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DEVELOPMENT OF BOSCH RATE OF INJECTION MEASUREMENT PROCEDURE AND RESULTS

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DEVELOPMENT OF BOSCH RATE OF INJECTION MEASUREMENT
PROCEDURE AND RESULTS

By

Tyler John Menucci

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2018

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This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

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List of abbreviations

APS – Advanced Power Systems

APSRC – Advanced Power Systems Research Center

BP – Back Pressure

CARB – California Air Resources Board

E10 – 10% Ethanol

FP – Fuel Pressure

GCI – Gasoline Compression Ignition

GDI – Gasoline Direct Injection

HD – Heavy Duty

I/O – Input/Output

KAUST – King Abdullah University of Science and Technology

LD – Light Duty

LEV – Low Emission Vehicle

MOSFET - Metal Oxide Semiconductor Field Effect Transistors

MTU – Michigan Technological University

NI – National Instruments

ROI – Rate of Injection

RON – Research Octane Number

ULSD – Ultra Low Sulfur Diesel

Abstract

Recent developments in internal combustion engine technology have shown that gasoline compression ignition (GCI) combustion modes provide a viable pathway to meet future emission regulations. Lower octane middle distillate gasoline like fuels have also been formulated for GCI combustion applications and have shown similar benefits of improved fuel conversion efficiency and a reduction in particulate matter and nitrogen oxide emissions. As these gasoline like GCI fuels have not been well studied, characterization of their rate of injection (ROI) will be beneficial to supplement injector spray characterization measurements and the development of computational fluid dynamic simulations. A fuel collection method and data processing technique were defined to develop a measurement procedure for making rate of injection measurements with a Bosch type rate of injection (ROI) rig. The measurement procedure was developed to quantify the ROI for both heavy duty (HD) and light duty (LD) injector applications.

The HD studies included ROI measurements using an Ultra-Low Sulfur Diesel (ULSD) and a research octane number (RON) 60 gasoline compression ignition (GCI) fuel. Rate of injection measurements for the HD fuels were obtained with an eight-hole high pressure common rail diesel Cummins XPI injector and electronic injection durations were successfully calibrated to provide a desired fuel quantity per injection. Single-hole ROI measurements were also made with a Cummins XPI injector designed to provide one-eighth of the flow of the multi-hole injector. These single-hole ROI measurements were used to supplement injector spray characterization data in an optically accessible combustion vessel.

The LD studies characterized ROI measurements of a custom ten-hole Bosch HDEV5 gasoline direct injection (GDI) injector. The LD fuels studied were a premium octane CARB LEV III 10% ethanol (E10) certification gasoline and a RON 70 GCI fuel. These LD studies were conducted to compare the RON 70 GCI fuel's ROI characteristics to those of the premium octane CARB LEV III E10 certification gasoline. Average trends showed higher rates of injection and total mass per injection for the premium octane E10 cert gasoline and was attributed to the higher density of the fuel. Conclusions were also made that the higher viscosity of the E10 cert gasoline provided longer injector opening delays when compared to the RON 70 GCI fuel.

1 Introduction

1.1 Motivation

Petroleum-based liquid fuels are the largest energy source for the transportation sector accounting for 96% of the energy consumed in 2012 and are projected to provide 88% of the energy consumed in 2040 [1]. As petroleum-based liquid fuels will remain a dominant energy source, it is important to combat their harmful pollutants with more stringent emission regulations. The efficiency and associated emission pollutions of diesel and gasoline combustion relies heavily on the fuel injection process. The development of a rate of injection (ROI) measurement procedure will allow for a better understanding of the injection process and provide insight on the effects of combustion.

Although the ROI rig is capable of measuring rates of injection for conventional fuels such as diesel and gasoline, its' use will be most beneficial for emerging technologies and alternative fuels whose injection characteristics are not yet well known. With the need for advancement in internal combustion engine technologies, comes the interest in exploring different combustion modes. Recent studies have shown that gasoline compression ignition (GCI) combustion has the potential to obtain high fuel conversion efficiencies and emit very low levels of particulate matter and nitrogen oxides [2, 3]. It has also been observed that these benefits were further improved by using a lower octane middle distillate gasoline like fuel in GCI combustion [2, 3]. The ROI data for these newly formulated GCI fuels can be used in conjunction with spray characterization and computational fluid dynamic modeling to aid the advancement of new combustion technologies.

1.2 Background

Research partners at Aramco Research Center and King Abdullah University of Science and Technology (KAUST) contracted Michigan Technological University's (MTU) Advanced Power Systems Research Center (APSRC) to investigate critical technologies for advanced internal combustion engines. A portion of the scope of work was to develop a ROI measurement procedure to identify and compare characteristics of the rate of fuel injection for a variety of fuels and injectors. A Bosch type ROI meter had been previously constructed internally at MTU's APSRC, but an experimental procedure to use the device effectively had yet to be developed. This research aimed to develop an experimental procedure for using the Bosch type ROI meter while simultaneously collecting test condition data.

The project was split into two categories; light duty (LD) and heavy duty (HD) injector applications. The LD studies focused on comparing a baseline premium octane CARB LEV III E10 certification gasoline and RON 70 GCI fuel while the HD studies compared a certified Ultra Low Sulfur Diesel (ULSD) and a RON 60 GCI fuel. The metrics used to

compare each fuels' injection characteristics include; total mass of fuel per injection, injector opening delay, injector closing delay, and their rate of injection profiles.

The injector specified for the LD studies is a 10-hole Bosch HDEV5 gasoline direct injection (GDI) injector capable of injection pressures up to 450 bar with 165 micrometer hole diameters. The LD test conditions included ROI measurements with varying injection pressures, durations, and back pressures. Injection durations included a 1.75 ms electronic injection duration to match conditions in conjunction with testing in the lab's optically accessible combustion vessel. A number of other injection durations were calibrated to reach a nominal targeted mass of 20, 40, and 60 milligrams of fuel per injection. An overview of the test conditions for LD studies of both fuels can be seen below in Table 1.

Table 1: LD ROI Test Conditions

Parameter	Range/Number
Injector	Bosch HDEV5 GDI (Injector 0261.B32.305-01)
Fuels	Premium Octane CARB LEV III E10 Cert Gasoline and RON 70 GCI Fuel
Injection Pressure (bar)	100 / 300 / 450
Injection Duration (ms) / Targeted Mass per Injection (mg)	1.75 ms / 20, 40, and 60 mg per injection
Back Pressure (bar)	4 / 20 / 65

The baseline fuel for LD testing is a premium octane E10 certification fuel from Haltermann Solutions formulated in accordance with the California Air Resources Board (CARB) Low Emission Vehicle (LEV) III program, for the remainder of the document this fuel will simply be referred to as E10 Cert Gasoline. A full list of the E10 Cert Gasoline's fuel properties is provided in Appendix A. The RON 70 GCI fuel is a proprietary fuel formulated by Saudi Aramco for GCI applications. Fuel properties relevant to this study are tabulated below in Table 2.

Table 2: LD Fuel Properties

Fuel Property	Units	Premium CARB LEV III Cert E10 Gasoline	RON 70 GCI Fuel
Density at 15.56° C	$\frac{g}{mL}$	0.743	0.723
Kinematic Viscosity	$\frac{mm^2}{sec}$	0.669	0.575

The HD studies utilized both a multi-hole and single-hole Cummins XPI injector. The multi-hole injector was an 8-hole injector with orifice diameters of 186 micrometers while the single hole orifice was 176 micrometers in diameter. The single-hole injector was specifically designed to provide one-eighth of the flow compared to the multi-hole injector. A variety of test conditions were experimented with to match engine relevant conditions for single-hole and multi-hole injectors as displayed in Table 3 and Table 4 respectively.

Table 3: HD Single-Hole ROI Test Conditions

Parameter	Range/Number
Injector	Single-Hole Cummins XPI Injector
Fuels	ULSD and RON 60 GCI Fuel
Injection Pressure (bar)	1000 / 1500 / 2500
Injection Duration (ms)	2 ms
Back Pressure (bar)	60 / 100

Table 4: HD Multi-Hole ROI Test Conditions

Parameter	Range/Number
Injector	Multi-Hole Cummins XPI Injector
Fuels	ULSD and RON 60 GCI Fuel
Injection Pressure (bar)	1300 - 2500
Injection Duration (ms)	0.9 – 2.8 (Range of durations to meet fuel demands at steady state engine set points)
Back Pressure (bar)	60 / 100

The baseline fuel for the HD studies was a cert ULSD and a Saudi Aramco formulated RON 60 GCI fuel. A full list of the ULSD fuel properties is provided in Appendix B. The fuel properties relevant to the HD ROI studies are shown below in Table 5.

Table 5: HD Fuel Properties

Fuel Property	Units	Cert ULSD	RON 60 GCI Fuel
Density at 15.56° C	$\frac{g}{mL}$	0.848	0.705
Kinematic Viscosity	$\frac{mm^2}{sec}$	2.60	0.58

1.3 Goals and Objectives

The following goals and objectives were set forth to develop a Bosch type ROI measurement procedure and analyze the differences in injection characteristics between fuels:

1. Conduct experiments at test conditions and define a test procedure for acquiring data:
 - a. Develop a code to post-process the acquired raw pressure trace to derive the ROI with respect to time and integrate to compute mass per injection.
 - b. Define a collection method to collect the fuel regulated out of the ROI rig and experimentally mass fuel for comparison to integrated mass value.
 - c. Compute a scale factor for each fuel based on the average differences between experimentally massed fuel and integrated mass fuel values to compensate for the underestimated mass per injection inherent to the Bosch ROI measurement principle.
 - d. Apply scale factor to the originally acquired data and compute ROI characteristics: mass per injection, injector opening delay, injector closing delay, cumulative mass injected with respect to time, and discharge coefficient over a steady-state portion.
2. Analyze each fuel's ROI characteristics and use physical fuel properties to draw conclusions and highlight trends observed.
 - a. Compare total mass of fuel injected and quasi-steady rate of injection period with differences in fuel density
 - b. Understand the impact of kinematic viscosity on injector delays
 - c. Examine injection duration impact on total mass of fuel injected

2 Literature Review

2.1 Bosch Rate of Injection Measurement Technique

The Bosch ROI measurement principle relies on acquiring a dynamic pressure increase in a column of fluid directly downstream of an injector nozzle. The injector is clamped to an injector hold down fixture which houses a dynamic pressure transducer. A coil of tubing, known as the measuring tube, is fitted to the fixture and filled with the test fuel. This pressure increase in the measuring tube from the injection event is then used to realize the rate of injection. Figure 1 below shows a schematic of the Bosch ROI measurement meter as provided by Bower and Foster [4].

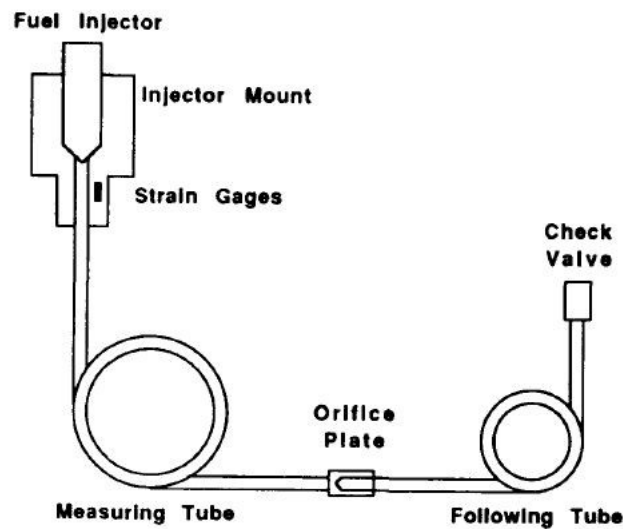


Figure 1: Bosch Rate of Injection Meter Schematic [4]

The check valve at the end of the following tube is used to regulate the pressure in the measuring and following tubes to a desired back pressure to replicate in-cylinder engine conditions. This check valve makes sure that a constant pressure and volume of fuel in the measuring and following tubes is maintained during testing, and that any amount of fuel leaving the check valve is representative of the amount of fuel from the injection event. The measuring tube is used to record the pressure increase during the injection while both the measuring and following tubes damp the pressure oscillations before the next injection event occurs. An orifice plate is placed between the two tubes to adjust the portion of the pressure wave which enters the following tube. The following text outlines how the dynamic pressure trace acquired during an injection event can be used to compute the mass flowrate during said injection.

In order to determine the mass flow-rate of a substance \dot{m} , the density ρ of the substance, cross sectional area of pipe A , and velocity of the substance V must be known. The density of the fluid and cross-sectional area can be directly measured, leaving the velocity of the fluid as the only unknown variable. Although the density of the fluid is not constant at different pressure conditions, the effect has been deemed negligible on the mass flow rate [5]. See mass flowrate equation below:

$$\dot{m} = \rho * A * V$$

The concept of the Bosch ROI measurement relies on the relationship between pressure and velocity of a transient, one-dimensional fluid flow [5]. This relationship is described below in the following equation where P is pressure in Pascals, a is the speed of sound in the fluid $\frac{m}{s}$, ρ the fluid density in $\frac{kg}{m^3}$, and V is velocity in $\frac{m}{s}$:

$$P = a * \rho * V$$

Re-arranging the above equation to solve for the unknown variable, velocity, we now have:

$$V = \frac{P}{a * \rho}$$

Substituting the above equation for velocity into the mass flow-rate equation and canceling like terms yields the following:

$$\dot{m} = \frac{\rho * A * P}{a * \rho} = \frac{A}{a} * P$$

The mass flowrate of an injection event can be quantified by knowing the cross-sectional area of pipe, the speed of sound in the fluid, and the dynamic pressure change in the fluid during the injection event. If the total mass of fuel per injection is to be quantified, separation of variables and integration is carried out to provide the mass per injection from start of injection (SOI) to end of injection (EOI):

$$\frac{dm}{dt} = \frac{A}{a} * P$$

$$dm = \frac{A}{a} * P dt$$

$$\int_{SOI}^{EOI} dm = \frac{A}{a} * \int_{SOI}^{EOI} P dt$$

$$m = \frac{A}{a} * P \Delta t|_{SOI}^{EOI}$$

The speed of sound in the fluid is also computed using the dynamic pressure transducer. It is found by taking twice the length of the measuring tube and dividing it by the time between pressure increases observed by the transducer. An initial pressure increase occurs at the start of the injection event and a secondary increase occurs from a reflection of the initial pressure pulse. The initial injection event sends a pressure pulse along the length of the measuring tube until coming in contact with the back-pressure regulator at the end of the tubing. The pressure pulse is then reflected and travels back up to the pressure transducer where the second increase in pressure is observed. The time it takes to travel from the transducer, to the back-pressure regulator, and back up to the transducer is computed in post processing and used to compute the speed of sound in the fluid.

The integrated mass value of fuel acquired by the Bosch rate rig can be compared to the amount of fuel which exits the rate rig through the back-pressure regulator or check valve. It has been observed that the integrated mass value underestimates the amount of fuel collected by a number of sources. Bower and Foster realized the integrated values for volume per injection underestimated the collected volume of fuel by as much as 6.7%, Bosch showed maximum differences in the volume of fuel injected up to 11.5%, and Phan's studies resulted in integrated mass values underestimating the collected fuel mass by up to 15% [4 5 6]. Conclusions from Bosch's paper state that the underestimated values are due to a non-uniform velocity profile of the injected fuel where the pressure measurement occurs. This stems from the measurement's use of the pressure velocity relationship in a transient fluid flow and assumes a uniform velocity profile and one-dimensional flow. Bosch ROI measurements can be calibrated/adjusted to better match the accepted values of collected mass of fuel per injection.

