PHILIPPINE ENGINEERING JOURNAL
PEJ 2016; Vol. 37, No. 1: 79-90

Determination of Injection Parameters using Line Pressure and Solenoid Signals from a Common-Rail Direct Injection Diesel Engine

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Abstract— The determination of fuel injection parameters is very important in studying diesel engines. Knowing what happens to the fuel as it is being injected onto the engine cylinders may help in understanding the outcome of different engine operations. Fuel injector behavior affects what happens inside the engine cylinders and may help explain fuel consumption, torque and power produced, emission characteristics, and other engine performance metrics. Much attention is given to the operation of diesel engines nowadays brought about by the interest in alternative fuel sources. This study describes a method of estimating actual main injection (excluding pilot injection) parameters: start, end, and duration of injection for a Common-Rail Direct Injection (CRDI) engine based on the information given by the fuel supply line pressure sensor mounted on the tubing that connects the fuel injector to the common rail. The timing of the fuel supply line pressure signal was compared to that of the associated Electronic Control Unit (ECU) injection command signal to validate a sensible phase relationship. Distinct shape characteristics of the line pressure signal were identified and considered as start and end of actual main fuel injection. The estimation method was used to determine fuel injection behavior of a CRDI engine running at full load from 800 to 4000 rpm. The study also showed that increasing RPM increases the injection duration, average line pressure and advances the injection timing.

Keywords— ***CRDI, line pressure, solenoid signal, injection duration***

1. INTRODUCTION

1.1 Background of the Study

A diesel or Compression Ignition (CI) engine is an internal combustion engine that typically runs on diesel fuel and does not need a spark to initiate combustion because the injected fuel is ignited by the high temperature air inside the cylinder towards the end of the compression stroke. For the same rated power, diesel engines are usually bigger and bulkier than gasoline engines to get that high compression ratio needed for combustion. Diesel engines are typically seen on power plants, heavy machinery, buses, trucks and SUV's but have gained popularity in automobiles as well due to advancements in its technology.

The fuel injection system is a very important part of the diesel engine. Dictating how much fuel is burned per cycle, careful injection control generally leads to good performance and efficiency. Research works have constantly improved fuel injection systems from mechanically controlled plunger systems to the electronically controlled injection systems available today. One system that has gained commercial success in the past few decades is the Common-Rail Direct Injection (CRDI) system. It consists of a common rail that regulates and keeps the high pressure of the fuel in a single line making it ready for injection anytime. Individual injectors are connected to this rail, each dedicated to an engine cylinder. Each injector has a solenoid, connected to the Electronic Control Unit (ECU), which controls the opening and closing of the needle and thus has control of the timing, duration and amount of fuel injected per cycle. The ECU, through its own programmed algorithm, calculates proper injection parameters based on inputs given by the sensors connected to the engine. This algorithm differs among different engine and ECU models but typical inputs considered for the injection parameter calculation include engine speed, pedal position, fuel temp, intake air, and fuel pressure [1].

Injection parameters are generally divided into two different forms; static and dynamic [3]. The static injection parameters refer to the injection commands as calculated and given by the ECU. The dynamic injection parameters refer to the actual physical injection events that occur inside the engine cylinder.

Static injection commands may be obtained or read through the use of ECU scanners or by splicing and tapping onto the ECU command wires. This is a generally accepted practice and has been used by many researchers in their works [1, 3-8]. Ye and Boehman [3] did a study on the effect of ECU commands on engine performance. In their study, they showed that adjustments on the static injection commands directly impact the performance and emissions of a CRDi engine; particularly its NOx and particulate emissions. Tziourtzioumis et al. [1] did a similar study, involving the use of biodiesel and its effect on static injection commands. These changes, in turn, had an effect on the engine's performance as well.

Dynamic injection parameters, on the other hand, are more difficult to obtain. These parameters are deduced through the use of different sensors placed in an engine. One popular tool in use is the needle lift sensor; it is able to detect injector needle movement as it opens and closes the injector nozzle tip during fuel injection. Together with the crank angle position signal from a crankshaft angle encoder, the actual injection timing and duration can be obtained. This tool has been used by many studies involving the determination of dynamic injection parameters. Torres-Jimenez et al. [9] did a study on the injection characteristics of bioethanol-diesel and bioethanol-biodiesel blends and a needle lift sensor was used to determine the dynamic injection parameters. Bittle et al. [5] also used a needle lift sensor when they tested the impact of injection timing and duration on a biodiesel-fed CRDI engine.

