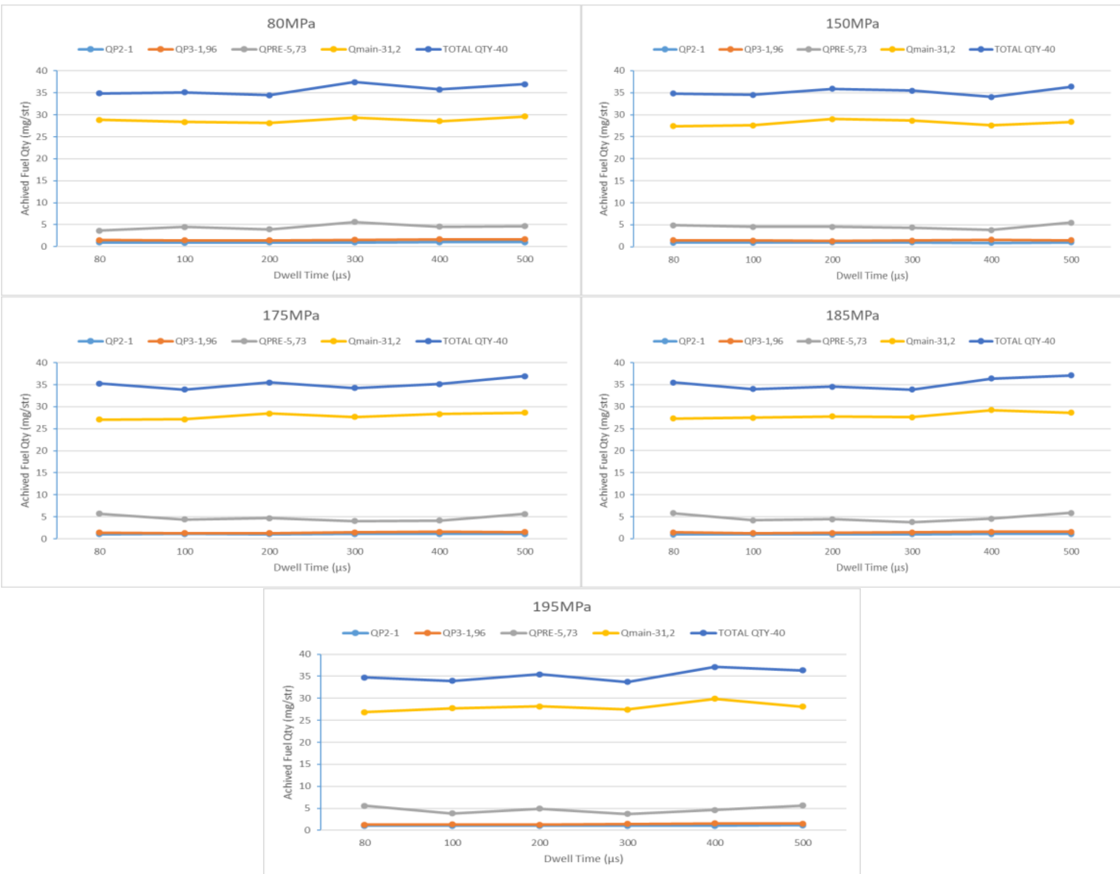


Figure 8.18 - Achieved fuel quantity of each injection vs requested TINT3 dwell at different rail pressure (80, 150, 175, 185 & 195 MPa)

8.2.4 Tests are done varying TINT3 (Quantity doubled)

Table 8.10 - Values of fixed parameters with TINT3 as a variable parameter, only QP3 doubled because QP2 is not affected by TINT3

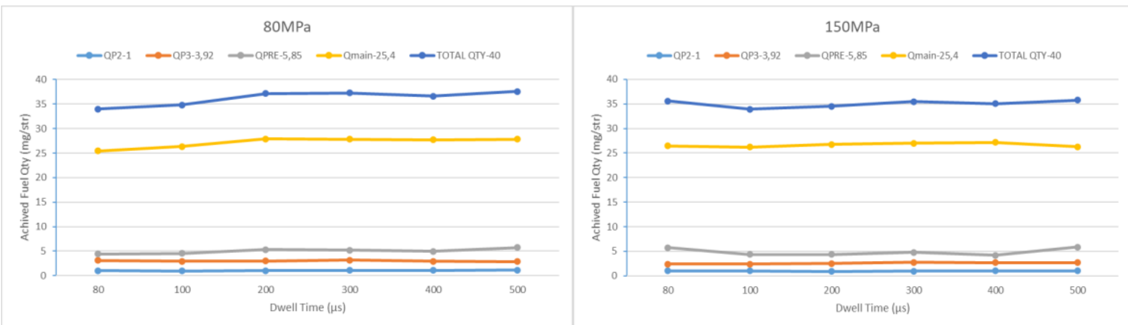
Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINTPre (µs)
1	1.96	5.73	31.2	40	371	115