2.2 Physical Fuel Property Effects on Rate of Injection

Rate of injection profiles are influenced not only by operating conditions but also by the fuel's physical properties. The fuel's viscosity and density are the main physical fuel properties which can explain differences in the rates of injection. Desantes et al. observed rate of injection differences between diesel fuel and biodiesel blends using a Bosch type rate of injection meter. Their work concluded that the dynamics of the injector needle are affected by the fuel's viscosity and that the higher viscosity of the biodiesel fuel blends lead to a slower needle lift during opening [7]. Suh and Lee also concluded impeded rates of injection for short injection durations due to fuel viscosity [8]. Both works observed that as injection durations are increased, the dominant factor on the magnitude of the rate of injection is driven by the fuel density.

3 Experimental Setup

3.1 Bosch ROI Rig Hardware

The ROI rig was developed internally at APS Labs. The measuring tube is constructed of 3/8" stainless steel tubing with a 0.020" wall thickness and is mounted to a custom injector hold down fixture. The hold down fixture is responsible for clamping the injector in place as well as housing the dynamic pressure transducer. Injector hold down fixtures were designed and fabricated for both a Cummins XPI injector for HD applications and a Bosch GDI injector for LD studies. The ROI rig is also equipped with a bourdon tube pressure gage from WIKA and a back pressure regulator from GO Regulators to control the back pressure. The back pressure regulator is capable of regulating back pressures up to 4,000 psi or 276 bar, the specific part number of the regulator is BP66-1A41Q4N151. Although the back pressure regulator is capable of withstanding pressures up to 276 bar, the tubing is only rated to 110 bar and is currently the limiting factor for the rigs' back pressure capabilities. See Figure 2 below for ROI rig and hold down fixture pictures.

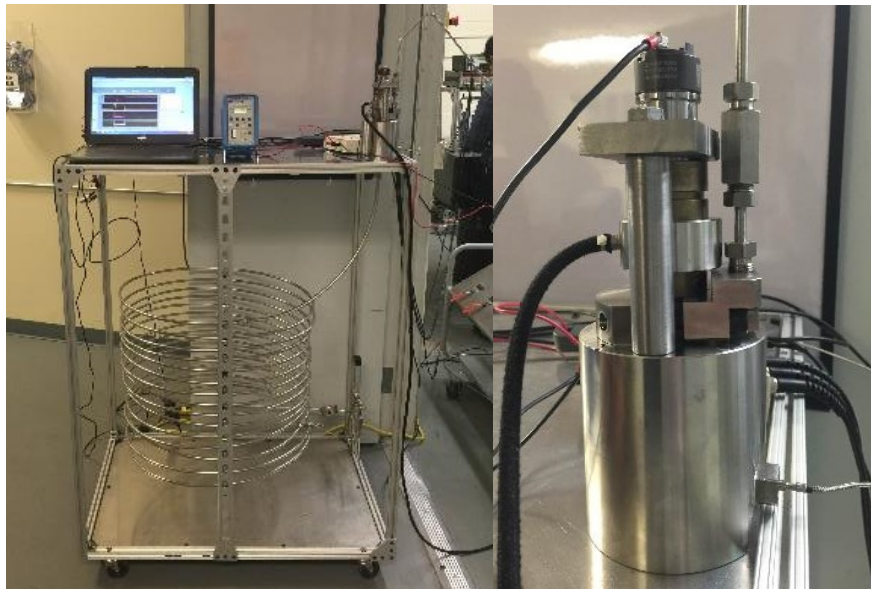


Figure 2: Left; ROI Rig and Right; Injector Hold Down Fixture

The dynamic pressure transducer used is a Kistler 6125c piezo transducer and is capable of withstanding dynamic pressures to 300 bar with a sensitivity of 36 picocoulombs per bar. The charge generated in the transducer from changes in pressure is then converted to voltage through the use of a Kistler 5010B dual mode charge amplifier. Settings on the charge amplifier should be set to a transducer sensitivity of 36 pC/MU with a scale of 30 MU/Volt and a medium time constant. A Fluke 80i-11s current probe measures the injector current and outputs a voltage reading at the scale of 100 millivolts per amp.

The data acquisition system uses National Instruments (NI) compact daq 9178 chassis to operate a NI 9223 analog input and NI 9401 input/output (I/O) card. The NI 9223 card has 4 channels of differential analog input with an input range of ± 10 Volts. This analog input card is responsible for logging the dynamic pressure trace and the injector current measurement at a sample rate of 1 Mega-sample per second and a resolution of 16 bits. The configuration of the NI LabVIEW Virtual Instrument software requires the NI 9223 analog input card to be placed in “slot 3” of the data acquisition chassis. The software also requires the pressure signal to be acquired on the analog input 0 channel and the injector current on the analog input 3 channel for proper scaling. The NI 9401 input/output (I/O) card is used to send a 5 volt TTL signal to command the injector driver to inject, this card must be placed in “slot 5” of the chassis. See Figure 3 below for data acquisition component details.



Figure 3: National Instruments Data Acquisition Setup

The injector is driven using a GW Instek Model: GPR-30H10D DC power supply, a Quantum Composer 9614+ pulse generator, and a set of three metal oxide semiconductor field effect transistors (MOSFET). The DC power supply provides the necessary drive voltage for the injector driver circuit while MOSFETs are used to open and close the circuit in a rapid manner to regulate the current to the injector. The timing of the MOSFETs operations are controlled by the respective pulse train sent to the gate of the MOSFET by the Quantum Composer pulse generator. Appendix C provides details on the necessary Quantum Composer pulse generator settings to achieve the correct current profile for the LD and HD injectors. The LD and HD injector driving voltage should be set to 65 and 50 volts respectively.

3.2 Experimental Procedure

The experimental procedure was developed and refined over both LD and HD studies to provide a standard operating procedure of making ROI measurements. The procedure is as follows:

1. Fill up ROI rig with the test fuel:
 - a. Attach the appropriate injector hold down fixture to the upper portion of the measuring tube via the 1/4" NPT fitting. Fasten the pressure transducer adapter fitting to the injector hold down fixture.
 - b. Drain any remaining fuel in the rig by first closing the ball valve at the end of the measuring tube, removing the back-pressure regulator, and placing a container at the end of the tubing before re-opening the ball valve. Use compressed air through the hold down fixture to force out remaining fuel if needed.
 - c. Fill up a clean container with at least two liters of the test fuel. Fit one end of a 3/8" inner diameter poly tube over the end of the measuring tube and place the other in the test fuel container.
 - d. Fit a properly sized rubber stopper and poly-tubing line in the injector hold down fixture and attach to vacuum pump. Make sure the ball valve at the end of the measuring tube is still open and use the vacuum pump to draw fuel up the measuring tube. Maintain a vacuum until fuel is drawn out the top of the rig through the injector hold down fixture, close the ball valve at the end of the rig and remove vacuum. If needed, gently pour extra fuel into the hold down fixture so that the sealing surface between the injector and fixture is submerged in fuel.
 - e. Remove the poly-tubing at the end of the measuring tube. Fill the short section of tubing downstream of the ball valve with test fuel before re-attaching the back-pressure regulator.
 - f. Keep the ball valve closed and turn the back-pressure regulator adjustment two full rotations in the clockwise direction to increase the back-pressure setting to ensure no fuel leaves the measuring tube during setup.
2. Install injector and fuel delivery cart:
 - a. Insert injector into the hold down fixture and torque to the required spec (5 N-m for LD injector and 15 N-m for HD).
 - b. Fill high pressure fuel cart with test fuel and fit high-pressure fuel line from the outlet of the fuel cart to the inlet of the injector, leaving the fitting at the injector fuel inlet loose. Slowly pump fuel out of the fuel cart to force air out of the fuel line before tightening the fitting to the fuel inlet of the injector.
 - c. Increase fuel pressure on the fuel cart to the operating condition while watching for leaks in between the fuel cart and the injector. Reduce fuel pressure and fix any leaking fittings before moving on.

3. Setup injector driver hardware:
 - a. Connect the DC power supply, MOSFETs, and Quantum Composer pulse generator.
 - b. Set Quantum Composer pulse generator settings to the provided specs in Appendix C for desired injector current profile
 - c. Place fluke current probe around one of the injector leads, turn on using the 100 mV/A setting and connect the BNC cable to AI channel 3 of the NI 9223 card.
 - d. Connect 5 Volt TTL output signal from the NI 9401 card to the EXT/GATE BNC port on the Quantum Composer.
4. Connect pressure transducer for data acquisition:
 - a. Connect BNC from pressure transducer to the charge input port on the Kistler 5010B charge amplifier.
 - b. Set the sensitivity of the charge amplifier to 36 pC/MU, the scale to 30 MU/V, the time constant to medium, and the mode to charge.
 - c. Connect the output of the charge amplifier to AI channel 0 of the NI 9223 card
5. Open LabVIEW Virtual Instrument and connect to cdaq:
 - a. On the CV Lab Laptop, open the virtual instrument software titled ROI_DAQ(4)_HigherSampleRate.vi
 - b. Set the “pulses” text box to 500, and cycle period to 0.25 seconds. The sample window period and pulse delay settings are arbitrary for this step. The cycle period setting determines how often an output signal is sent by the data acquisition system to command an injection while the “pulses” defines how many injections the software will run for. These settings will strictly be used for building back-pressure in the rig before obtaining any saved data. A sample of the virtual instrument’s front panel is shown below in Figure 4 for reference.

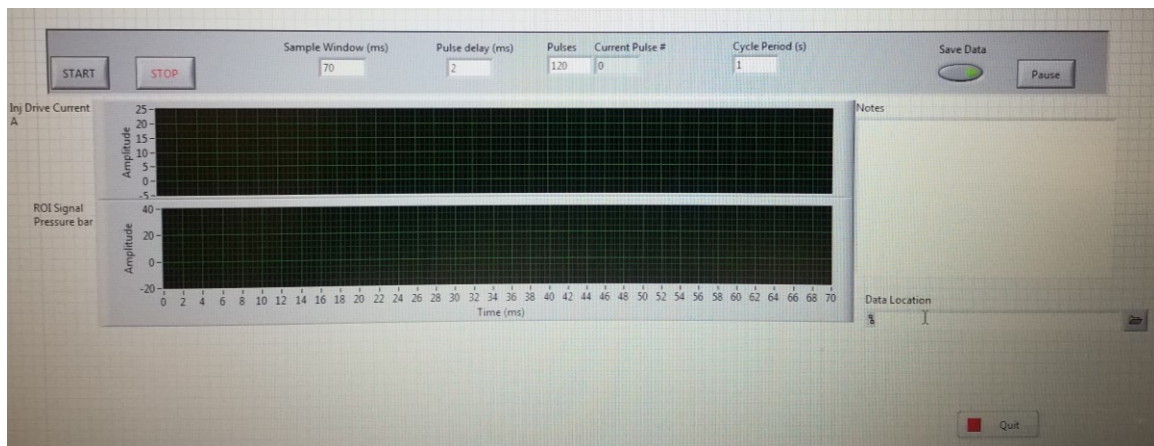


Figure 4: LabVIEW ROI Virtual Instrument Front Panel

- c. Plug in the NI c-daq chassis to the laptops USB port

6. Set fuel pressure and back-pressure in ROI rig to operating condition:
 - a. Increase fuel pressure on the fuel cart to the desired operating condition
 - b. Keep the ball valve on the measuring tube closed and the back-pressure regulator set to the previously described setting in step 1 part f.
 - c. Place a beaker at the outlet of the back-pressure regulator
 - d. Turn on the DC power supply and set the voltage to the required injector driver voltage (50 V for HD injector and 65 V for LD injector)
 - e. Ready the Quantum Composer to receive an injection command from the virtual instrument software. Navigate to the Quantum Composer's TRIG/GATE setting by first pressing "Function" and then "TRIG/GATE". Use the up and down arrows to cycle to the Trigger Enabled setting. Press the "Run" button to ready the unit for a command.
 - f. Begin injecting fuel into the measuring tube by clicking run in the upper left-hand corner of the virtual instrument front panel and then clicking start. Allow the back-pressure in the rig to build up to 500 psi while simultaneously checking the rig for leaks. Once the pressure in the rig reaches 500 psi the ball valve may be opened, this will help force any small amount of air trapped in-between the back-pressure regulator and the ball valve out of the measurement tube.
 - g. After the ball valve is opened the injections can be terminated by clicking "stop" on the virtual instrument software. Change the cycle period to 1 second as this will be the setting used to acquire data. Run the software again while adjusting the back-pressure regulator to the required operating condition.
7. Setup for collecting fuel for massing measurements:
 - a. Measure the mass of a clean plastic Nalgene® beaker and one sheet of paper towel using the Acculab ALC80.4 analytic balance capable of measure 0.1 mg. If testing is to be done with an E10 gasoline, RON 60 or RON 70 GCI fuel then include a sheet of 12"x12" cellophane wrap in the massing measurement. The paper towel will be used to absorb the fuel during testing and the cellophane will be used to cover the beaker and keep the fuel from evaporating into the atmosphere. Record this mass in grams in a test matrix for later use. See Figure 5 on the next page for massing measurement equipment.

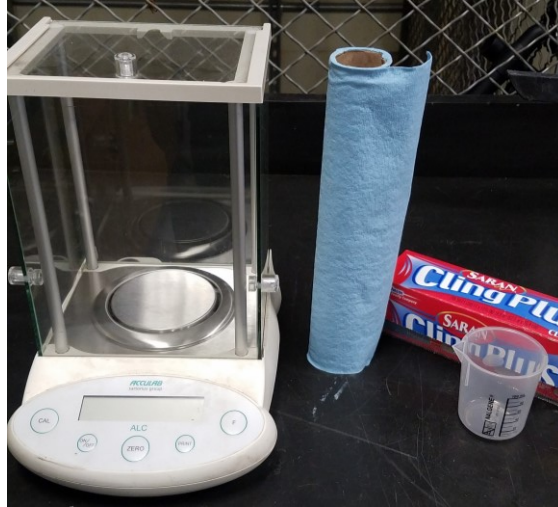


Figure 5: Mass Measurement Equipment

- b. Wipe out the remaining fuel in the back-pressure regulator outlet leftover from previous test or back-pressure adjustment. Cut 1/3 of the paper towel sheet which was massed earlier and keep off to the side. This will be used to wipe out the regulator outlet after testing to make sure all of the fuel injected during a test set is collected and massed. Place the beaker and remaining 2/3 of the paper towel sheet under the outlet of the regulator. Cover the beaker with cellophane wrap tightly so that no gaseous fuel can escape.
8. Acquire data for given test condition:
 - a. On the virtual instrument software, adjust the “sample window” to be 70 ms so that the pressure data is recorded for a long enough time to measure a reflection of the initial injection pressure wave off the end of the following tube. This pressure reflection will need to be acquired for speed of sound measurements necessary for processing the data. Adjust the “pulse delay” setting to 2 ms, this setting determines how long the data is acquired before an output signal is sent to command an injection. The pressure and injector current data will be acquired at 1 MS/s.
 - b. Change the cycle period of the virtual instrument software to a 1 second cycle period. Running injections at one injection per second provides ample time for pressure oscillations in the measuring tube to be damped before the next injection event.
 - c. Specify the file name and path of where the data should be saved to by filling in the data location input parameter on the virtual instrument software. Data will be saved in a text file for post-processing use. Record this file name and path in a test matrix along with operating conditions.
 - d. Click run in the upper left-hand corner of the software, click the “Save Data” button and make sure it lights up green, click start to begin taking data.