Another way of determining dynamic injection parameters is through the use of an injection rate meter, a device that utilizes the pressure waves produced in the fuel injector to measure the flow rate. Park et al. [6] estimated the start of actual injection timing to be at the moment when the injection rate is 5% of the maximum injection rate of a cycle. Desantes et al. [10] and Han et al. [7] also used injection rate meters in their studies on diesel engine injection parameters. Pandian et al. [11] used a different approach in their study; the parameters were obtained by locating the fuel in the line before injection while rotating the flywheel manually. This method, however, provides an accuracy of only 1 degree crank angle. Gu and Ball [12] developed a diesel injector dynamic model to estimate injection parameters as a non-intrusive way as opposed to installing transducers which may interfere with the dynamics and actual operation of the diesel engine.

Some engines, such as the one used in this study, employ the use of a pilot injection. This is an auxiliary injection that happens before the main injection to gently start the combustion and reduce combustion noise and spikes in cylinder pressure.

1.2 Objectives

This study aims to describe the use of the fuel supply line pressure signal together with the ECU injection command signal to estimate the dynamic injection parameters start of injection, end of injection, and injection duration of a CRDI diesel engine. The study is limited to the main fuel injection and excludes pilot injection. Fuel injector behavior based on an interpretation of the fuel supply line pressure signal is also offered.

1.3 Significance of the Study

In the study of diesel engines, it is important to understand fuel injection parameters. Fuel injector behavior affects what happens inside the engine cylinders and may help explain fuel consumption, torque and power produced, emission characteristics, and other engine performance metrics. Dynamic injection parameters also tend to influence spray characteristics, ignition parameters, and combustion behavior. This method of injection parameter estimation may aid future researches such as evaluation of new fuel injection technologies, additives or alternative fuels and engine operating conditions.

2. METHODOLOGY

2.1 Experimental Setup

The experiment was conducted at the University of the Philippines - Vehicle Research and Testing Laboratory. The tests were performed using an AVL Engine Dynamometer system whose schematic diagram is shown in Figure 1.

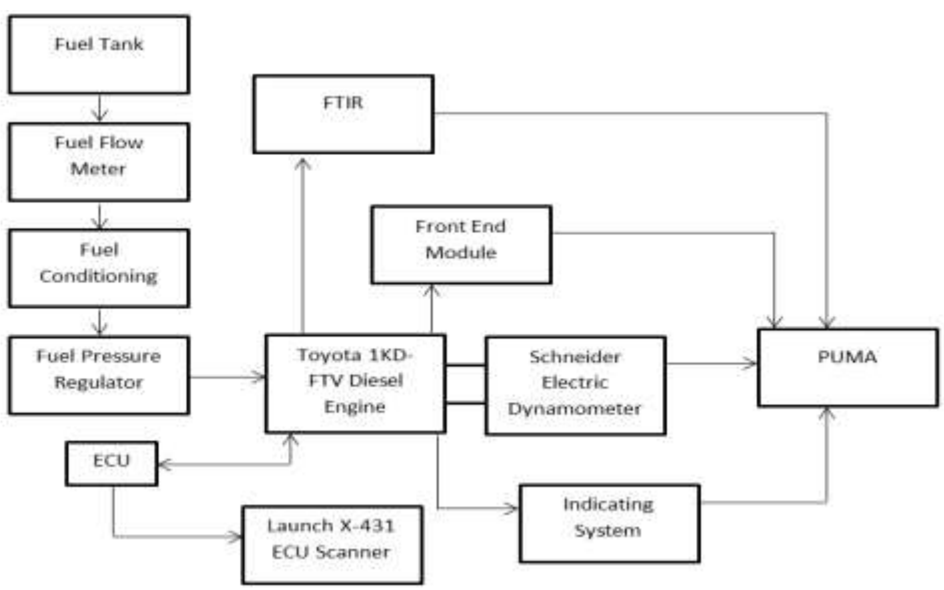

Figure 1: Experimental Setup for AVL Engine Dynamometer System

The fuel coming from the fuel tank, passes thru the fuel flow meter, fuel conditioning system and the fuel pressure regulator to ensure proper conditions before being fed to a Toyota 1KD-FTV CRDi diesel engine. The engine runs the dynamometer which reads the torque and engine speed as performed by the engine. Emission characteristics are read thru the FTIR (Fourier Transform Infrared) system. Readings from the pressure and temperature sensors are delivered to the Front End Module, while the indicating characteristics goes thru the Indicating System and is processed by the Indicom software. All these performance information ultimately go to the AVL PUMA dynamometer software. Simultaneously, ECU command readings are shown thru the Launch x-431 ECU Scanner.

