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Optical Access Engine Setup and Validation

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Optical Access Engine Setup and Validation

By

Jiongxun(Justin) Zhang

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

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In Mechanical Engineering

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

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Abstract

The optical access engine integrated with the diagnostic and optical measurement techniques is a great platform for engine research because it provides clear visual access to the combustion chamber inside the engines. An optical access engine customized based on a 4-cylinder spark ignited direct injection (SIDI) production engine is located in the Advanced Power Systems Laboratories (APS LABS) at Michigan Technological University. This optical access engine inside the test cell has been set up for different engine research.

In this report, two SAE papers in engine research utilizing the optical access engine are reviewed to gain basic understanding of the methodology. Though the optical engine in APS LABS is a little bit different from the engines used in the literature, the methodology in the papers provides guidelines for engine research through optical access engines. In addition, the optical access engine instrumentation including the test cell setup and the optical engine setup is described in detail in the report providing a solid record for later troubleshooting and reference. Finally, the motoring tests, firing tests and optical imaging experiment on the optical engine has been performed to validate the instrumentation.

This report only describes so far the instrumentation of the optical engine in the APS LABS by April 2015.

CHAPTER 1 Introduction

1.1 Background

An optical engine customized based on a 2013 Ford Escape 2.0L EcoBoost 4 cylinder spark ignited direct injection (SIDI) production engine is located in the Advanced Power Systems Laboratories (APS LABS) at Michigan Technological University. The optical engine, as the name suggests, allows visual access to the combustion chamber helping understand the different aspects of combustion and its diagnostics. Optical engines provide a realistic engine environment to study in-cylinder flow, mixing, combustion and emissions phenomena by a qualitative and quantitative non-intrusive, imaging diagnostic technique.

1.2 Goals and Objectives

The long-term goal of the optical access engine is to perform ignition research sponsored by Ford Motor Company utilized laser diagnostics and optical measurement techniques. The research team will continue working toward the goal and cooperated with engineers at Ford Motor Company for ignition research. The short-term goal of the project is to set up the optical access engine to run basic experiments without integrated the diagnostic and optical measurement techniques. The following list outlines the objectives of the optical engine research.

- Optical access engine instrumentation including data acquisition system and engine control system.
- Integration the optical access engine with the diagnostic and optical measurement techniques such as high speed camera setup and particle image velocimetry (PIV).
- Ford Motor Company ignition research through optical access engine including spark plasma stretching and spark energy study.

The objective of this report is to record the current status of the optical access engine instrumentation, which includes the test cell setup and the optical engine setup. The test cell setup covers the layout of the test cell, the fuel system, the data acquisition (DAQ) system and the dynamometer system. The optical engine setup consists of engine specification, hardware setup and engine control unit (ECU) setup. Moreover, basic experiment on the optical engine has been performed to validate the setup. The motoring tests, firing tests and optical imaging results captured by high-speed camera are discussed.

CHAPTER 2 Literature Review

A lot of researchers use the optical access engine for different engine parameters study such as fuel injection system and ignition. Two technical papers are reviewed to study how researchers use the optical engine for research. Although not all of the papers study SIDI engine, their research apparatus, conclusions provide a reasonable support and theory guide for later experimental research utilizing the optical engine.

Lucchini et al. developed computational fluid dynamics (CFD) models for the air/fuel mixing process in stratified charge, spark-ignited engines. They validate the CFD model with experimental results from a constant volume vessel as well as a 4-stroke, 4-cylinder optically accessible gasoline direct injection (GDI) Engine[1].

Grill et al. studied in-cylinder fuel injection and combustion process through a narrow cone fuel injector of a high-speed direct injection (HSDI) single cylinder optical diesel engine. They found out that “the indicated mean effective pressure (IMEP) values were fairly low with multiple injections strategy because of limited performance of an optical engine and the difficulty in achieving good mixture formation and combustion with multiple injections”[2].

---

[1].Lucchini, T., Fiocco, M., Onorati, A., Montanaro, A. et al., "Full-Cycle CFD Modeling of Air/Fuel Mixing Process in an Optically Accessible GDI Engine," SAE Int. J. Engines 6(3):1610-1625, 2013, doi:10.4271/2013-24-0024.