- e. Monitor the fuel pressure, back-pressure, injector driver voltage, and injector current profile throughout the duration of the testing.
9. Determine mass of fuel per injection from fuel collection:
 - a. After the 120 injections are complete, use the remaining 1/3 of a sheet of paper towel to swab out any remaining fuel in the outlet of the regulator. Place the paper toweling swab into the beaker and keep cellophane wrapping tightly covered.
 - b. Mass the beaker and its' contents again to acquire the total mass in grams for the beaker, fuel, paper towel, and cellophane. Record this value in the test matrix.
 - c. Take the difference between the two massed values of the “wet” and “dry” beaker measurements to obtain the mass of fuel injected. Multiply this by 1,000 mg/g and divide it by 120 injections to provide the final average mass per injection in milligrams per injection and record this value in the test matrix.
 - d. Repeat steps 7 thru 9 until 3 tests of 120 injections each have been acquired for each test condition
10. A scale factor needs to be developed to help compensate for the underestimated mass per injection values inherent to the Bosch measurement. Determine scale factor for each respective fuel and injector pair tested:
 - a. Repeat steps 6-9 until completion of the entire test matrix for a given fuel and injector
 - b. Run each test conditions acquired data through the first 171 lines of the provided “RefinedROI.m” code shown in Appendix D. Obtain the unscaled integrated mass values of the Bosch ROI measurement which is given in the MATLAB workspace as “m_injected” with the units of mg/injection. Record these values in the test matrix alongside the respective mass of fuel per injection from collected massing measurements.
 - c. Compute the difference in the mass per injection measurements for each test condition. Do this by subtracting the underestimated integrated mass per injection from the mass of fuel per injection from collected massing measurements. Divide this difference by the integrated mass value. Average this difference for all test conditions of a fuel and injector test set and add one to it. This will be the scale factor used for that specific fuel and injector combination to scale the rate of injection to closer match the collected mass of fuel injected. Table 6 on the next page for an example of the scale factor determination for the HD single hole injector with ULSD.

Table 6: Scale Factor Computation Example for HD Single-Hole ULSD Measurements

Fuel Pressure (bar)	Back Pressure (bar)	Average Collected Mass per Injection (mg/inj)	Average Integrated Mass per Injection (mg/inj)	Percent Difference (%)	Scaled Integrated Mass per Injection (mg)
1,000	60	33.5	30.7	9.1	32.4
1,000	100	31.1	29.9	4.2	31.5
1,500	60	40.1	39.0	2.7	41.1
1,500	100	42.1	38.9	8.2	41.0
2,500	60	55.1	52.8	4.3	55.7
2,500	100	55.1	52.9	4.1	55.8
				Average	5.4
				Scale Factor	1.054

11. Apply scale factor and compute injector characteristics:
 - a. Re-run the entire provided “RefinedROI.m” code and type in the computed scale factor when prompted. This will scale the originally acquired rate of injection signal values to their final values.
 - b. The code will then compute finalized average scalar values of: scaled mass per injection, injector open delay, injector close delay, hydraulic duration, and the discharge coefficient of the injector during the steady state portion of the injection rate.
 - c. The code will also provide the following vectors used to generate plots; time with zero being the start of the hydraulic injection event, average corrected rate of injection, average cumulative mass injected with respect to time, and average injector current.
 - d. Record the necessary parameters from the MATLAB code in the test matrix and conduct desired analysis.

3.3 Data Processing

A MATLAB code was generated to process the acquired data and convert the raw pressure and injector current traces into useful data for rate of injection characterization. See Appendix D for the full data processing code. The following data processing steps are listed in the order of which the code processes the data and are outlined with the necessary adjustments future users will have to make:

1. Read in raw data for a given test condition (lines 4-22):
 - a. Specify the folder pathway in line 4 where the text file of raw data written by the virtual instrument software was saved to.
 - b. Input the number of injections recorded for each test and the number of tests conducted for a given test condition. Following the previously outlined procedure the number of injections is 120 and the number of tests is 3. An example of the raw pressure data read in for 360 injection events is shown below in Figure 6.

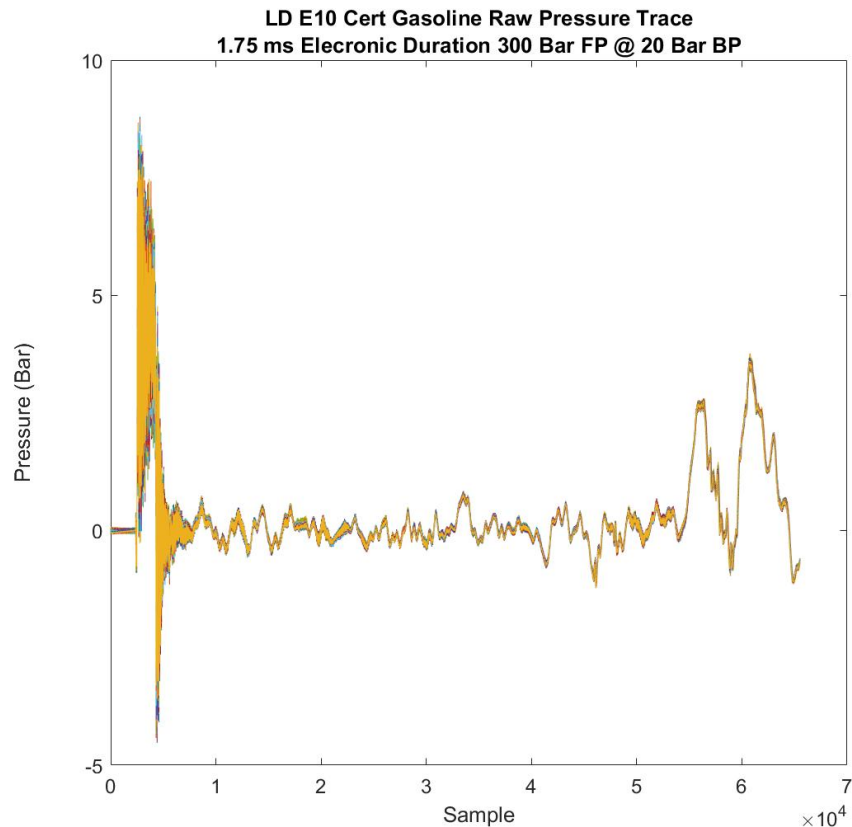


Figure 6: Raw Pressure Trace

2. Compute metric for injections with the largest time varying pressure drift before the injection. Remove the offset observed in the raw pressure data and set pressure values before the injection to zero. Figure 7 below shows the pressure data at the beginning of the injection event after the offset has been removed and the pressure before injection has been pegged to zero (lines 24-36).

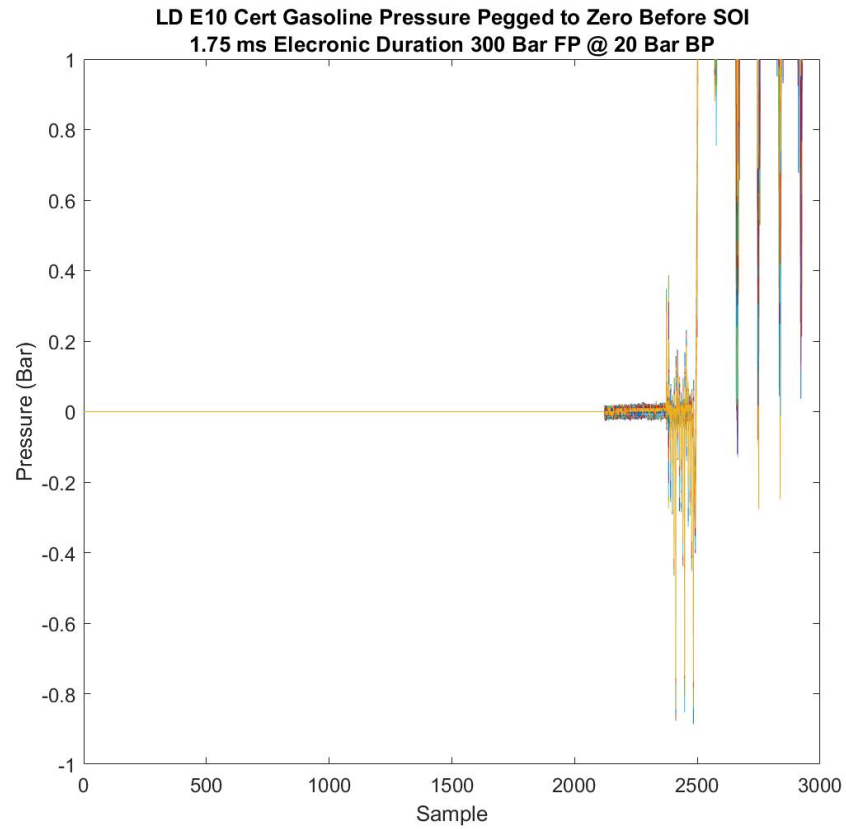


Figure 7: Pressure Data Pegged to Zero

3. Plot the raw pressure data power spectral density to determine the amount of energy in the pressure signal with respect to frequency as shown Figure 8 (lines 38-40). The x-axis of this plot represents the normalized frequency. As the pressure data was acquired at a rate of 1 MHz, a normalized frequency of 0.015 would represent a frequency of 15 kHz. Normalized frequencies under 0.015 account for a majority of the energy in the pressure signal, as the injection event is the main source of pressure increase in the rig, these lower frequencies are determined to be from the injection. The lower energy, higher frequency pressure data is hypothesized to be attributed to vibrations of the ROI rig and electromagnetic interference from injector driver hardware.

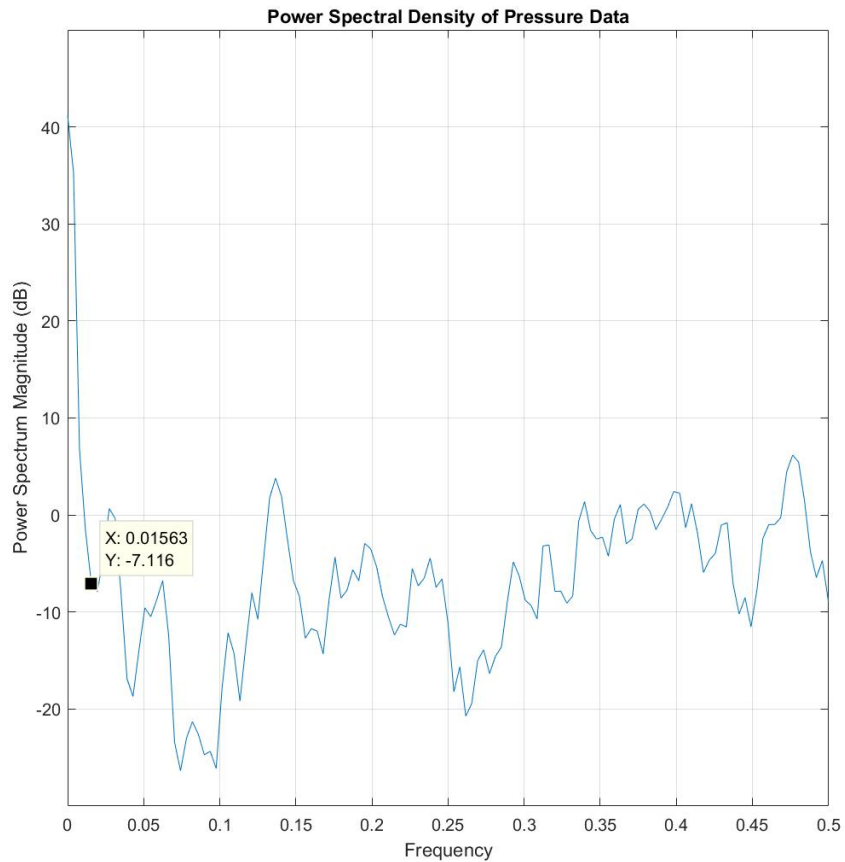


Figure 8: Power Spectral Density of Pressure

4. Use a third order Butterworth low-pass filter at the previously determined normalized cutoff frequency of 0.015 to filter pressure data. Figure 9 below shows the unfiltered and filtered average pressure traces. The filter cut-off frequency was selected to remove high-frequency noise content not related to the pressure increase from the injection event (41-43).

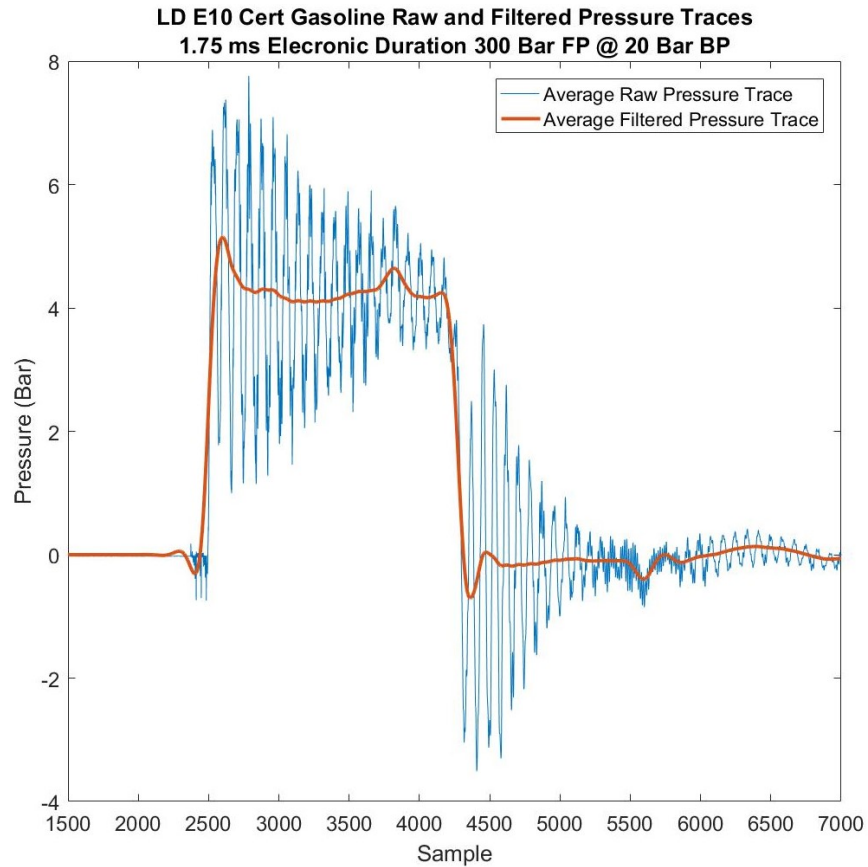


Figure 9: Average Raw and Filtered Pressure Traces

5. Locate the start of injection and end of injection of the filtered pressure data and create a time vector zeroed at start of injection (lines 45-59). The start of injection is defined by observing the first 2500 data points of filtered pressure and finding the last data point/index that is less than zero. The end of injection is defined by looking for the first filtered pressure data point after 0.5 ms that goes below zero. Figure 10 below shows the average filtered pressure trace with pressure values zeroed before and after the injection. These values are set equal to zero so that integrating the data to solve for the mass injected is not influenced by pressure oscillations outside the injection event.