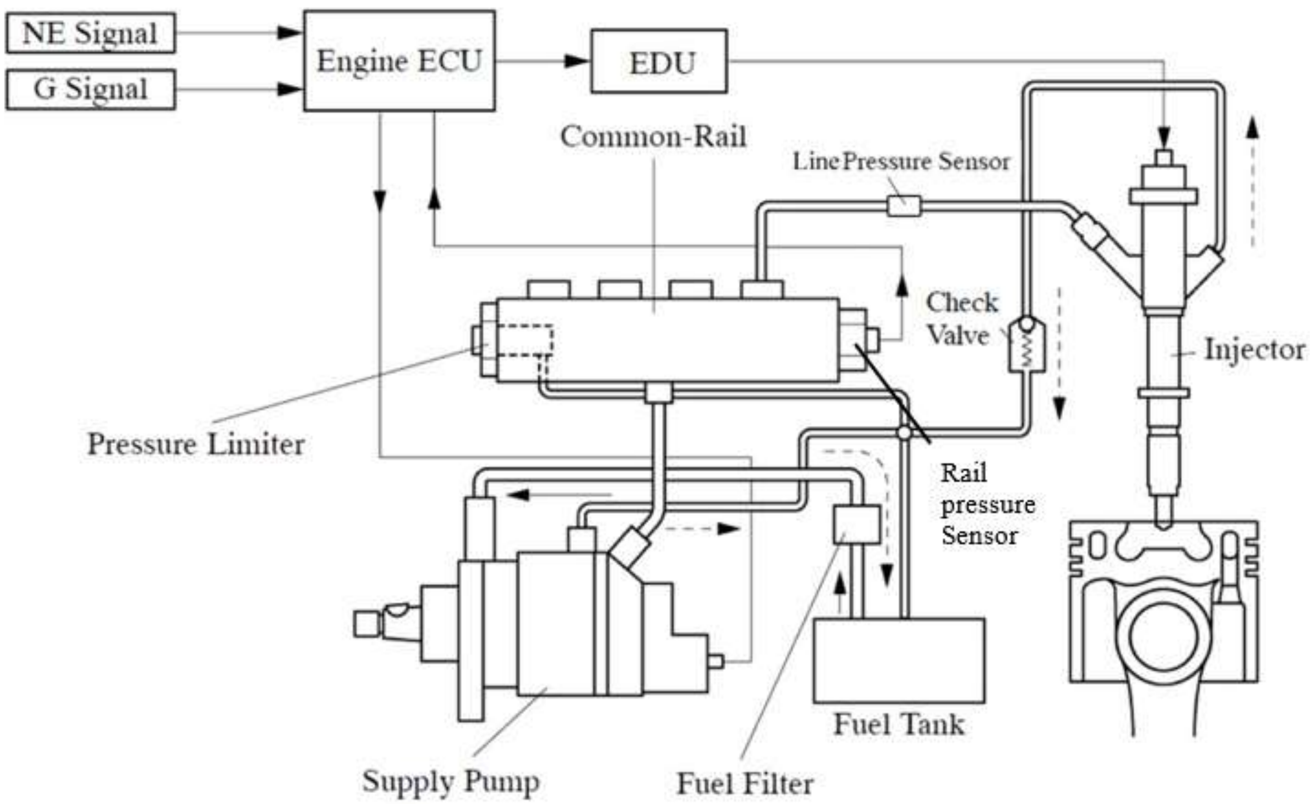

Figure 2: Fuel System of Toyota 1KD FTV Engine [13]

A schematic diagram of the engine fuel supply system is shown in Figure 2. The engine ECU calculates injection commands based on its input signals. The command is given to the EDU which drives the Injector through a solenoid valve. The fuel comes from the supply tank and is brought by the supply pump to the common-rail. The common-rail is connected to the fuel injector; this is where the line pressure sensor is located. Figure 3 shows an image of the line pressure sensor installed in the engine.