[2] Gill, K. and Zhao, H., "In-cylinder Studies of Fuel Injection and Combustion from a Narrow Cone Fuel Injector in a High Speed Single Cylinder Optical Engine," SAE Technical Paper 2008-01-1789, 2008, doi:10.4271/2008-01-1789.

For the first paper, several engine simulations point results were validated through the optical access engine. The geometry exploded view and the real engine on test bench are shown in Figure 2-1. Four optical access elongated pistons were installed. The optical engine piston similar to commercial piston was transparent through a sapphire window place in the bowl region[1]. Unlubricated Teflon-bronze composite piston rings were used for the optical engine. The detail parameters of the optical engine are listed in Table 2-1.

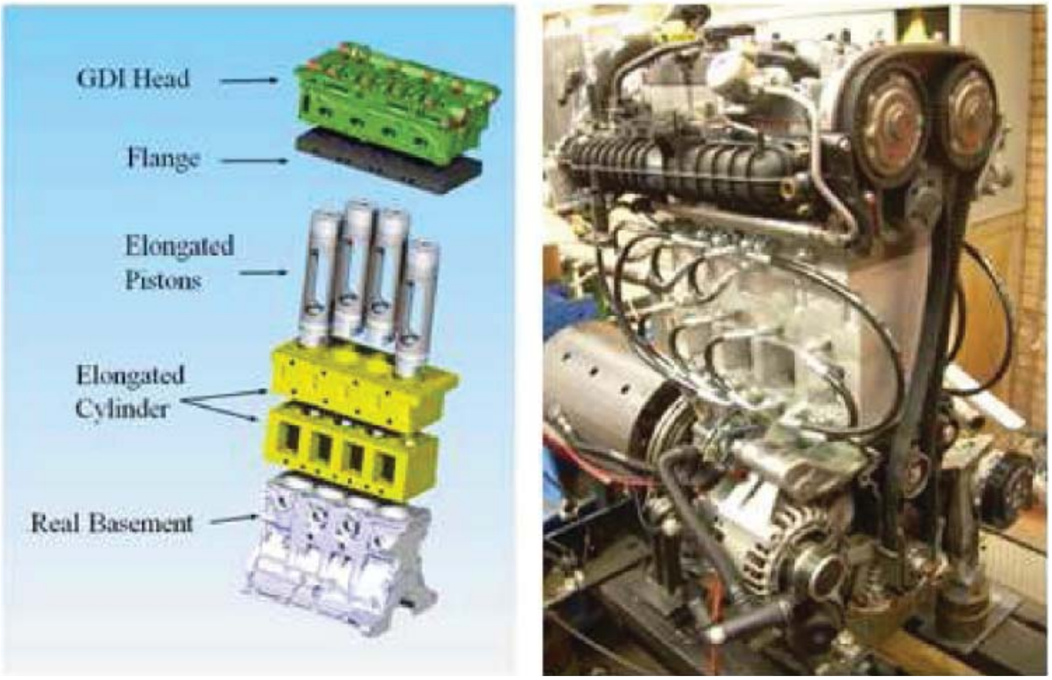

Figure 2-1: Exploded View and Photo of the Optical Accessible Engine on the Test Bench.[1]

Table 2-1: Optical Engine Geometrical Specifications[1]

Engine Specification	4 stroke 4 cylinder SIDI Optical Engine
Bore (mm)	83
Stroke (mm)	80.5
Compression Ratio	9.5:1
Swept Volume (cm^3)	1742
Swept Volume per cylinder (cm^3)	435.5
Max Torque (Nm)	320.4 at 1400 rpm
Max Power (kW)	147.1 at 5000 rpm
Max Boost Pressure (bar)	2.5

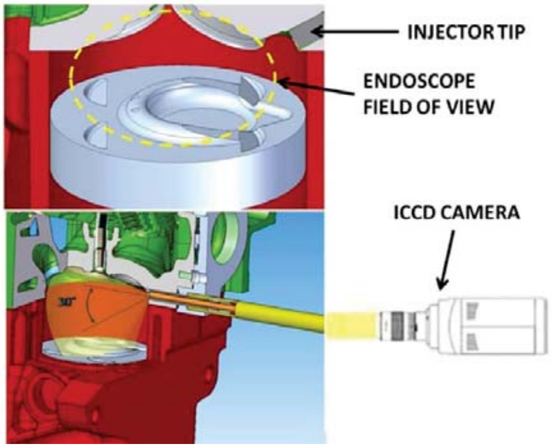

Figure 2-2: Sketch of the experimental setup for optical investigation and detail of combustion chamber and ICCD for UV- Visible [1]

The sapphire window was placed in the fourth cylinder head providing optical access for an endoscope, whose field of view was centered in the combustion chamber and perpendicular to the axis of the cylinder. The endoscope had a 30-degree viewing angle to capture the area of the spark and the injection of fuel and coupled with an intensified charge coupled device (ICCD) camera as shown in Figure 2-2. With the optical access engine setup, the authors were able to compare their CFD results with synchronized chemiluminescent images as shown in Figure 2-3.