- **TINT3 Separation**

	80	100	200	300	400	500
80	183	243	310	399	529	640
150	216	264	347	420	546	643
175	210	274	353	441	562	658
185	251	288	358	465	580	672
195	258	275	362	461	586	672
215	254	258	356	456	593	679

Figure 8.19 - Requested TINT3 hydraulic dwell vs Achieved TINT3 dwell at different rail pressures (80, 150, 175, 185, 195 & 215 MPa) for pilot quantities doubled

- **Quantities of each injection**



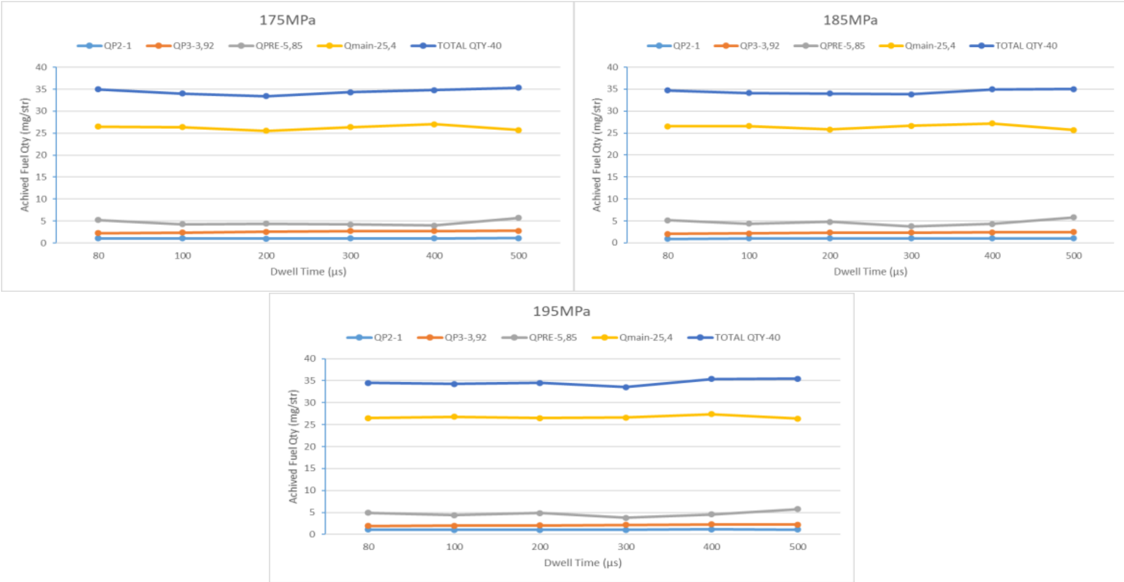


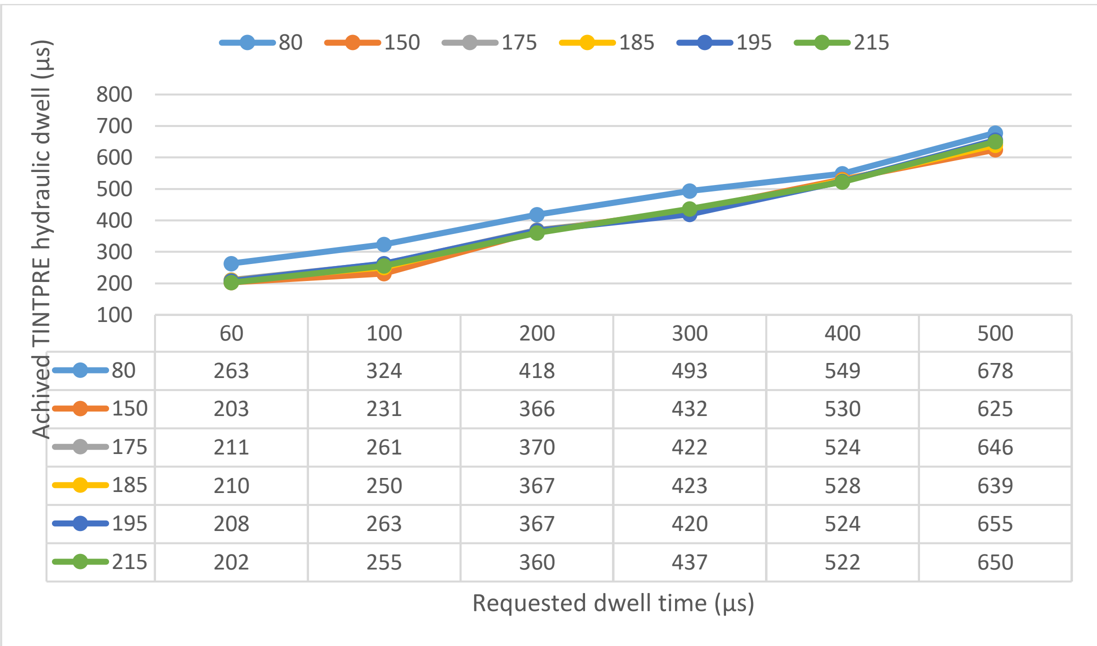
Figure 8.20 - Achieved fuel quantity of each injection vs requested TINT3 dwell at different rail pressure (80, 150, 175, 185 & 195 MPa) for pilot quantities doubled

8.2.5 Tests are done varying TINTPRE

Table 8.11 - Values of fixed parameters with TINTPRE as a variable parameter

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)
1	1.96	5.73	31.31	40	371	114

- **TINTPRE Separation**



	60	100	200	300	400	500
80	263	324	418	493	549	678
150	203	231	366	432	530	625
175	211	261	370	422	524	646
185	210	250	367	423	528	639
195	208	263	367	420	524	655
215	202	255	360	437	522	650

Figure 8.21 - Requested TINTPRE hydraulic dwell vs Achieved TINTPRE dwell at different rail pressures (80, 150, 175, 185, 195 & 215 MPa)