Figure 3: Toyota 1KD-FTV Engine, showing exact location of Line Pressure Sensor

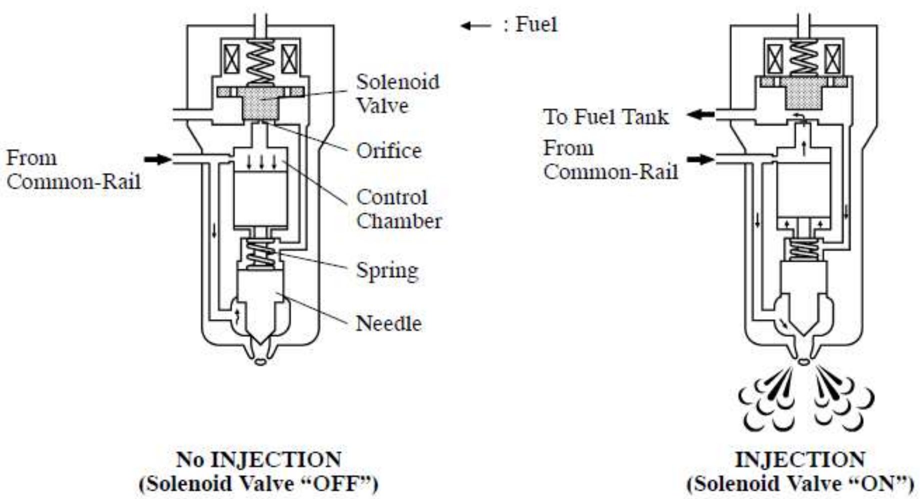

Figure 4: Fuel Injector of Toyota 1KD-FTV CRDi Engine [13]

The dynamic injection parameters represent actual physical injection as it happens inside the cylinder. To be able to analyze data on these parameters, an understanding of the events that happen inside the fuel injector is needed. Figure 4 shows a schematic of the Toyota 1KD-FTV CRDi engine's fuel injector. Initially, when the solenoid is not energized, the solenoid valve blocks the orifice located above the control chamber. During this time, a pressure is built up in the chamber forcing the needle to be pushed down and closes the nozzle; no injection occurs. When a command for fuel injection is sent from the ECU, the solenoid is energized. This lifts the solenoid valve and opens the orifice in the control chamber. This allows some fuel to go back to the fuel tank and the pressure in the chamber is relieved. This eventually lifts the needle and allows for more fuel to come from the common-rail then out of the injector through the opened needle. This continues until a command is sent to stop the injection by cutting the voltage supply to the solenoid causing the solenoid valve to close the orifice. Given this information, it is important to note that the ECU command (solenoid) signals come first before actual physical movements of injector parts occur.

2.2 Experimental Procedure

The engine was run at full load with neat diesel at different engine speeds covering the entire operating range (800, 1200, 1600, 2000, 2400, 2800, 3600, and 4000 rpm). At each speed, the engine was run at steady state prior to the collection of data. Injection command signals are obtained via an ECU scanner. Solenoid command signals from the ECU were also tapped into and collected via the Indicom to verify ECU scanner readings. The solenoid signals were in the form of voltages and collected every 0.1 degree crank angle. Simultaneously, temperature and pressure signals from the engine sensors were collected via the engine dyno software, PUMA and Indicom. Fuel supply line pressure data were collected at a maximum resolution of 0.1 degree crank angle in the vicinity of and including the main injection location and at 1 degree crank angle elsewhere due to equipment data processing limitation. The Indicom collected 50-cycle samples at each engine speed. The test was done in three trials.

3. DATA AND RESULTS

3.1 Static Injection Parameters

The static injection parameters injection timing and duration coming from the ECU scanner were directly read out from the scanner screen. These information were collected and are shown in columns 2 and 3 of Table 1. A sample solenoid signal data obtained at 1600 RPM is shown in Figure 5. As can be seen in the plot, the solenoid is at rest throughout the cycle except during injection. As a command is given by the ECU to open the injector needle, a voltage of around 3.8 Volts is given to the solenoid to lift the needle. To close the nozzle, the voltage is brought back to zero. The static injection timing and duration as obtained from the solenoid are reflected in columns 4 and 5 respectively of Table 1.