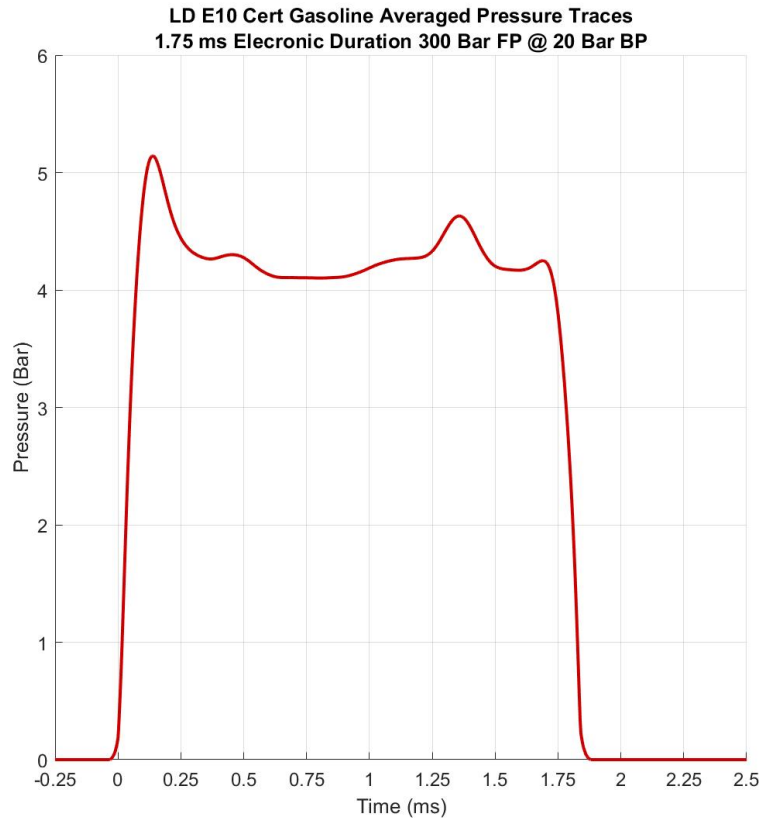


Figure 10: Average Filtered Pressure Trace with Respect to Time

6. Generate plots to observe differences in raw and filtered pressure traces (lines 61-79)
7. Compute metric for injections with largest deviation in integrated pressure. Eliminate 60 injections with the worst deviation in integrated pressure and 60 injections with the worst pressure drift before the injection, keeping only the injection events that meet both criteria (lines 82-94). This will eliminate injection events that deviate from the average values and will retain a minimum of 240 injection events to be used throughout the remainder of the processing.

8. Compute an average of the good criteria injection events and use another third order low-pass Butterworth filter at a cutoff of 0.01 normalized cutoff frequency. Peg the pressure before and after the injection to zero again as filtering makes previous values of zero small numbers (lines 97-119).
9. Plot the averaged pressure trace against all individual injections which met the previous deviation in integrated pressure and pressure drift criteria for comparison (lines 121-138)
10. Compute the speed of sound in the fluid by finding the amount of time it takes for the pressure wave generated by the injection event to travel the 58.5 meters from the pressure transducer, to the back-pressure regulator, and back to the pressure transducer (lines 140-145). An average of the raw pressure traces is used in this computation as the pressure values after the injection have not ben pegged to zero, the computation is executed by first finding the amount of data samples between the initial pressure rise from the injection and the secondary reflection of the pressure wave as shown in Figure 11. The amount of data samples between the pressure events is then converted to time using the sampling rate of the data acquisition system which is 1 Mega-sample per second.

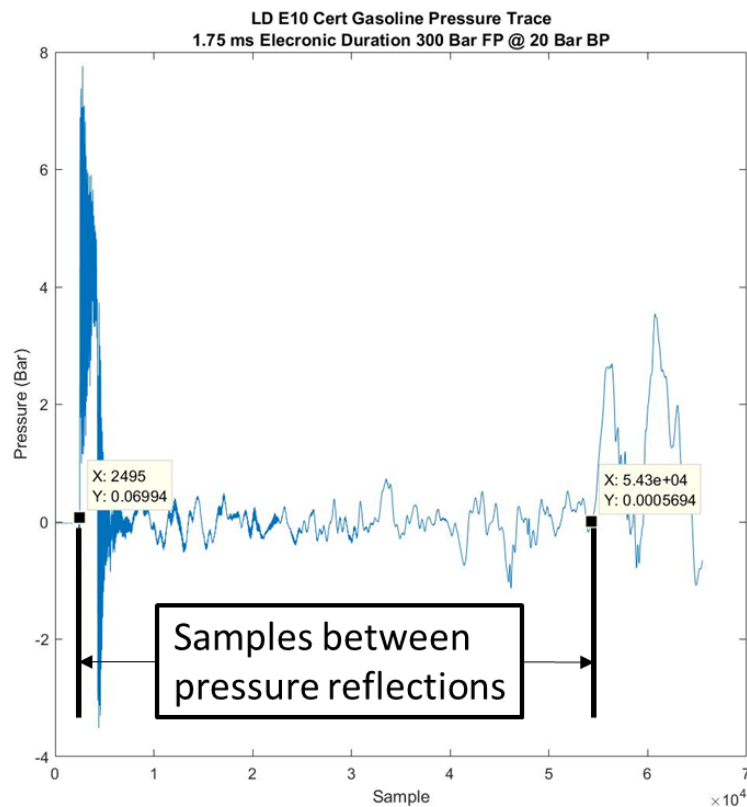


Figure 11: Speed of Sound Calculation

11. Calculate unscaled mass injected and rate of injection and create time vector where time zero begins at start of injection (line 147-155):
- If a new hold down fixture is implemented, adjust the diameter of the “Area” variable accordingly. This should be the diameter of the cross-sectional area in inches of the hold down fixture where the pressure transducer port taps into the fixture. See Figure 12 below for an example the defined cross-section area diameter for the HD ROI fixture shown in red. The code will convert the units of this area to meters.

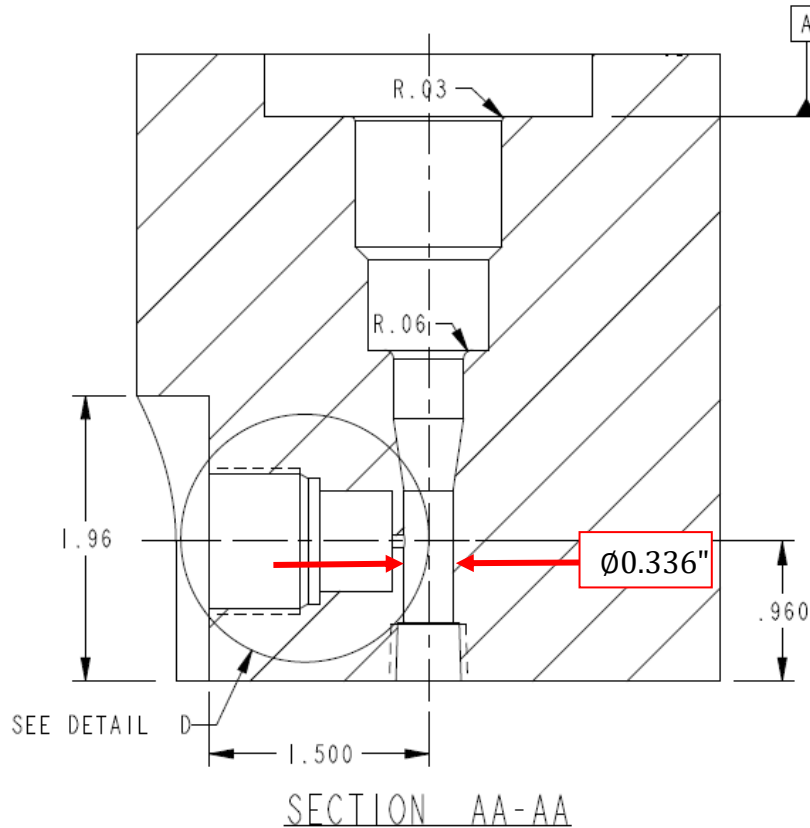


Figure 12: Cross-Sectional Area

12. Plot the average unscaled rate of injection, in red, and all individual good criteria injection events, in grey, as shown in Figure 13 (line 156-171). Run the code to line 171 for all test conditions and obtain the unscaled average of the integrated mass per injection value “m_injected”. Compare the average integrated mass per injection value to the average collected mass per injection value. Compute the scale factor as previously defined before running any further lines of code.

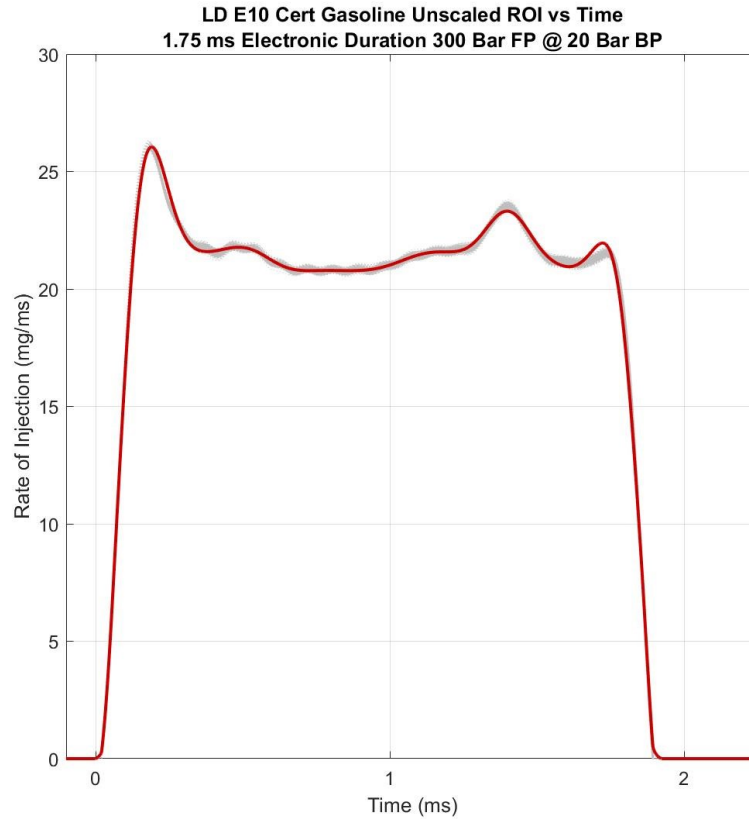


Figure 13: Averaged and Individual Unscaled ROI vs Time

13. Compute the scaled rate of injection and scaled mass per injection value by inputting the fuel's determined scale factor when prompted (lines 173-177).
14. Calculate the cumulative mass of fuel injected with respect to time and plot as seen in Figure 14 (lines 179-188)

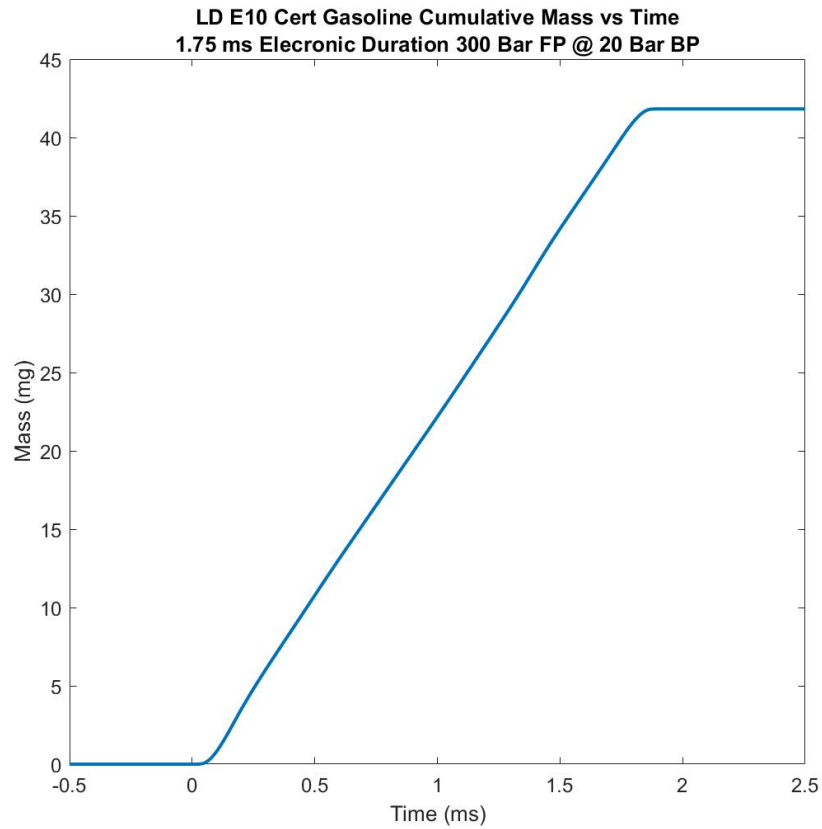


Figure 14: Cumulative Mass vs Time

15. Read in the injector current data and calculate injector opening and closing delays as well as the hydraulic duration. Plot the injector current and scaled rate of injection versus time shown in Figure 15 below (lines 190-230).

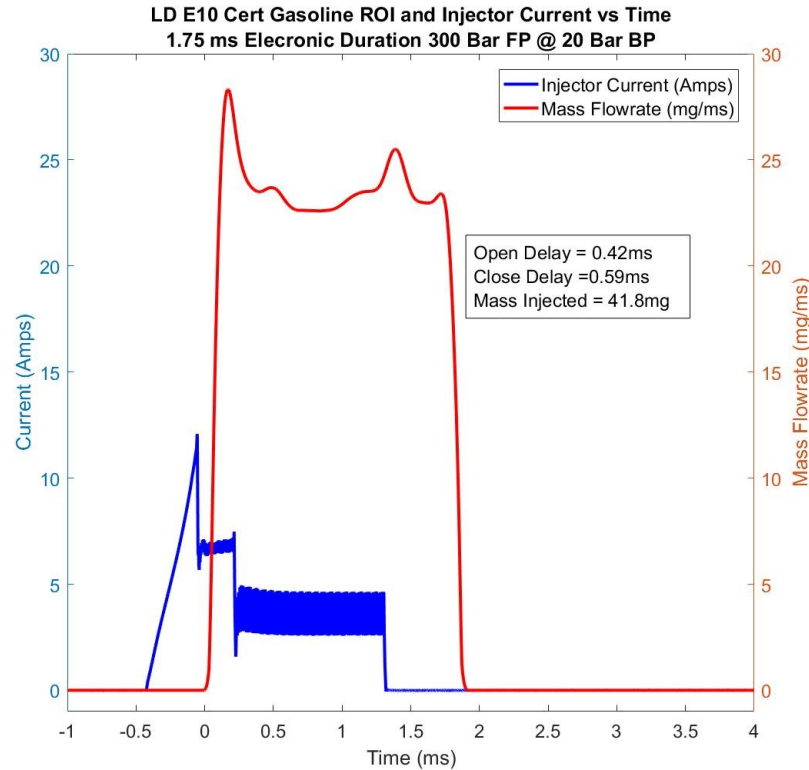


Figure 15: ROI and Injector Current vs Time

16. The code will automatically calculate the average steady state rate of injection for the discharge coefficient computation using the determined injector open and closing delays (line 232-246).
- Input values for fuel pressure (bar), back pressure (bar), number of holes in the injector nozzle, diameter of injector nozzle holes (meters), and the fuel density ($\frac{kg}{m^3}$) when prompted.
 - The code will then compute the discharge coefficient after converting units where \dot{m}_{steady} is the steady state mass flowrate ($\frac{kg}{s}$), n is the number of injector holes, A is the area of one injector hole (m^2), ΔP is the pressure difference across the injector (Pa), and ρ is the density of fuel ($\frac{kg}{m^3}$) as follows:

$$C_d = \frac{\dot{m}_{steady}}{n * A * (\sqrt{2 * \Delta P * \rho})}$$

17. Save any data desired to an excel sheet test matrix or to a MATLAB workspace .mat file by adjusting lines 248-270 to specific needs.

4 Results

4.1 HD Single-Hole Results

Single-hole heavy duty injector studies revealed an interesting phenomenon occurring when injection rate measurements were first made. The measurements showed a large overshoot of the rate of injection before settling in at a lower rate. Injection rate shapes were expected to have more of a square wave profile with relatively consistent rate of injection values after opening of the injector. Collected mass per injection measurements were also compared and showed the integrated mass value underestimated the total fuel injected by as much as 50% in some conditions. An example of this uncharacteristic rate shape can be seen below in Figure 16 when using ULSD at fuel pressure (FP) of 1500 bar and a back-pressure (BP) of 60 bar with an electronic injection duration of 2 ms. The integrated mass per injection for this test condition estimated 26.6 mg per injection while the average collected mass of fuel per injection was 40.1 mg per injection.