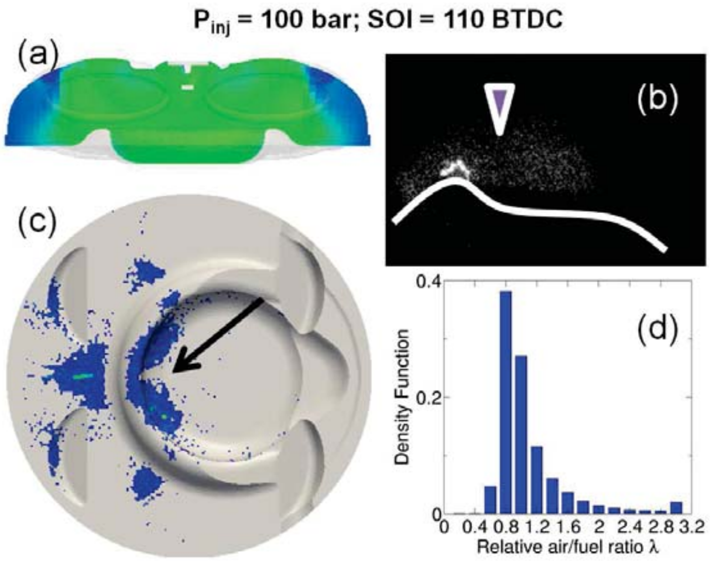

Figure 2-3: (a); computed fuel-air equivalence ratio distribution at spark-timing, range 0 (blue) - 2 (red); (b) combustion chemiluminescent image; (c) computed liquid film distribution on the piston at spark-timing; (d) computed distribution of the relative air-fuel ratio inside the cylinder at spark-timing. Injection pressure: 100 bar; SOI: 110 CAD BTDC [1]

In Grill et al.'s paper, the authors used a single cylinder Ricardo Hydra HSDI optical access engine to investigate a narrow cone fuel injector with multiple injection strategy and various alternated fuels[2]. The author analyzed the CHO and OH radical chemiluminescence images with an intensified camera to study the auto ignition and combustion characteristics. The test setup schematic was shown in Figure 2-4. The optical engine had a flat quartz window in the piston crown, and the piston was a Bowditch piston which is an extension piston with space for a 45 degree mirror in the middle to observe the combustion chamber.

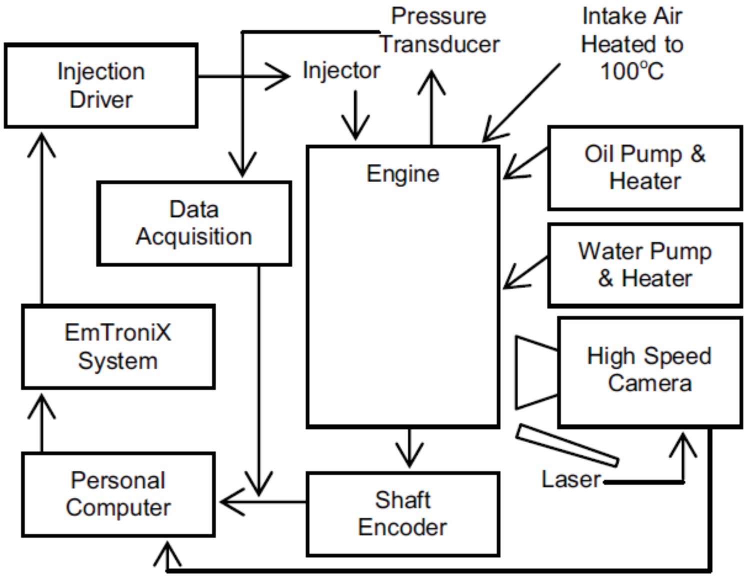

Figure 2-4: Engine Test Bed Schematic [2]