Table 1: Static Injection Parameters

RPM	ECU Inj. Timing (°CA)	ECU Inj. Duration (°CA)	Sol. Inj. Timing (°CA)	Sol. Inj. Duration (°CA)	Sol/ECU Inj. Dur. % Diff.
800	-7.95	6.80	-10.70	5.90	-13.24
1200	-3.75	9.80	-7.30	9.70	-1.02
1600	-3.00	11.75	-7.40	11.60	-1.28
2000	-3.85	13.55	-9.30	13.60	0.37
2400	-5.67	14.48	-12.00	14.50	0.14
2800	-6.75	16.43	-14.20	16.40	-0.18
3200	-8.55	19.09	-17.70	19.00	-0.47
3600	-11.62	21.35	-21.70	21.20	-0.70
4000	-14.49	21.38	-25.60	21.70	1.50

Comparison of the static injection parameters obtained from the scanner and the solenoid signal show differences in the crank angle of the injection timing or start of injection. However, upon inspection of the static injection duration data, both data sets give roughly similar values. Column 6 of Table 1 shows the percent difference between the solenoid and ECU injection duration readings, it can be seen that aside from the 800 rpm (idling rpm) reading, the readings do not differ beyond 1.5%. The differences in injection timing is interpreted as a difference in the crank angle reference between the ECU scanner and Indicom's interpretation of the solenoid signals. The small differences in the static injection duration may be attributed to signal lags.

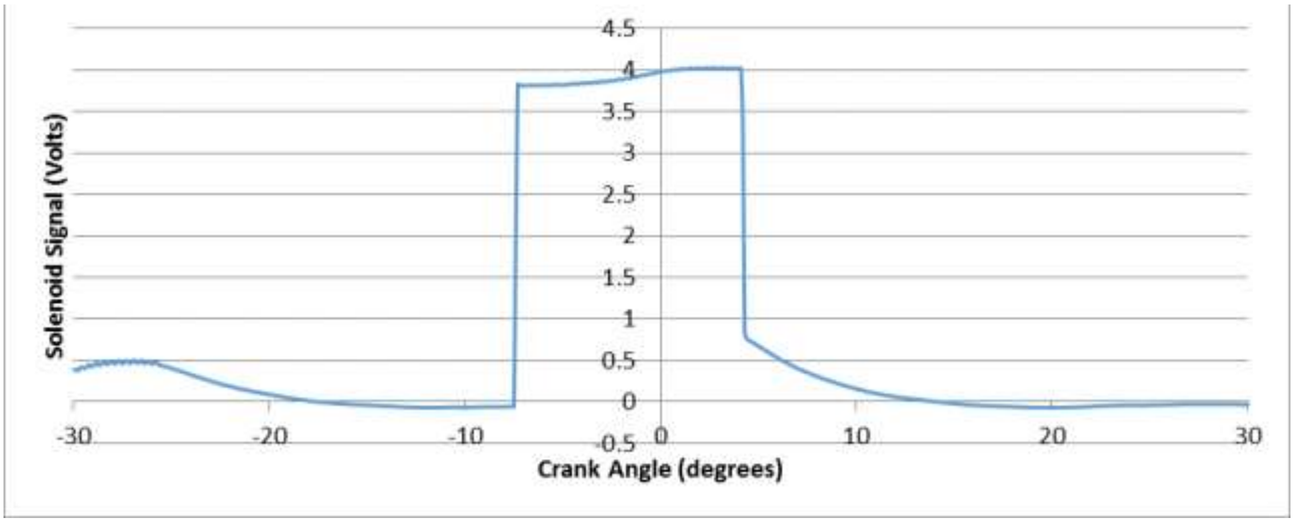

Figure 5: Sample Solenoid Signal Data (at 1600rpm)

Figure 6 shows the solenoid injection duration obtained at different speeds. It can be seen that the injection duration increases along with increasing RPM. This command to increase the injection duration per cycle at full load is necessary to increase the amount of fuel injected to supply more energy to raise the engine speed. Figure 7 shows the solenoid injection timing, it is noted that the start of fuel injection shifts to the left (i.e., "advanced") with increasing RPM (except at 800 rpm, which is at idling). This advancement is attributed to the ECU's reaction to the longer duration and attempt to end the injection at roughly the same crank angle location for proper combustion.