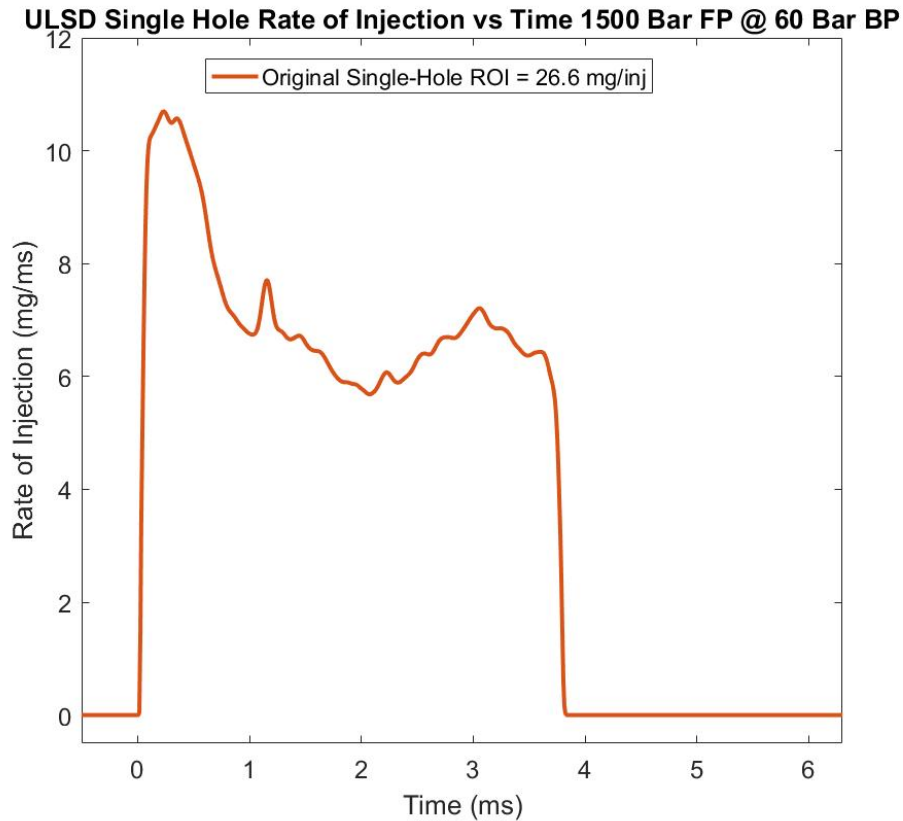


Figure 16: Single-Hole ROI Measurement

Estimates of the rate of injection profiles for the single-hole test conditions were generated to compare to the uncharacteristic rate of injection measurements for a better understanding of the measurement error. The generated rate of injection profile was developed to better match the collected mass of fuel per injection. These profiles were generated using the hydraulic injection durations observed in the original measurements. To compute the steady state mass flow rate for the generated profiles, estimates of the velocity of the fuel exiting the orifice were made using Bernoulli's equation and an estimated discharge coefficient of the injector nozzle of 0.8 was selected. The known values of fuel density and injector orifice diameter were also used to compute the injection rate. The following equation shows how estimated steady state flow rates were computed:

$$\dot{m}_{steady} \left(\frac{kg}{s} \right) = C_d * \rho \left(\frac{kg}{m^3} \right) * A(m^2) * \sqrt{\frac{2 * \Delta P (Pa)}{\rho \left(\frac{kg}{m^3} \right)}}$$

Integrated mass values of the generated ROI shape estimated 40.6 mg per injection in comparison to the 40.1 mg per injection from the collected mass per injection value. Figure 17 below shows an example of the generated ROI profile overlaid with the original measurement for the same test condition as previously shown.

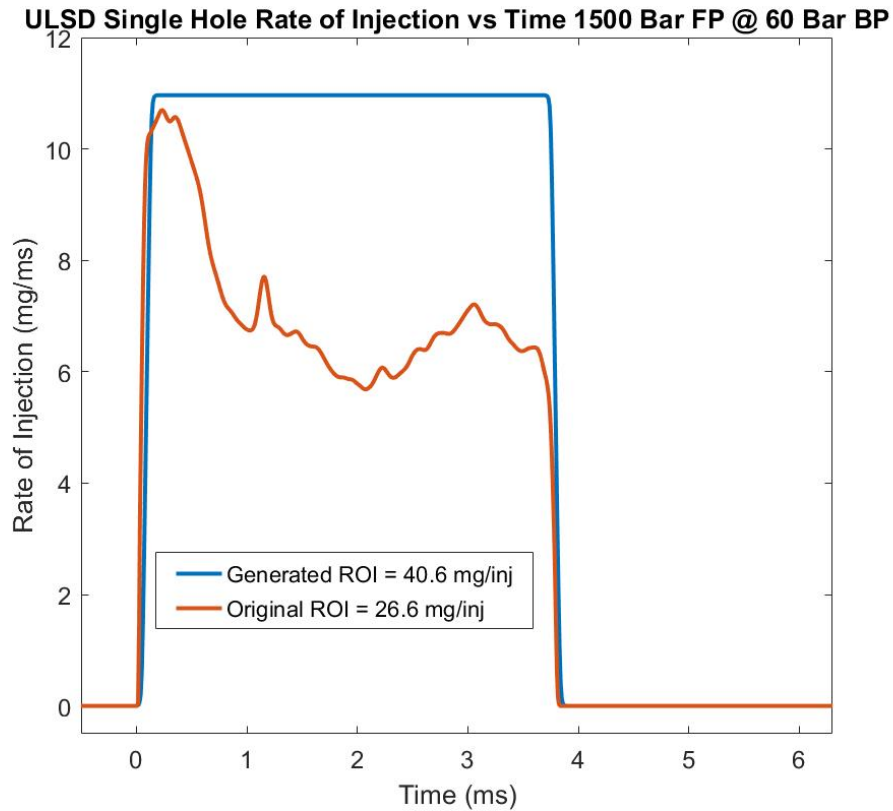


Figure 17: Generated ROI Profile

This uncharacteristic rate shape was observed for both the ULSD and RON 60 GCI fuels for the single-hole heavy duty studies. As the Bosch ROI measurement principle relies on the relationship between pressure and velocity of a one-dimensional transient fluid flow, the rate of injection would not be accurately measured if the pressure wave in the measuring tube was neither uniform or one-dimensional. A hypothesis was formed that the centrally located single hole nozzle was injecting a pressure wave into the measuring tube and creating a multi-dimensional fluid flow. As the single hole orifice is centrally located on the injector nozzle, the injected fuel jet travels down the center axis of the measuring tube. Due to the much larger diameter of measuring tube, in comparison to the orifice diameter in the injector nozzle, the injected fuel jet is unconstrained by the measuring tube's walls. A stagnant boundary layer of fluid exists between the injected fuel jet and measuring tube walls, allowing vortices to shed behind the leading edge of the injected fuel jet. These vortices cause a recirculation of the fluid in the measuring tube and the assumption of a uniform one-dimensional flow in the measuring tube is no longer valid.

A diffuser was designed to disperse the fuel injected from the single hole nozzle into a uniform velocity profile across the entire cross section of the measuring tube. It is placed in the injector hold down fixture, directly down-stream of the fuel injector nozzle. Measurements were made once again and compared to the original ROI trace as well as the generated ROI trace as provided in Figure 18 below. Measurements with the diffuser provided rate shapes which closer matched the generated rate shapes, and collected mass measurements, and proved the hypothesis of the measurement error being attributed to a recirculating vortex phenomenon occurring between the injector and pressure measurement.

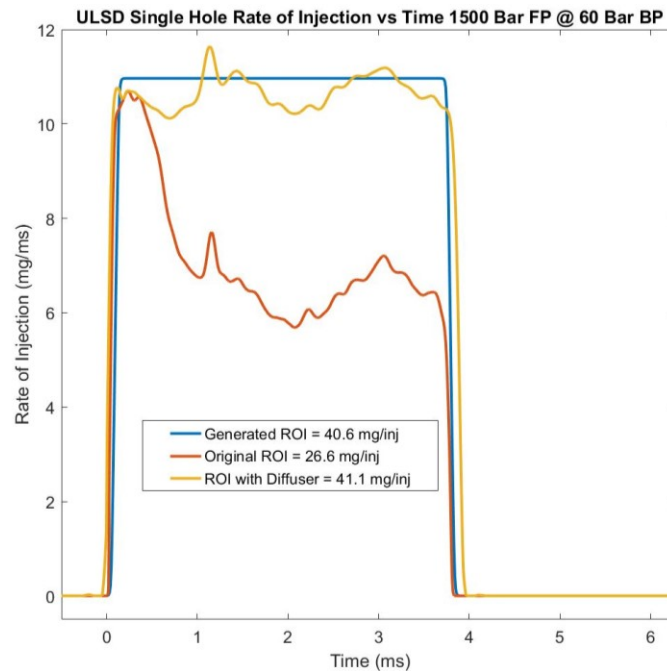


Figure 18: ROI Measurements with Diffuser

Measurements were completed for all ULSD test conditions before moving on to the RON 60 GCI fuel tests. After switching to the RON 60 GCI fuel, a malfunction of the injector was observed. A reduction of the maximum rate of injection occurred while injection durations became prolonged. An example of the malfunction is shown below in Figure 19.

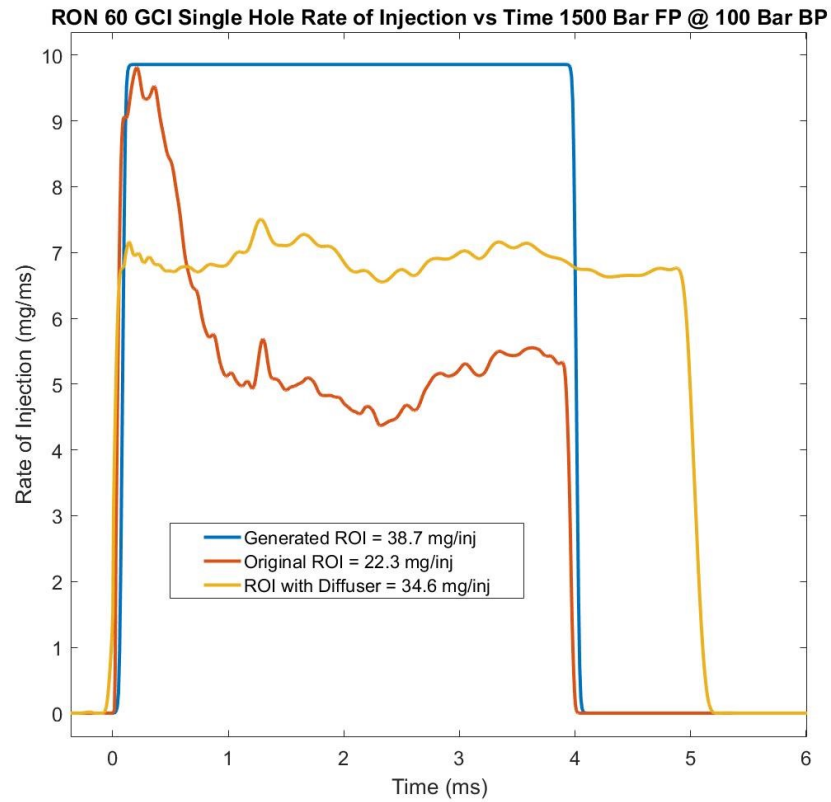


Figure 19: Injector Malfunction with RON 60 GCI Fuel

As this malfunction was not observed with ULSD testing, it was speculated that the malfunction was due to an issue with fuel compatibility and injector hardware. Efforts were made to recover the expected injection rates and durations by flushing the injector with diesel fuel. After operating the injector for thousands of injections and making more measurements, the injection rates and durations could not be recovered. Figure 20 shows a comparison of the rate shapes before the malfunction occurred and after flushing the injector with diesel prior to the malfunction.

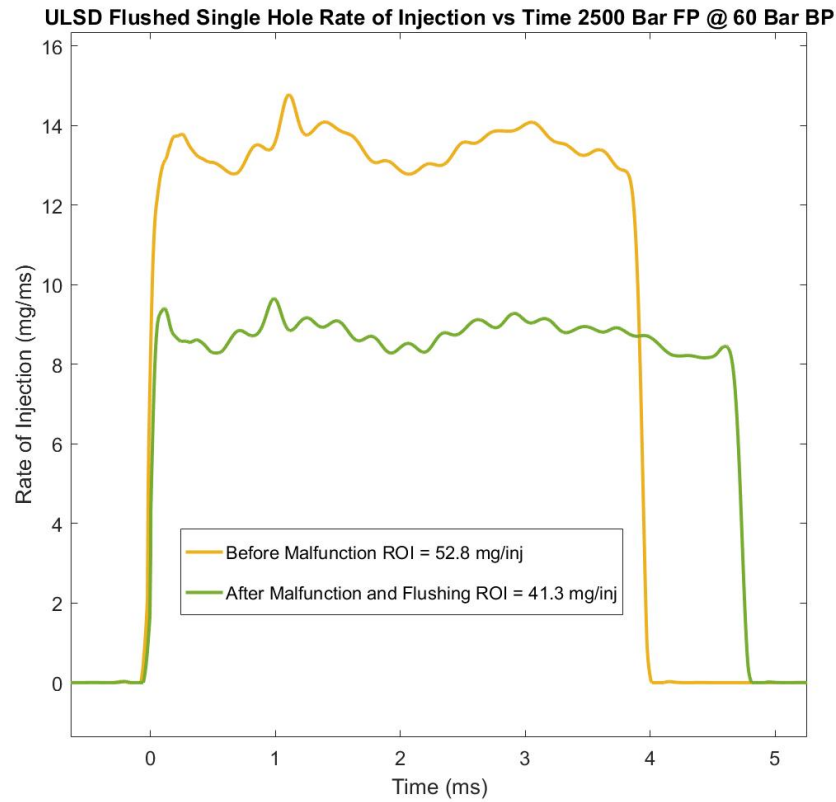


Figure 20: Flushed Injector ROI Comparison

To verify the fuel compatibility issue with the RON 60 GCI fuel and injector hardware, rate measurements were made with an identical secondary backup injector. Measurements were first made with ULSD to compare the backup injector's rate shapes to the original injector measurements before the malfunction. The backup injector showed lower rates of injection and a slightly longer injection duration when compared to the original injector's measurements but provided similar amounts of fuel per injection shown below in Figure 21. The lower rate of injection and longer injection duration of the backup injector are attributed to its previous exposure to the RON 60 GCI fuel during spray characterization measurements. Comparisons of injector rate shapes were observed between the two injectors at a variety of ULSD test conditions and showed similar trends. Injector malfunctions were not observed for the backup injector when used with ULSD.