Two cameras were used in authors' test. One is NAC Memrecam fx6000 video camera for recording images of spray and flame. "The camera has a frame rate of up to 10,000 fps at a resolution of 512 X 248 obtained through a high-resolution high-speed CMOS sensor. To record images of the spray and flame, the combustion chamber is illuminated by a copper vapor laser operating at a repetition rate of 10 KHz. The output from the laser is coupled to an optical fiber, the end of which is mounted in front of the mirror providing light into the combustion chamber"[2]. Several footages of the video captured by the camera is shown in Figure 2-5 first row. The spray and the flame development are easily observed through the optical engine. The other camera was an intensified CCD camera for CHO and OH radical imaging and two-color method imaging[2]. The camera was triggered based on the heat release rate data. The results are shown in Figure 2-5. Based on the images, the authors analyzed the injector spray and in-cylinder combustion.

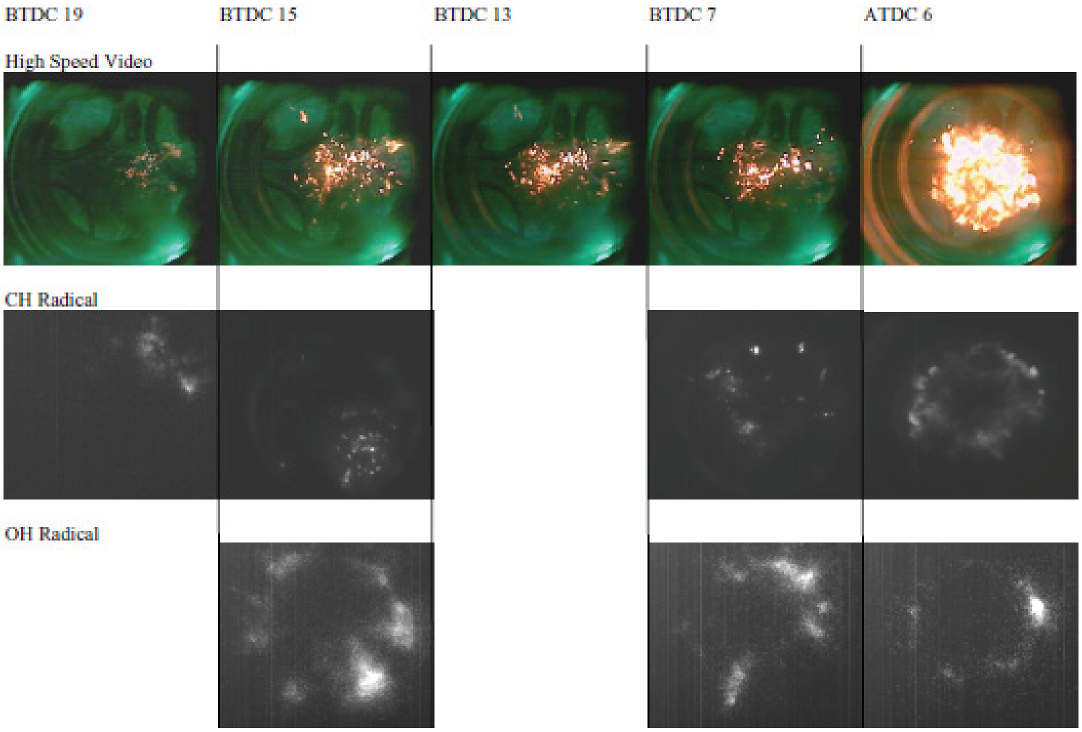

Figure 2-5: Base Diesel Image Sequence [2]

Through the two papers above, the optical access engines are used for fuel injection research either in SIDI gasoline engines or in HSDI diesel engine. Both of these researches had specified injectors to study the fuel injection system or alternative fuel system, which was a main factor of spray characteristics. In the first paper, various spray models were investigated through the penetration difference and fuel injection rate. The second paper studied the fuel spray through the analysis of image obtained from the optically accessible engine.

The differences between the optical engines' setup are listed in Table 2-2. For the way of observation, the first research group chose an endoscope probe inserting inside the cylinder to obtain the in-cylinder combustion images, and the second research group used a 45 degree mirror to reflect in cylinder view and recorded video or images through two different cameras. Both of these two papers studied fuel injection system including fuel spray characteristics, injection pressure, fuel flow rate and fluid dispersion. The images captured by the cameras through the optical access engines provides clear visualization match to the injection phenomena.