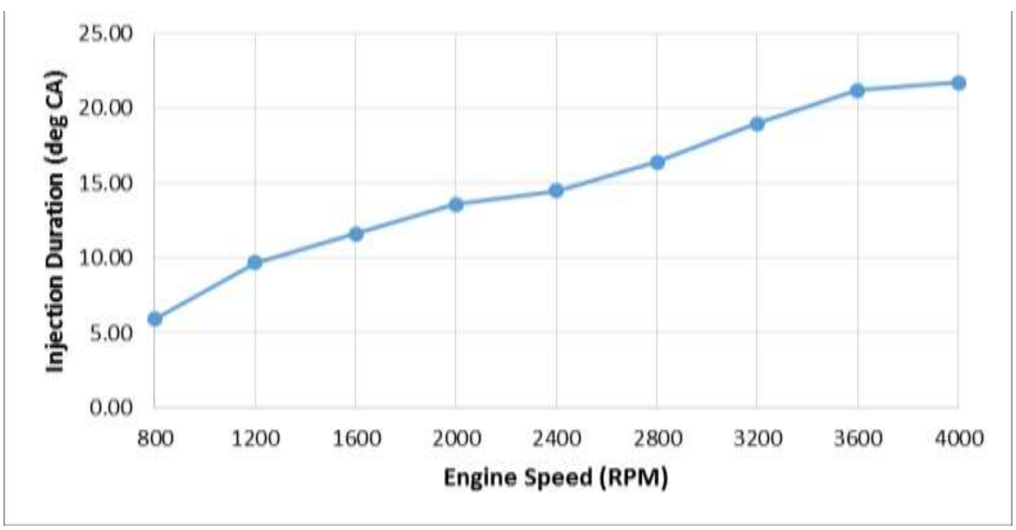

Figure 6: Solenoid Injection Duration at Different Engine Speeds

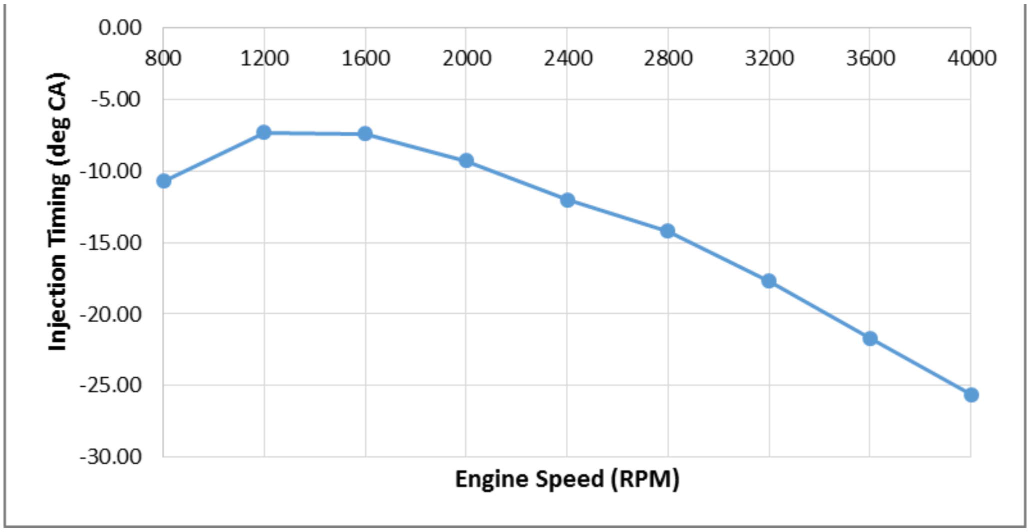

Figure 7: Solenoid Injection Timing at Different Engine Speeds

3.2 Dynamic Injection Parameters

Analysis of the dynamic injection parameter data anchors on the operating principle as discussed in the Experimental Setup section and shown in Figure 4.