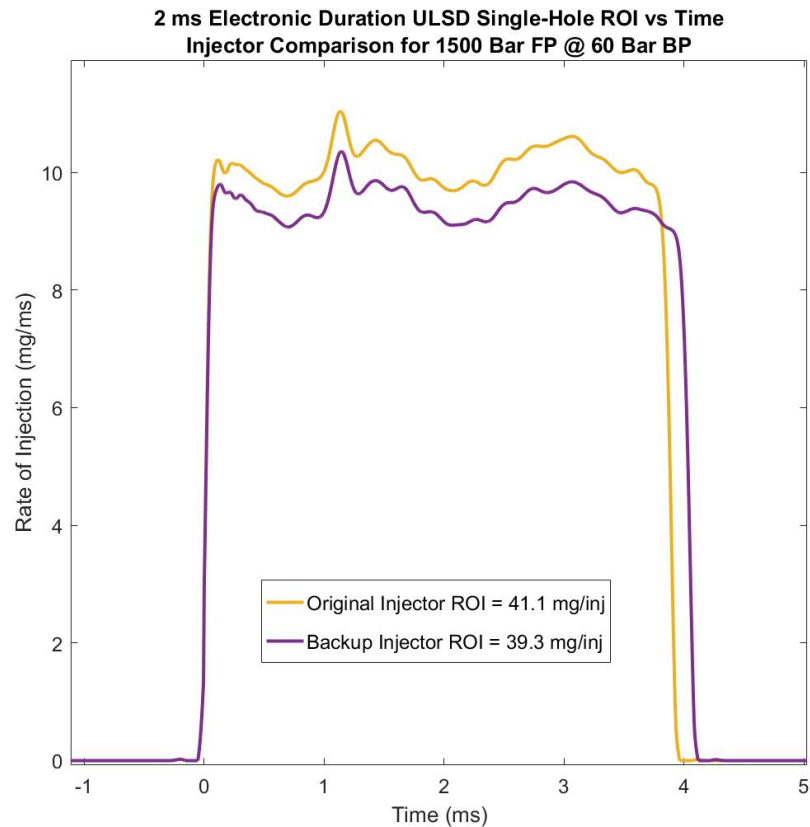


Figure 21: Original and Backup Injector ULSD Comparison

Injection rate measurements of the backup injector were then made with the RON 60 GCI fuel and showed immediate signs of the injector malfunctioning as seen below in Figure 22. The immediate malfunction of the backup injector after being exposed to the RON 60 GCI fuel helps to solidify the hypothesis of a fuel compatibility issue being the cause of the malfunction. Although injection rates of the malfunctioning backup injector closer match the generated ROI values compared to the original injector malfunction, both injectors exhibit a prolonged injection duration.

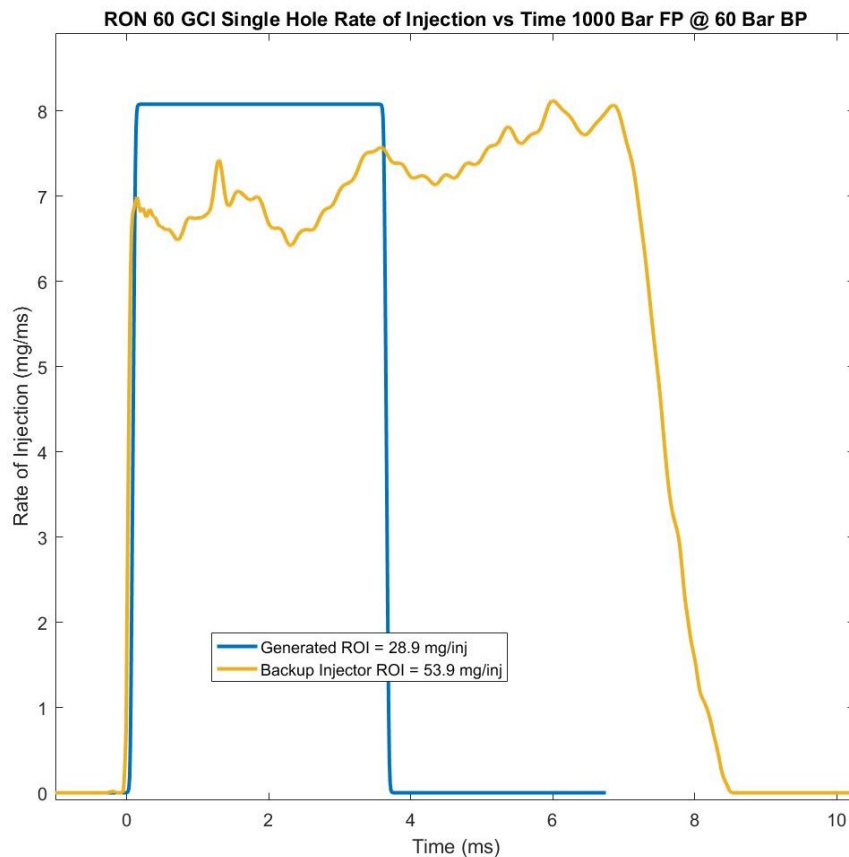


Figure 22: Backup Injector Malfunction with RON 60 GCI Fuel

Both single-hole injectors were sent to IAV Germany for supplemental rate of injection testing and concluded comparable results of reduced injection rates and increased durations. Injectors were then sent to Cummins for an analysis which also confirmed the irregular behavior both before and after cleaning the injectors and checking for debris and blockages. The injection rates with the RON 60 GCI fuel show signs of the injector needle sticking during operation and a potential hypothesis for the malfunction could be due to the differences in the added lubricity packages between fuels. Additional inspection is underway to determine the cause of the malfunction.

While the single-hole rate of injection test conditions could not be completed with the RON 60 GCI fuel, results were gathered for ULSD with the original/primary injector. Results were also gathered at three test conditions with the backup injector for comparison. A comparison of the two injectors ROI results with ULSD can be found in Appendix E. As the backup injector was previously subjected to the RON 60 GCI fuel, the primary injector measurements were used as the final results. These scaled results are displayed below in Table 7 and were acquired before any malfunctions occurred.

Table 7: HD Single-Hole ULSD Results

Fuel Pressure (bar)	Back Pressure (bar)	Average Collected Mass per Injection (mg/inj)	Average Integrated Mass per Injection (mg/inj)	Percent Difference (%)	Scaled Integrated Mass per Injection (mg)
1,000	60	33.5	30.7	9.1	32.4
1,000	100	31.1	29.9	4.2	31.5
1,500	60	40.1	39.0	2.7	41.1
1,500	100	42.1	38.9	8.2	41.0
2,500	60	55.1	52.8	4.3	55.7
2,500	100	55.1	52.9	4.1	55.8
				Average	5.4
				Scale Factor	1.054

4.2 HD Multi-Hole Results

Heavy duty multi-hole measurements for ULSD and RON 60 GCI fuels have successfully calibrated electronic injection durations to meet targeted mass of fuel per injection values and are tabulated for reference in Appendix F. As the investigation of the RON 60 GCI fuel compatibility is on-going, conclusions of the fuels' physical properties effects on the multi-hole rate of injection measurements have yet to be made. Comparison of the multi-hole and single-hole injectors was out of the scope of this work and overlapping test conditions were not acquired.

4.3 LD Study Results and Analysis

LD rate of injection measurements are tabulated in Appendix G for reference of individual test condition results. The results of these measurements include mass per injection, injector opening delay, and injector closing delay, and the standard deviation of scaled integrated mass per injection of the 240 plus injections kept as good data. The resulting rate of injection, mass per injection, and injector opening delay values are used to draw conclusions of the fuel's physical property effects on rate of injection characteristics.

A majority of the test results agree with literature and show that the density of the fuel becomes the driving factor when comparing rates of injection during the steady state portion of the injection [7, 8]. The higher density E10 Cert Gasoline achieves higher rates of injection in comparison to the RON 70 GCI fuel in-between the opening and closing of the injector. An example of this for operating conditions of a 300 bar fuel pressure, 20 bar back pressure, and 1.75 ms electronic injection duration is shown below in Figure 23. For the provided test condition, the standard deviation of the 240 plus injection events used to compute the final average mass per injection was ± 0.1 mg per injection for both fuels, showing highly repeatable injection quantities at this condition.

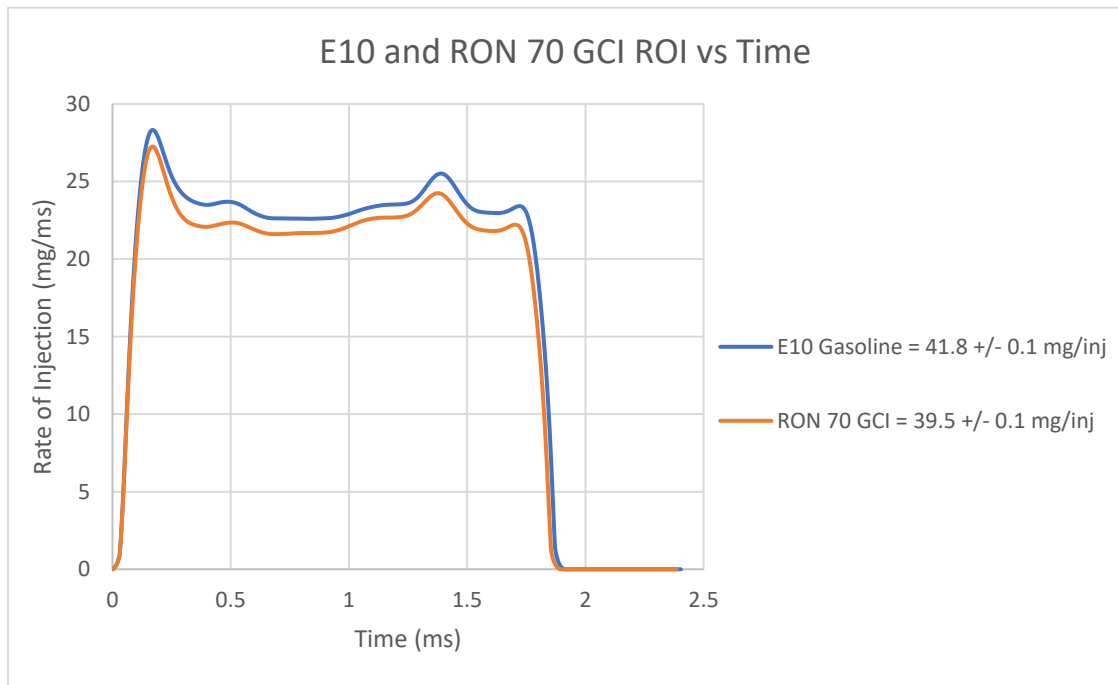


Figure 23: 1.75 ms Electronic Duration 300 Bar FP @ 20 Bar BP
E10 Gasoline and RON 70 GCI ROI Comparison

Fuel pressure fluctuations may account for the reversal of this trend which was observed in 9 of the 33 test conditions. Due to the fuels' minimal differences in fuel density, $20 \frac{kg}{m^3}$, small fluctuations in the fuel pressure during testing could contribute a greater effect on the rate of injection compared to density differences. In the future, acquiring fuel pressure data will be imperative to drawing more accurate conclusions upon the rate of injection measurements and the effects of the fuel's density.

As density has been concluded to be the physical fuel property driving rates of injection, it would also be expected to see larger differences in the total mass per injection between two fuels of different density as hydraulic injection durations increase. The more-dense E10 Gasoline shows larger differences in mass per injection compared to the RON 70 GCI fuel as the injection duration increases as expected. Figure 24 shows these observed results for each respective fuel pressure tested as annotated on the plot.

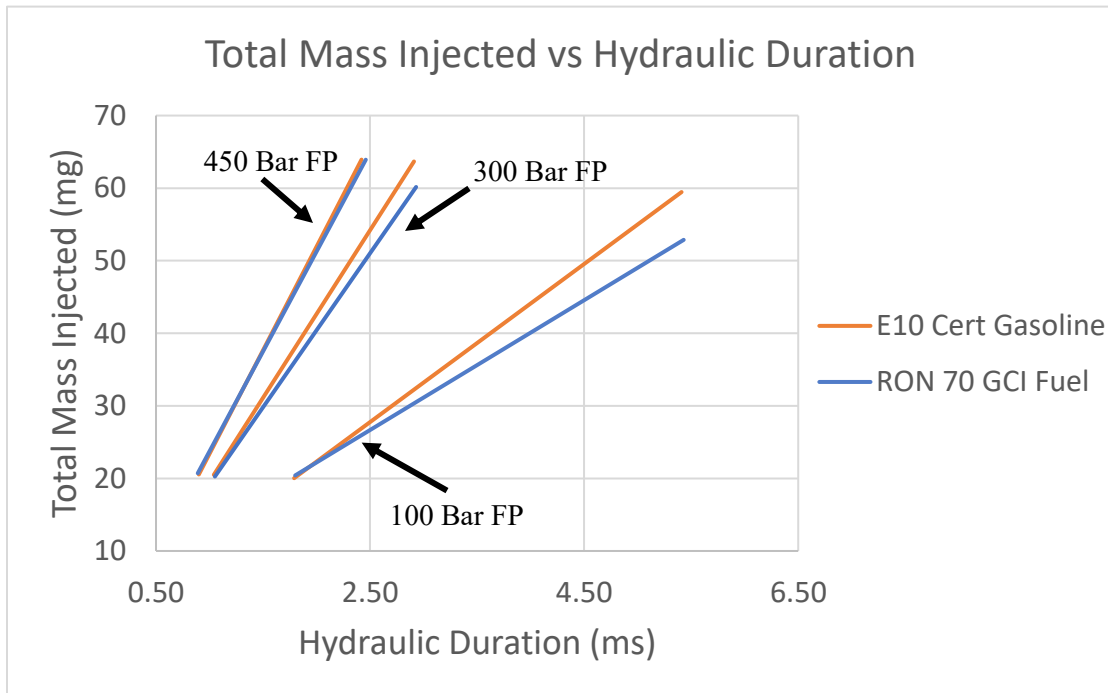


Figure 24: Total Mass Injected vs Electronic Injection Duration Comparison

While the density of the fuel drives the steady-state rate of injection, the viscosity of the fuel is responsible for the differences observed in the injector opening time. The viscosity of the fuels is 0.669 centistokes and 0.575 centistokes for E10 and RON 70 GCI respectively. The injector opening delay of both fuels is plotted against the pressure difference across the injector. A linear trend line is fit to each fuel's data for ease of comparison. Results support literature findings and show a longer injector opening delay for the more viscous E10 Cert Gasoline [7, 8]. See Figure 25 below.

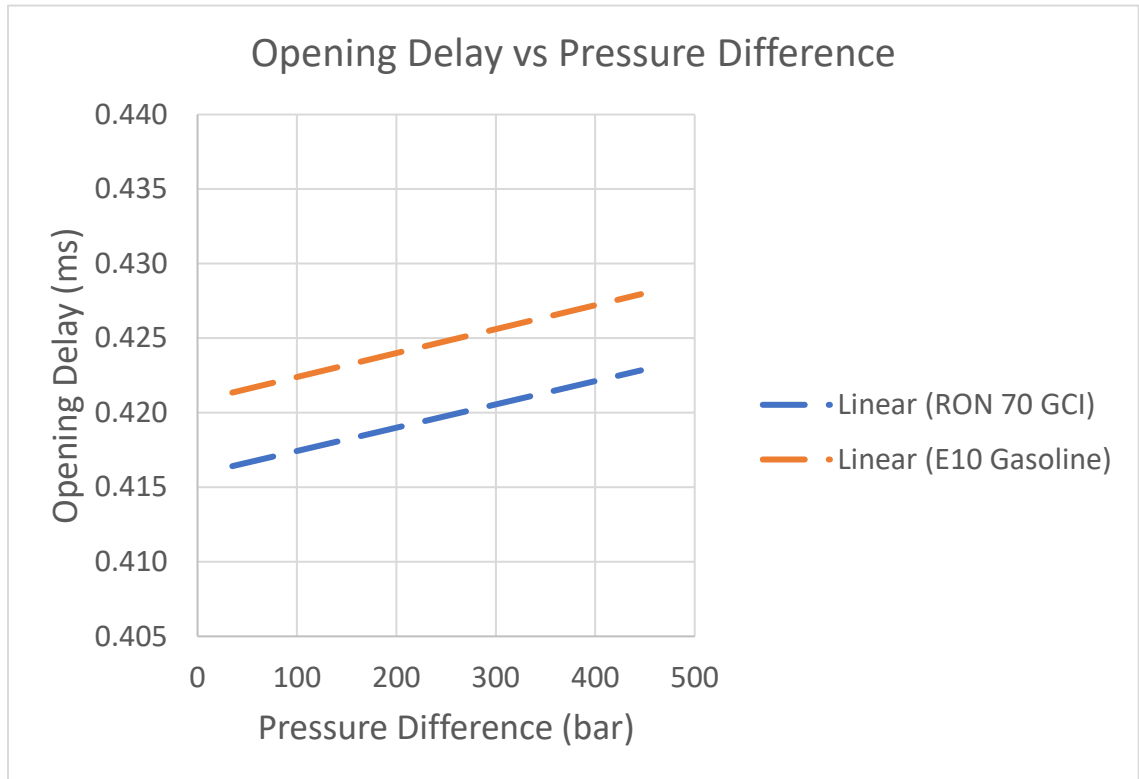


Figure 25: Fuel Comparison of Opening Delay

5 Conclusions

A rate of injection measurement procedure was developed through the implementation of a standard practice for collecting mass fuel samples and creation of a data processing code. A method was also developed to calibrate the Bosch type ROI measurements to closer match the collected mass of fuel to compensate for the inherent underestimation of the Bosch measurement technique. This measurement procedure was used to collect ROI measurements using both multi-hole and single-hole Cummins XPI injectors for HD studies using both ULSD and a RON 60 GCI fuel. ROI measurements were also obtained with a ten-hole Bosch HDEV5 GDI injector for LD studies using a premium octane CARB LEV III E10 Certification Gasoline and a RON 70 GCI fuel.