From Table 2-2, the optical engine in the Advanced Power Systems Laboratories (APS LABS) is a little bit different from these engines. Compared with the engine in the first paper, the optical engine in the APS LABS does not utilize endoscopic probe to capture images. In the second paper, the engine used in the research was a single cylinder diesel engine. Though the engines were not the same with the one in APS LABS, the methodology of utilizing optical access engines in fuel injection research from these papers provides a detailed guide and reference for future research with the optical engine in APS LABS.

Table 2-2: Optical Engine Setup Comparison [1,2]

Optical Engine Setup	Full-Cycle CFD Modeling of Air/Fuel Mixing Process	Fuel Injection and Combustion from a Narrow Cone Fuel Injector
Piston Setup	Four optically accessible elongated piston	One Extended piston
Visual Window	Sapphire window (diameter of 5 mm)	A flat quartz window
Way of Observation	Endoscopic probe	45 degree silver coated mirror
Camera Setup	Intensified Charge Couples Device(ICCD) Camera	Two Camera: NAC Memrecam fx6000 Video Camera), Intensified CCD Camera
Illumination	Intense strobe lamp (enlighten the combustion chamber)	Cooper vapor laser at 10 kHz
Lens	78mm focal length, f/3.8 UV Nikon objective	-
Features	512*512 pixels and 16-bit dynamic range digitization at 10 kHz	512*248 pixel CMOS Sensor

CHAPTER 3 Engine Test Cell Setup

3.1 Layout of the Test Cell

The engine test cell is located at Michigan Tech's Advanced Power System Research Center (APSRC). In the test cell, hardware setup is shown in Figure 3-1, which includes an exhaust system, a fuel system and an engine mounted on the universal cart which connects an electric dynamometer and a data acquisition (DAQ) system on the wall. On the cart, there is an interface panel connecting the engine harness and engine control module (ECM) harness with the DAQ system.