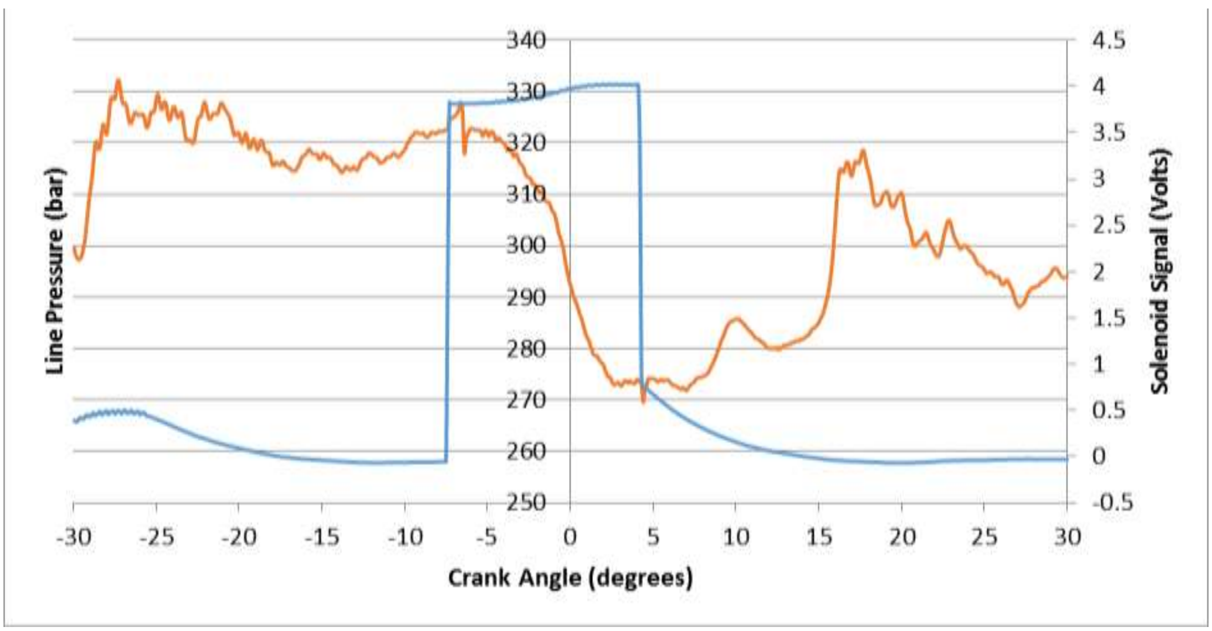

Figure 8: Sample Line Pressure Data (at 1600rpm)

Figure 8 shows a sample line pressure data (red line) overlaid with the solenoid signal (blue line) taken at 1600 RPM. There is a distinct drop in line pressure from around 323 bar to about 274 bar. The drop starts at around -6.6 degrees crank angle, near the location of the start of the solenoid command. This is expected as opening of the nozzle allows flow through the injector and thus releases the pressures built-up before the event. The end of injection can be seen at around 18 degrees crank angle where a rise in line pressure is observed upon closing of the nozzle. Figure 9 shows the line pressure data for the different speeds. It is important to note that the pressure level rises with increasing RPM.