Rate of injection measurements were made for both fuels in the multi-hole HD studies and electronic injection durations were determined to provide desired mass per injection quantities. Single-hole HD measurements required the use of a diffuser downstream of the nozzle to help disperse the injected fuel into a uniform flow profile. ULSD measurements were completed for the single-hole HD test set but RON 60 GCI fuel measurements could not be completed due to a fuel compatibility issue with the injector hardware. Further investigation of the single-hole HD injector is needed to conclude the reasoning for injector malfunction.

The LD rate of injection studies concluded that the higher density premium octane CARB LEV III E10 Cert Gasoline had higher rates of injection when compared to that of the lower density RON 70 GCI fuel. LD studies also showed that the more viscous E10 Gasoline required more time for the injector to open while the less viscous RON 70 GCI fuel had shorter opening delays. Fuel density was also responsible for driving the total mass of fuel per injection with an increasing effect on longer injection durations. Recommendations are made to implement the data acquisition system with a fuel pressure transducer and back-pressure transducer so that these values can be used to further analyze the trends observed.

6 Future Work

Future work to complete the HD single-hole rate of injection measurements for the RON 60 GCI fuel will be dependent upon the diagnoses and troubleshooting of the injector malfunctioning observed. After the single-hole injector is fixed as determined by Cummins, future tests will also include a RON 91 gasoline fuel for the HD study. LD studies will continue with rate of injection characteristics for two new light duty GCI fuels proposed by Aramco with the same Bosch HDEV 5 injector used in these LD studies.

7 Reference List

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Appendix A. E10 Cert Gasoline Fuel Properties



haltermannsolutions

Telephone: (800) 969-2542

Product Information

FAX: (281) 457-1469

PRODUCT: CARB LEV III E10 Certification Fuel

Batch No.: ED2721LT10-1

PRODUCT CODE: Premium Octane

PRODUCT CODE: HF0862

Tank No.: Pails

Date: 8/17/2016

TEST	METHOD	UNITS	SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F				107
5%		°F				132
10%		°F	130		150	137
20%		°F				144
30%		°F				150
40%		°F				160
50%		°F	205		215	208
60%		°F				231
70%		°F				247
80%		°F				282
90%		°F	310		320	319
95%		°F				334
Distillation - EP		°F			390	356
Recovery		vol %		Report		97.9
Residue		vol %			2.0	1.0
Loss		vol %		Report		1.1
Gravity @ 60° F	ASTM D4052	°API		Report		58.9
Specific Gravity	ASTM D4052	-		Report		0.743
R Reid Vapor Pressure	ASTM D5191	psi	6.9		7.2	7.2
Carbon	ASTM D5291	wt%		Report		82.44
Hydrogen	ASTM D5291	wt%		Report		13.84
Hydrogen/Carbon ratio	ASTM D5291	mole/mole		Report		2.000
Oxygen	ASTM D4815	wt %	3.3		3.7	3.6
Ethanol content	ASTM D4815	vol %	9.2		10.0	9.7
MTBE content	ASTM D4815	vol %			0.05	None Detected
Sulfur	ASTM D5453	ppm wt	8		11	9
Phosphorus	ASTM D3231	g/gal			0.005	None Detected
Lead	ASTM D3237	g/gal			0.01	None Detected
Composition, aromatics	ASTM D5580	vol %	19.5		22.5	21.3
Composition, olefins	ASTM D6550	vol %	4.0		6.0	4.4
Multisubstituted Alkyl Aromatics	ASTM D5769	vol %	13		15	13
Benzene	ASTM D5580	vol %	0.6		0.8	0.7
Oxidation Stability	ASTM D525	minutes	1000			1000+
Copper Corrosion	ASTM D130				1	1a
Existent gum, washed	ASTM D381	mg/100mls			3.0	<0.5
Existent gum, unwashed	ASTM D381	mg/100mls		Report		8.4
Research Octane Number	ASTM D2699			Report		96.8
Motor Octane Number	ASTM D2700			Report		88.0
R+M/2	D2699/2700		91.0			92.4
Sensitivity	D2699/2700		7.5			8.8
Net Heat of Combustion	ASTM D240	BTU/lb		Report		18064
Deposit Control Additive	Calculated	ptb active		75		75

APPROVED: _____

Gasoline and diesel specialty fuels from Haltermann Solutions shall remain within original specifications for a minimum of 3 years from the date on the COA so long as the drums are sealed and unopened in their original container and stored in a warehouse at ambient conditions. Specialty fuels that have been intentionally modified for aggressive or corrosive properties are excluded.

Appendix B. ULSD Cert Fuel Properties



Telephone: (800) 969-2542

Product Information

FAX: (281) 457-1489

Johann Haltermann Ltd.

PRODUCT: 2007 Certification Diesel

Batch No.: CK2021HW10

PRODUCT CODE: HF0582

Tank No.: 54

Analysis Date: 12/9/2014

TEST	METHOD	UNITS	SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F	340		400	344
5%		°F				395
10%		°F	400		460	418
20%		°F				444
30%		°F				470
40%		°F				494
50%		°F	470		540	514
60%		°F				533
70%		°F				551
80%		°F				571
80%		°F	560		630	599
95%		°F				629
Distillation - EP		°F	610		690	656
Recovery		vol %		Report		98.3
Residue		vol %		Report		1.4
Loss		vol %		Report		0.3
Gravity	ASTM D4052	°API	32.0		37.0	35.3
Specific Gravity	ASTM D4052		0.840		0.865	0.848
Flash Point	ASTM D93	°F	130			156
Cloud Point	ASTM D2500	°F		Report		1
Pour Point	ASTM D97	°F		Report		-22
Viscosity, 40°C	ASTM D446	cSt	2.0		3.2	2.6
Sulfur	ASTM D5453	ppm	7		16	8
Carbon	ASTM D6291	wt %		Report		86.80
Hydrogen	ASTM D5291	wt %		Report		13.20
Composition, aromatics	ASTM D5186	wt %		Report		28.2
Composition, aromatics	ASTM D1319	vol %	27			28
Composition, olefins	ASTM D1319	vol %		Report		1
Composition, saturates	ASTM D1319	vol %		Report		71
Cetane Number	ASTM D613		40.0		50.0	44.2
Cetane Index	ASTM D4737		40.0		50.0	47.2
Net heat content	ASTM D240	btu/lb		Report		18414
HFRR @60° C	ASTM D6079	mm		Report		0.570

APPROVED BY:

Appendix C. Quantum Composer Settings

C.1 HD Quantum Composer Settings

Many different injector current profiles were used throughout the duration of the multi-hole HD studies. The “B50” engine setpoint for the ULSD conditions was the most commonly used profile as it was also used for the single-hole ROI work. A description of the necessary quantum composer pulse generator settings are provided below in Table 8. Keep in mind that while driving the HD Cummins XPI injector, a drive voltage of 50 volts should be used. Although four channels are available for use, only three are needed, the fourth channel can be disabled.

Table 8: HD Quantum Composer Settings for B50 ULSD Injector Current Profile

Channel 1	Channel 2	Channel 3
Enabled	Enabled	Enabled
Sync To	Sync To	Sync To
Delay 0 sec	Delay 0 sec	Delay 0 sec
Width 0.000,116,80	Width 0.000,002,66	Width 0.000,002,62
Mode: Single Shot	Mode: Burst	Mode: Burst
N/A	#/Burst 69 pulses	#/Burst 262 pulses
Wait 0 pulses	Wait 31 pulses	Wait 100 pulses
Polarity Active High	Polarity Active High	Polarity Active High
Amplitude 6.00 V	Amplitude 7.95 V	Amplitude 7.45 V
MUX T4-0001-T1	MUX T4-0010-T1	MUX T4-0100-T1
Gate Disabled	Gate Disabled	Gate Disabled

C.2 LD Quantum Composer Settings

Only one injector current profile was needed for the LD studies. The duration of this injection event can be adjusted by changing the #/Burst setting on channel 3, adding bursts will lengthen the duration and subtracting bursts will shorten the duration. The LD injector was most often used at a duration of 1.75 ms and driven at 65 volts, see Table 9 for settings.

Table 9: LD Quantum Composer Settings for 1.75 ms Duration

Channel 1	Channel 2	Channel 3
Enabled	Enabled	Enabled
Sync To	Sync To	Sync To
Delay 0 sec	Delay 0 sec	Delay 0 sec
Width 0.000,371,80	Width 0.000,007,00	Width 0.000,009,10
Mode: Single Shot	Mode: Burst	Mode: Burst
N/A	#/Burst 73 pulses	#/Burst 300 pulses
Wait 0 pulses	Wait 104 pulses	Wait 181 pulses
Polarity Active High	Polarity Active High	Polarity Active High
Amplitude 4.25 V	Amplitude 5.45 V	Amplitude 5.50 V
MUX T4-0001-T1	MUX T4-0010-T1	MUX T4-0100-T1
Gate Disabled	Gate Disabled	Gate Disabled

Appendix D. Rate of Injection Post Processing Code

```
1 %% Define file path where ROI data is saved in line 4, Answer prompted questions to
  read in raw data
2 % clc;clear all;close all;
3 tic;
4 cd('D:\ROI_Data\20161025');
5 mat_ch1 = ['B7..B65541'];
6
7 prompt='How many injections were recorded? '
8 inj=input(prompt)
9
10 prompt='How many tests to average? '
11 tests=input(prompt)
12
13 for k=1:tests;
14 prompt='Filename/Time? '
15 filename(k)=input(prompt)
16 end
17
18 for k=1:tests;
19 for j=1:inj;
20 ch1(:,inj*(k-1)+j)=dlmread([[num2str(filename(1,k)) ' ' num2str(j) '
txt'],'\t',mat_ch1);
21 end
22 end

23 %% Provide indices near start of injection to help identify offset of pressure trace
  from zero
24 is = 2121; % index near start of injection
25 x=ch1;
26 % compute offset at points closes to start of injection
27 o = mean(x(is+[-100:0],:));
28
29 % compute cycles that have the largest time varying drift after offset has been
  removed.
30 foo = x(1:is,:);
31 x_drift = mean(foo,1);
32 x_drift = x_drift/median(x_drift);
33 %% Peg initial data points to zero bar pressure before SOI and define SOI for RAW
  data
34 % zero at start of injection
```

```

35 x = x-ones(size(x,1),1)*o;
36 x(1:is,:) = 0;

37 %% Look at frequency content to determine cutoff frequency and low pass filter data
38 figure;
39 psd(x(:,1),512);
40 title('PSD Plot of Pressure Data')
41
42 [b,a] = butter(3, 0.015);
43 fx = filtfilt(b,a,x);

44 %% Find SOI and EOI after pressure data is filtered, create time vector
45 for j=1:tests*inj
46 js(j) = max(find(fx(1:2500,j)<0)); % this is start of hydraulic injection
47 fx(1:js(j),j) = 0;
48 end
49
50 % add a time vector
51 t = 1:1:size(x,1);
52 t = (t-mean(js))/1e6*1000; % time (ms) zeroed at SOI
53
54 % Now zero after end of injection signified by signal going below zero.
55 for j=1:tests*inj
56 je(j) = min(find((fx(:,j)).*(t>0.5)<0))); %this is start of hydraulic injection
57 x(je(j):end,j) = 0;
58 fx(je(j):end,j)=0;
59 end

60 %% Plots to compare raw data, filtered data, and difference between the two
61 figure;
62 set(gcf, 'position', [50 -50 1500 1000]);
63 subplot(3,1,1);
64 plot(t,x);
65 axis([-0.1 2.5 0 35]);
66 grid on;
67 ylabel('Raw');
68 subplot(3,1,2);
69 plot(t,fx)
70 axis([-0.1 2.5 0 35]);
71 grid on;
72 ylabel('filtered')
73

```



```

74 subplot(3,1,3);
75 plot(t,fx-x)
76 axis([-0.1 2.5 -10 10]);
77 grid on;
78 ylabel('diff');
79 xlabel('time (ms)');

80 %% Sort injection events with largest drift and largest deviation in injected mass
from median value
81 % Sum up and use this to find outliers
82 x_sum = sum(x,1);
83 x_sum = (x_sum - median(x_sum))/median(x_sum);
84
85 % Take the top ten and bottom ten out based upon drift
86 [foo, i] = sort(x_drift);
87 id_good = i(10*tests+1:end-10*tests);
88 % Now take the top ten and bottom ten out based upon sum/integral
89 [foo, i] = sort(x_sum);
90 is_good = i(10*tests+1:end-10*tests);
91
92 % take only those that are good from both criteria.
93 i_good = intersect(id_good, is_good);
94 i = 1:length(x_drift);

95 %% Filter good data again and create "rounded" top hat profile
96 % Now compute the average/mean of only the good cycles
97 X = mean(fx(:,i_good), 2);
98
99 [b,a] = butter(3, 0.01);
100 fy = filtfilt(b,a,X);
101
102 my = median(X(X>0.5));
103 s = (X>=(0.3*my))*1.0;
104 [b,a] = butter(1, .01);
105 sf = filtfilt(b,a,s);
106
107 yy = fy.*sf + X.*(1-sf);
108
109 % set threshold to eliminate negative numbers (filtering makes zeros small
110 % neg numbers)
111 for k=1:1:size(yy, 1)
112 for kk=1:1:size(yy, 2)

```

```

113 if yy(k, kk)<0.001
114 yy(k, kk)=0;
115 else
116 fx(k, kk) = fx(k, kk);
117 end
118 end
119 end

120 %% Plot only the "good" test cycles
121 figure;
122 set(gcf, 'position', [250 150 1000 800]);
123 h = plot(t, fx(:,i_good), ':');
124 axis([-0.1 3.5 0 35]);
125 set(h, 'linewidth', 0.01);
126 set(h, 'color', [0.75 0.75 0.75]);
127 grid on;
128 ylabel('Pressure (Bar)', 'fontsize', 14);
129 hold on;
130 h = plot(t, yy);
131 legend('Ave ROI');
132 set(h, 'linestyle', '-', 'linewidth', 2, 'color', [0.8 0 0]);
133 axis([-0.25 3.5 0 35]);
134 set(gca, 'xtick', [-0.25:0.25:3.5]);
135 legend(gca, 'off');
136 title('B50 ULSD Pressure vs Time for 100 Bar Back Pressure Repeats', 'fontsize', 14)
137 xlabel('Time (ms)', 'fontsize', 14)
138 set(gca, 'fontsize', 12)

139 %% Calculate the speed of sound. Define the window of data points where the
pressure reflection occurs for computing speed of sound in fluid
140 Window_Vspeed_1 = 40000;
141 Window_Vspeed_2 = 55000;
142 CH1 = mean(ch1, 2);
143 SOI_Pressure = max(find(CH1(is:is+1000)<0))+is;
144 SOI_Reflection =
max(find(CH1(Window_Vspeed_1:Window_Vspeed_2)<0))+Window_Vspeed_1;
145 V_sound = 58.5/((SOI_Reflection-SOI_Pressure)/1000000); %length of measuring
tube is 58.5 meters, V_sound units m/s

146 %% Calculations
147 Area=pi*.336^2/4*.0254^2;%diameter of hold down fixture where injector sprays
148 X_pa=yy*100000; % converts pressure signal from bar to pascals