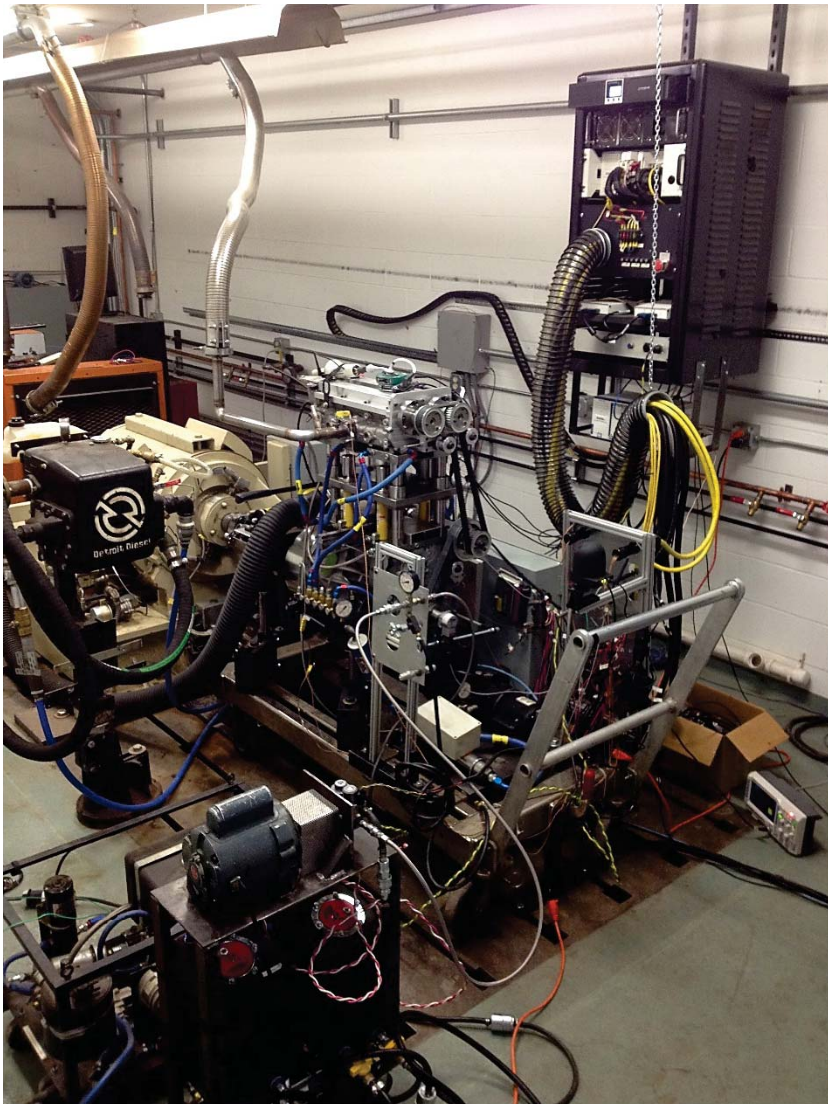

Figure 3-1: APSRC Test Cell Optical Engine Setup

A simplified block diagram in Figure 3-2 explains the layout of the engine test cell. The ambient air from outside of the test cell goes through a laminar flow element (LFE), then enters into the engine intake manifold through a black flexible plastic hose. The fuel system includes a low-pressure fuel pump and a high-pressure fuel pump system. The DAQ system consists of a DSP-ACAP combustion analysis system and a National Instrument (NI) system. The optical engine is mounted on a universal cart with interface panels installed. The exhaust system is stationary and has quick connections between the pipes mounted on the ceiling of the test cell and engine exhaust manifold pipe through a 3-inch V-Band clamp flange. The dynamometer in the test cell is an AC type dynamometer for motoring the engine and absorbing energy while the engine is running.

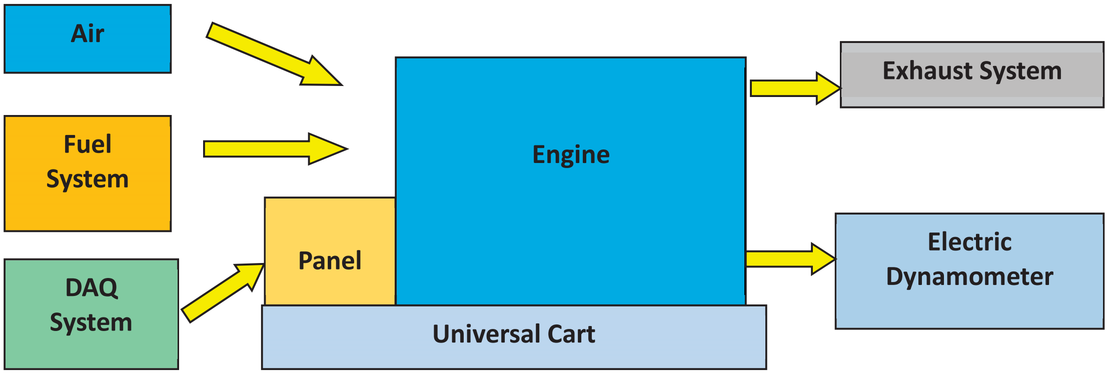

Figure 3-2: Block Diagram of Test Cell Layout

3.2 Fuel System

A low-pressure fuel pump system and a high-pressure fuel pump system are used in the test cell for the optical engine as shown in Figure 3-3. The optical engine is not equipped with a high-pressure pump same as the production Ecoboost engine. The fuel system for a regular engine has a low-pressure fuel pump inside the fuel tank to pump the fuel to the high-pressure fuel pump located near the common fuel rail in the engine. Therefore, the low-pressure and high-pressure fuel carts serve as the fuel system in the regular engine.