- **Quantities of each injection**

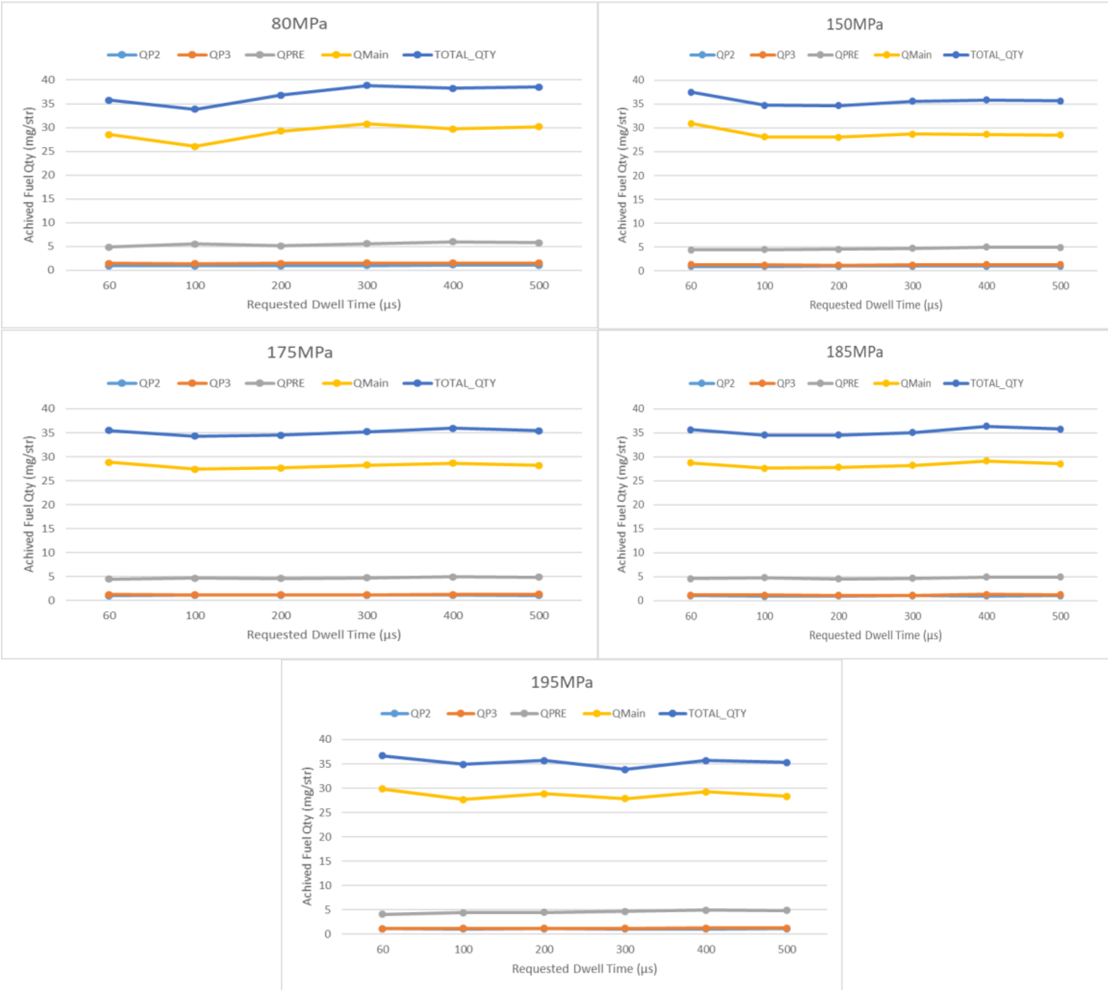


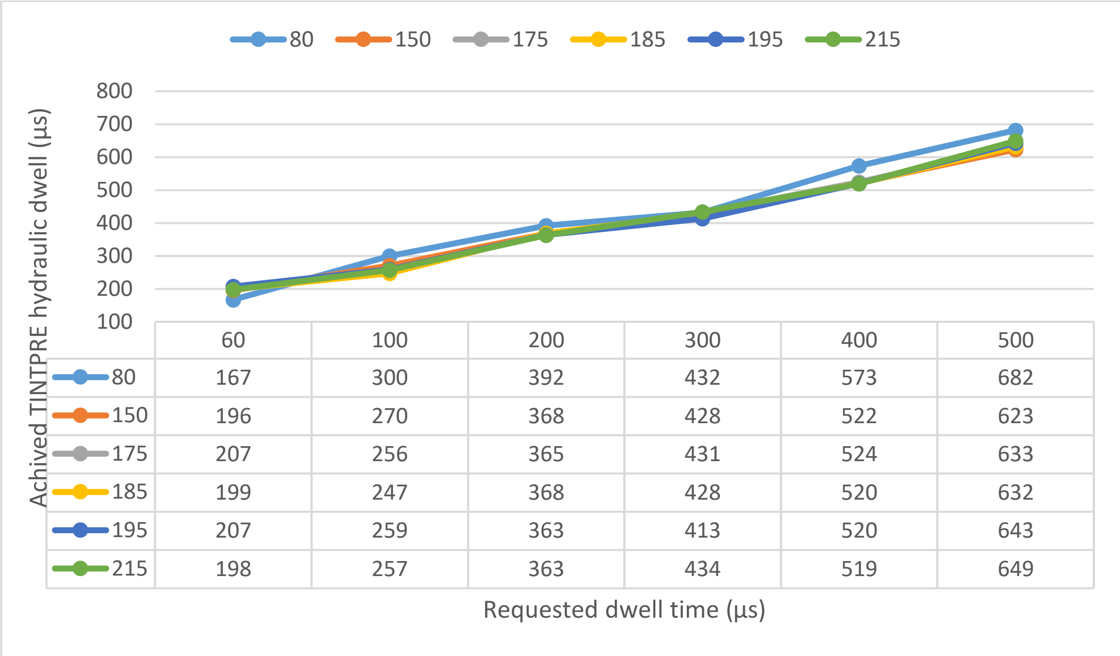
Figure 8.22 - Achieved fuel quantity of each injection vs requested TINTPRE dwell at different rail pressure (80, 150, 175, 185 & 195 MPa)

8.2.6 Tests are done varying TINTPRE (Quantity doubled)

Table 8.12 - Values of fixed parameters with TINTPRE as a variable parameter, only QP2 & QP3 doubled