```

```

149 int=sum(X_pa.*(1/1000000));
150 m_injected=(Area./V_sound).*int.*1E+6 % mg per injection
151 m_dot=(Area./V_sound).*X_pa.*1E+3; % mass flow rate in mg/ms
152 r = min(find(m_dot(1:2500,1)>0)); % this is start of hydraulic injection
153 % add a time vector re-zeroed at SOI
154 t = 1:1:size(x,1);
155 t = (t-r)/1e6*1000;

156 %% Plotting data grey lines show data filtered only once while red plot shows final
data
157 figure
158 h = plot(t,(Area./V_sound).*fx(:,i_good).*1000*100000, ':');
159 set(h, 'linewidth', 0.01);
160 set(h, 'color', [0.75 0.75 0.75]);
161 grid on;
162 ylabel('Rate of Injection (mg/ms)', 'fontsize', 14)
163 xlabel('Time (ms)', 'fontsize', 14)
164 hold on
165 axis([-0.1 5 0 30])
166 h=plot(t,m_dot)
167 set(h, 'linestyle', '-', 'linewidth', 2, 'color', [0.8 0 0]);
168 axis([-0.1 5 0 30])
169 set(gca, 'xtick', [-0.25:1:10]);
170 title('Unscaled ROI vs Time', 'fontsize', 14)
171 set(gca, 'fontsize', 12)

172 %% Compute corrected ROI and mass per injection values by applying scale factor
173 prompt='What is the scale factor for this fuel?'
174 SF=input(prompt)
175 m_inj_new=SF*m_injected; %SF=1.0876 for E10 and 1.0980 for RON 70
176 Press_corrected=SF*X_pa;
177 ROI_corrected=(Area./V_sound).*Press_corrected.*1E+3; %mg/ms

178 %% Variable for plotting cumulative mass per time
179 for k=1:1:65535
180 cmass(k)=(ROI_corrected(k)*1/1000);%mg/ms
181 cumulativemass(k)=sum(cmass(1:k));
182 end
183 figure
184 plot(t,cumulativemass)
185 title('Cumulative Mass of Injection vs Time')
186 xlabel('Time (ms)')

```

```

187 ylabel('Mass (mg)')
188 axis([-1 4 0 max(cumulativemass)+10])

189 %% Code for computing hydraulic injector delays from current trace
190 mat_ch2 = ['A7..A65541'];
191 for k=1:tests;
192 for j=1:inj;
193 ch2(:,inj*(k-1)+j)=dlmread([[num2str(filename(1,k)) ' ' num2str(j) ' .
txt'],'\t',mat_ch2);
194 end
195 end
196
197 current=mean(ch2,2);
198 offset=mean(current(1:2000));
199 current=current-offset;
200 pressure=ROI_corrected*V_sound.*1E-5/(Area.*1E+3);
201 elec_start=min(find(current(1:2150)>.2));
202 p_offset=mean(pressure(1:2100));
203 pressure=pressure-p_offset;
204 hyd_start=max(find(pressure(1:2600)<0.01));
205 Open_delay=(hyd_start-elec_start)/1e3
206 elec_end=min(find(current(2500:11000)<0.2));
207 hyd_end=min(find(pressure(3100:14500)<0.01));
208 Close_delay=((hyd_end+3100)-(elec_end+2500))/1000
209 [max_p,ind_p]=max(pressure);
210 zero_current=min(find(current(3000:4500)<0))+3000;
211 Bump_Delay=(ind_p-zero_current)/1000;
212 hyd_dur=(hyd_end+3100-hyd_start+1)/1000;
213
214 figure
215 yyaxis left
216 plot(t,current,'b','LineWidth',2)
217 ylim([-1 30]);
218 ylabel('Current (Amps)');
219 hold on
220 yyaxis right
221 plot (t,ROI_corrected,'r','LineWidth',2)
222 ylim([-1 30])
223 ylabel('Mass Flowrate (mg/ms)')
224 xlim([-1 4]);
225 xlabel('Time (ms)')
226 legend('Injector Current (Amps)','Mass Flowrate (mg/ms)')

```

```

227 title({'LD Injector A at 300 Bar Fuel Pressure',' 20 Bar Back Pressure ROI & Inj
Current vs Time'})
228 dim=[.58 .5 .2 .2];
229 str={['Open Delay = ',num2str(round(Open_delay,2)), 'ms'] , ['Close Delay = ',num2str
(round(Close_delay,2)), 'ms'] , ['Mass Injected = ',num2str(round(m_inj_new,1)), 'mg']};
230 annotation('textbox',dim,'String',str,'FitBoxToText','on')

231 %% Discharge coefficient computation
232 prompt='What is the fuel pressure (Bar)?'
233 FP=input(prompt)
234 prompt='What is the back pressure (Bar)?'
235 BP=input(prompt)
236 prompt='Number of holes/orifices in injector nozzle'
237 n=input(prompt)
238 prompt='Diameter of holes in meters'
239 D=input(prompt)
240 A=pi/4*D^2; %Area of one injector hole in meters squared
241 Delta_P=(FP-BP)*1e5; %Delta P in Pascals
242 prompt='What is the fuel density in kg/m3?'
243 rho=input(prompt)% E10 743.2 kg/m3 and RON 70 GCI 723.3 kg/m3
244 [max_ROI,ind_ROI]=max(ROI_corrected)
245 Cd_peak=max_ROI/(1000*n*A*(2*rho*Delta_P)^(1/2))
246 Cd_avg=mean(ROI_corrected(hyd_start+300:3100+hyd_end-500))/(1000*n*A*
(2*rho*Delta_P)^(1/2))

247 %% Save/write variables to Excel sheet test matrix
248 prompt=' What Excel row to write to? '
249 row=input(prompt);
250 cd('D:\AERB\Aramco\LD Project\Folder for Processing')
251 file='AramcoLD_MatrixForProcessingResults_20180222.xlsx';
252 sheet=2;
253
254 xlRange=['O',num2str(row)];
255 xlswrite(file,m_injected,sheet,xlRange)
256 xlRange=['S',num2str(row)];
257 xlswrite(file,m_inj_new,sheet,xlRange)
258 xlRange=['U',num2str(row)];
259 xlswrite(file,V_sound,sheet,xlRange)
260 xlRange=['X',num2str(row)];
261 xlswrite(file,Close_delay,sheet,xlRange)
262 xlRange=['Z',num2str(row)];
263 xlswrite(file,Open_delay,sheet,xlRange)

```

```

264 xlRange=['AA',num2str(row)];
265 xlswrite(file,Cd_peak,sheet,xlRange)
266 xlRange=['AB',num2str(row)];
267 xlswrite(file,Cd_avg,sheet,xlRange)
268
269
file=['J80Blend_',num2str(FP),'BarFP@',num2str(BP),'BarBP',num2str(round(m_inj_new,
2)), 'mg.mat']
270 save
([file], 'fx', 'i_good', 'cumulativemass', 't', 'ROI_corrected', 'current', 'Open_delay', 'Close_delay', 'm_inj_new', 'Cd_peak', 'Cd_avg', 'hyd_dur', 'max_ROI', 'V_sound')
271

272 toc;

```

Appendix E. HD Single Hole ULSD Injector Comparison

Table 10 below shows the tabulated ROI results obtained for both the primary and backup single hole injector with ULSD. The longer closing delays of the backup injector are attributed to its prior exposure to the RON 60 GCI fuel before ROI measurements.

Table 10: HD Single Hole ULSD Injector ROI Comparison

Injector	Fuel Pressure (bar)	Back Pressure (bar)	Mass per Injection (mg)	Open Delay (ms)	Close Delay (ms)
Primary	1,000	60	32.4	0.34	2.24
	1,000	100	31.5	0.34	2.25
	1,500	60	41.1	0.31	2.31
	1,500	100	41.0	0.31	2.31
	2,500	60	55.7	0.28	2.35
	2,500	100	55.8	0.27	2.35
Backup	1,500	60	39.3	0.36	2.61
	1,500	100	39.9	0.31	2.61
	2,500	100	56.0	0.27	2.76

Appendix F. HD Multi-Hole ROI Results

Table 11: HD Multi-Hole ULSD ROI Results

Fuel Pressure (bar)	Back Pressure (bar)	Mass per Injection (mg/inj)	Calibrated Electronic Injection Duration (ms)
1300	60	73.5	0.91
	100	73.7	
1400	60	132	1.32
	100	131	
1600	60	262	2.65
	100	248	
1700	60	195	1.84
	100	193	
1700	60	122	1.10
	100	123	
1900	60	191	1.63
	100	190	
1900	60	174	1.50
	100	173	
2100	60	254	2.20
	100	240	
2500	60	232	1.69
	100	230	
	160	228	

Table 12: HD Multi-Hole RON 60 GCI ROI Results

Fuel Pressure (bar)	Back Pressure (bar)	Mass per Injection (mg/inj)	Calibrated Electronic Injection Duration (ms)
1400	60	73.2	1.36
	100	72.1	
1500	60	129	1.39
	100	129	
1800	60	254	2.86
	100	258	
1800	60	116	1.06
	100	116	
1900	60	126	1.13
	100	127	
1900	60	191	1.87
	100	190	
2000	60	169	1.56
	100	169	
2200	60	253	2.41
	100	254	
2500	60	231	1.91
	100	235	
	160	232	

Appendix G. Tabulated LD ROI Results

The LD rate of injection results for E10 Cert Gasoline are split into two tables for formatting purposes and are shown below in Table 13 and Table 14. Mass per injection values are shown with a \pm of one standard deviation of the 240 injection events used.

Table 13: LD Rate of Injection Results for E10 Cert Gasoline (Pt. 1)

Fuel Pressure (bar)	Back Pressure (bar)	Electronic Duration/Mass Target	Mass injected (mg/inj)	Close Delay (ms)	Open Delay (ms)
100	4	1.75 ms	25.5 \pm 0.2	0.63	0.41
100	20		25.4 \pm 0.2	0.63	0.42
100	65		21.6 \pm 0.3	0.65	0.43
300	4	1.75 ms / 40 mg per inj	42.8 \pm 0.2	0.59	0.41
300	20		41.8 \pm 0.1	0.59	0.42
300	65		40.2 \pm 0.1	0.58	0.42
450	4	1.75 ms	51.3 \pm 0.1	0.56	0.42
450	20		49.3 \pm 0.1	0.55	0.43
450	65		47.3 \pm 0.2	0.55	0.43
100	4	1.59 ms / 20 mg per inj	21.3 \pm 0.1	0.63	0.42
100	20		21.1 \pm 0.1	0.63	0.43
100	65		17.3 \pm 0.2	0.64	0.43
300	4	0.94 ms / 20 mg per inj	21.3 \pm 0.1	0.57	0.42
300	20		20.3 \pm 0.1	0.56	0.43
300	65		19.5 \pm 0.04	0.56	0.43
450	4	0.80 ms / 20 mg per inj	22.3 \pm 0.3	0.55	0.42
450	20		20.7 \pm 0.1	0.53	0.43
450	65		20.4 \pm 0.1	0.54	0.43

Table 14: LD Rate of Injection Results for E10 Cert Gasoline (Pt. 2)

Fuel Pressure (bar)	Back Pressure (bar)	Electronic Duration/Mass Target	Mass injected (mg/inj)	Close Delay (ms)	Open Delay (ms)
100	4	3.91 ms / 40 mg per inj	46.9±0.5	0.63	0.42
100	20		45.5±1.3	0.63	0.43
100	65		38.0±0.9	0.65	0.43
450	4	1.57 ms / 40 mg per inj	43.0±0.1	0.57	0.42
450	20		42.1±0.1	0.55	0.43
450	65		41.7±0.1	0.55	0.43
100	4	5.17 ms / 60 mg per inj	65.6±0.8	0.64	0.41
100	20		63.9±0.7	0.64	0.42
100	65		52.4±1.5	0.66	0.43
300	4	2.76 ms / 60 mg per inj	63.7±0.1	0.59	0.42
300	20		62.8±0.1	0.58	0.43
300	65		62.8±0.2	0.58	0.43
450	4	2.29 ms / 60 mg per inj	65.4±0.1	0.56	0.43
450	20		62.4±0.1	0.54	0.43
450	65		63.0±0.1	0.54	0.44

The LD ROI results for the RON 70 GCI fuel are shown below in Table 15 and Table 16:

Table 15: LD Rate of Injection Results for RON 70 GCI Fuel (Pt. 1)

Fuel Pressure (bar)	Back Pressure (bar)	Electronic Duration/Mass Target	Mass injected (mg/inj)	Close Delay (ms)	Open Delay (ms)
100	4	1.75 ms	25.3±0.3	0.61	0.41
100	20		25.2±0.5	0.63	0.41
100	65		21.5±0.4	0.62	0.43
300	4	1.75 ms / 40 mg per inj	40.0±0.1	0.57	0.41
300	20		39.5±0.1	0.57	0.42
300	65		38.0±0.1	0.57	0.42
450	4	1.75 ms	50.3±0.1	0.56	0.42
450	20		47.0±0.1	0.54	0.43
450	65		46.4±0.1	0.54	0.43

Table 16: LD Rate of Injection Results for RON 70 GCI Fuel (Pt. 2)

Fuel Pressure (bar)	Back Pressure (bar)	Electronic Duration/Mass Target	Mass injected (mg/inj)	Close Delay (ms)	Open Delay (ms)
100	4	1.59 ms / 20 mg per inj	21.1±0.3	0.63	0.41
100	20		20.5±0.3	0.63	0.42
100	65		16.5±0.5	0.65	0.43
300	4	0.94 ms / 20 mg per inj	20.6±0.4	0.56	0.42
300	20		20.1±0.04	0.56	0.42
300	65		19.3±0.04	0.56	0.42
450	4	0.80 ms / 20 mg per inj	22.3±0.1	0.53	0.42
450	20		20.9±0.1	0.52	0.43
450	65		20.3±0.1	0.52	0.43
100	4	3.91 ms / 40 mg per inj	47.5±0.7	0.64	0.41
100	20		46.0±0.9	0.66	0.42
100	65		31.1±2.9	0.67	0.42
450	4	1.57 ms / 40 mg per inj	44.8±0.2	0.58	0.42
450	20		42.4±0.1	0.58	0.43
450	65		42.0±0.1	0.57	0.43
100	4	5.17 ms / 60 mg per inj	61.2±1.0	0.66	0.41
100	20		58.1±1.2	0.64	0.42
100	65		38.9±3.0	0.67	0.42
300	4	2.76 ms / 60 mg per inj	61.5±0.5	0.60	0.41
300	20		57.5±0.2	0.60	0.42
300	65		60.4±0.2	0.60	0.42
450	4	2.29 ms / 60 mg per inj	65.7±0.3	0.59	0.42
450	20		63.3±0.3	0.57	0.42
450	65		61.1±0.3	0.56	0.43