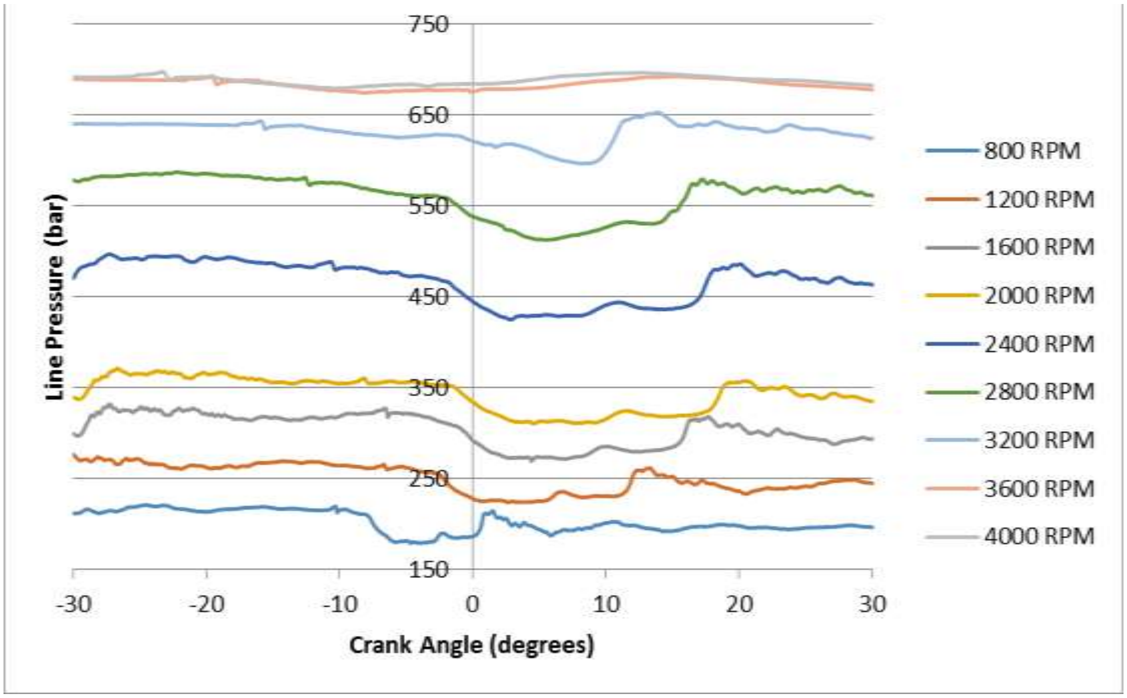

Figure 9: Line Pressure at Different Engine Speeds

It was difficult to pinpoint exact locations on the start of injection just by looking at the plots. Actual fuel injection should start after the command was given, so it has to be to the right of where the solenoid signal starts. Looking through all the line pressure plots, a small sharp drop in pressure is seen. In Figure 8, for example, a peak is seen at around -6.6 degrees then suddenly drops before it rises a little then continues to drop until a minimum value is attained. This sudden drop is also visible in all engine speeds and is considered as the start of dynamic injection timing. With respect to the static injection timing as determined by the solenoid signals, there is an injection command delay that is seen at all speeds indicating a lag between solenoid signal and the start of line pressure drop. Converting the crank angle delays to seconds, the delay is computed to be 80 to 100 microseconds. Exact locations were obtained by finding the maximum value at the location near the start of static injection timing; the values were collected and are shown in Table 2.

Table 2: Dynamic Injection Parameters

RPM	Pline Inj. Timing (°CA)	Pline Inj. Duration (°CA)
800	-10.3	11.8
1200	-6.7	20.0
1600	-6.6	24.3
2000	-8.2	28.6
2400	-10.7	30.8
2800	-12.6	29.8
3200	-15.9	29.8
3600	-19.6	35.1
4000	-23.3	36.1

Following through the start of injection, the line pressure drops until a minimum value is attained. Pressure then slowly rises back then drops again; this initial peak (at around 10 degrees CA in Figure 7) can be attributed to the pressure wave felt by the line pressure sensor as the solenoid valve is being closed. Note that this happens near the location where the solenoid voltage drops back to zero. As the solenoid is closed, there is a sudden pressure buildup near the orifice and is again relieved as the fuel still continuous to flow out of the needle. After this event, the pressure rises until a maximum value is attained. At this point, the nozzle is closed and this maximum value was then considered the end of dynamic injection. The difference between the end and start of dynamic injection is called the dynamic injection duration and is tabulated and shown as well in Table 2.

4. CONCLUSIONS AND RECOMMENDATIONS

This study has demonstrated the following:

1) The static injection duration obtained from the spliced solenoid signal command wire shows good correspondence (less than 2% difference) with the ECU command signals despite the difference in the crank angle referencing.
2) The start and end of dynamic injection may be inferred from the line pressure signals with the aid of the solenoid voltage signals.
3) Injection timing advances with increasing RPM in response to the increase in injection duration.
4) Injection duration and line pressure increases with increasing RPM.

The method for injection parameter determination described in this study is important for future studies. This method can possibly be used to test different alternative fuel effects, combustion and heat release, effects of property alteration, etc. This study can further be improved by doing the same analysis in comparison with data obtained from a needle lift sensor. Another way of looking at this further is by relating fuel flow rates with the length of injection obtained and finding out if there’s a correlation.

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