Fixed parameters						
QP2 (mg/str)	QP3 (mg/str)	QPre (mg/str)	QMain (mg/str)	Q_Total (mg/str)	TINT2 (µs)	TINT3 (µs)
2	3.92	5.73	28.35	40	371	114

- **TINTPRE Separation**



	60	100	200	300	400	500
80	167	300	392	432	573	682
150	196	270	368	428	522	623
175	207	256	365	431	524	633
185	199	247	368	428	520	632
195	207	259	363	413	520	643
215	198	257	363	434	519	649

Figure 8.23 - Requested TINTPRE hydraulic dwell vs Achieved TINTPRE dwell at different rail pressures (80, 150, 175, 185, 195 & 215 MPa) for pilot quantities doubled

- **Quantities of each injection**

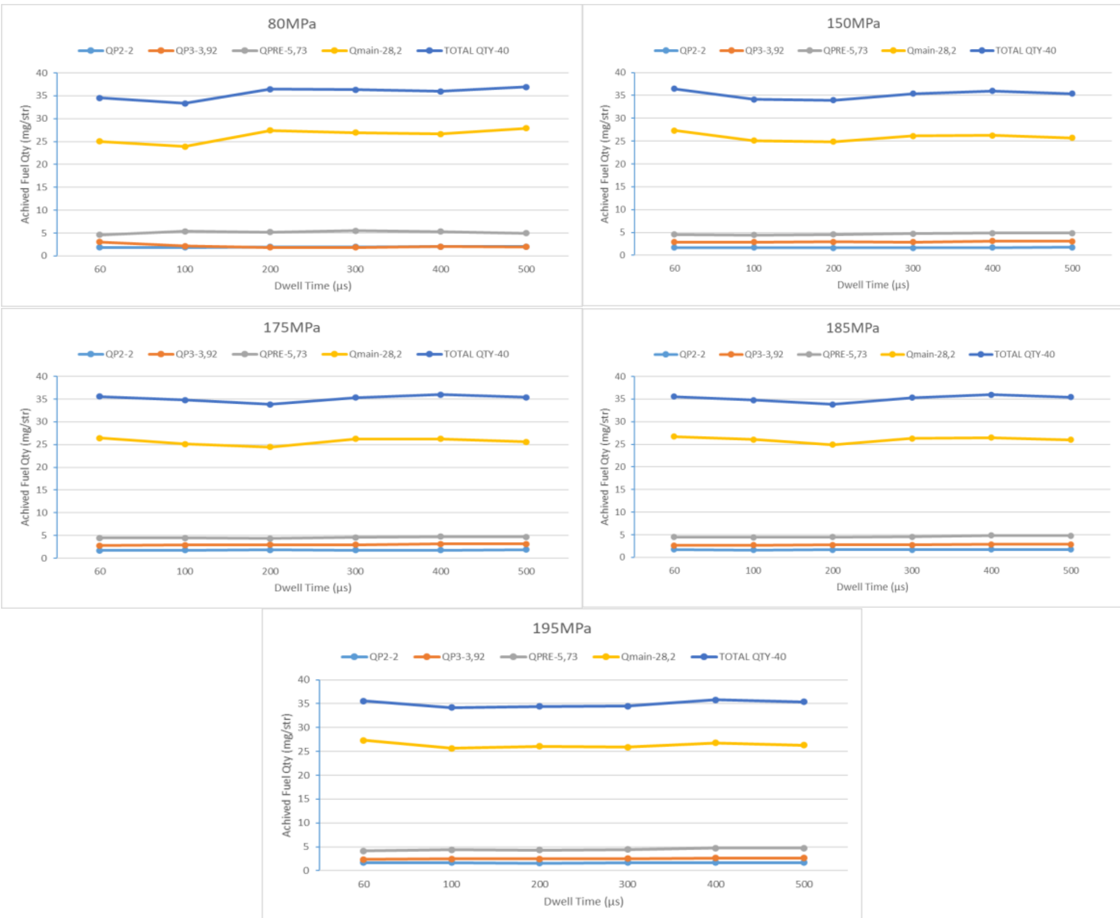


Figure 8.24 - Achieved fuel quantity of each injection vs requested TINTPRE dwell at different rail pressure (80, 150, 175, 185 & 195 MPa) for pilot quantities doubled