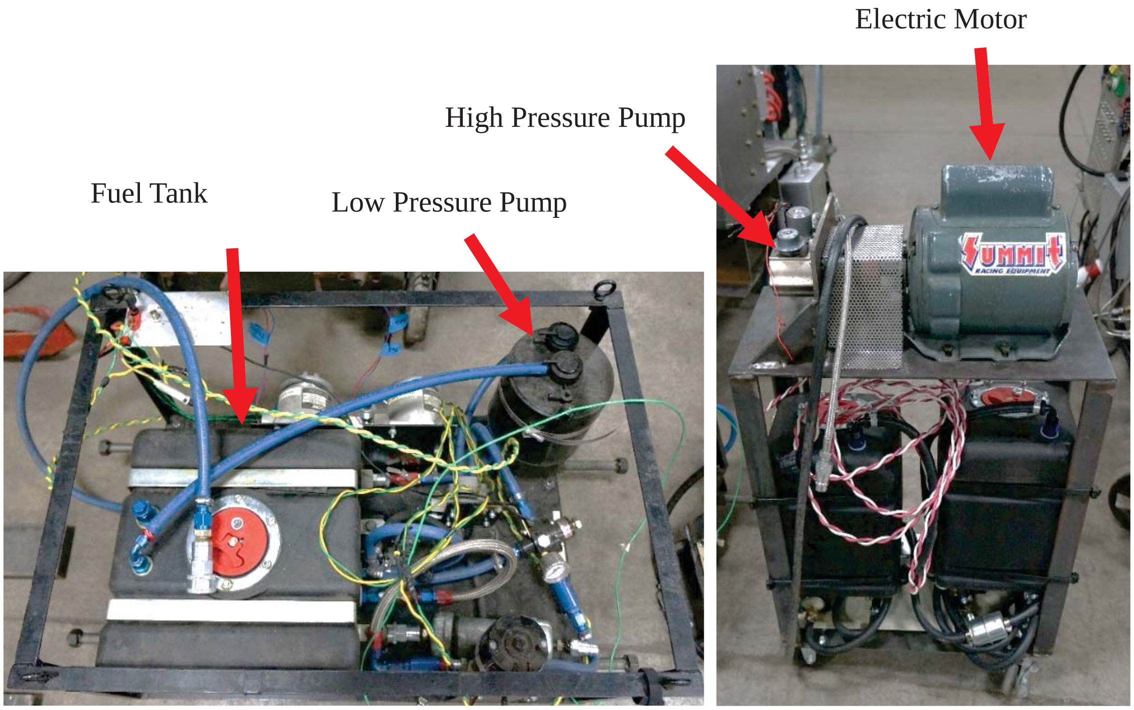

Figure 3-3: Low Pressure Fuel Cart (Left); High Presure Fuel Cart (Rigt)

As the low-pressure fuel cart shown in Figure 2-3, the thin green and yellow wire connects to the DAQ system in the test cell to obtain power. The blue fuel tube connects to the high-pressure fuel pump. For the high-pressure fuel cart, the useful components for the optical engine are the electric motor, the high-pressure fuel pump on the top of the cart and a switch on the bottom of the cart. The a 1 Horsepower electric motor is powered by regular 110V outlet and used to drive the high-pressure fuel pump.

The fuel flow across the high-pressure pump is controlled by a signal from the engine control unit. Then a fuel line connects the high-pressure fuel pump and the common fuel rail on the optical engine through a valve mounted on the interface panel. The connections of the fuel system are simplified as shown in Figure 2-4. This block diagram shows the basic connections between the fuel system and the optical engine. The switch of the low-pressure fuel pump is embedded in the NI LabVIEW program, but the switch of the high-pressure fuel pump is on the cart, which is turned on or off manually.

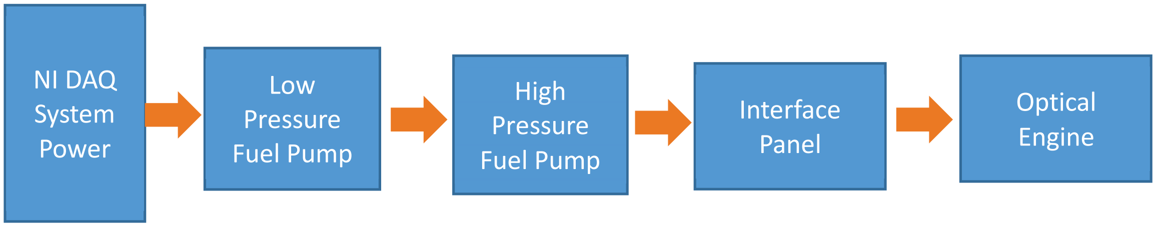

Figure 3-4: Fuel System Connection Block Diagram

3.3 Data Acquisition (DAQ) System

3.3.1 DSP-ACAP Combustion Analysis System

The data acquisition system for the test cell includes a DSP-ACAP combustion analysis system and a National Instrument system. The combustion analysis system is a PC-based program for real-time internal combustion engine analysis and general data acquisition from DSP Technology[3]. In the test cell, the DSP-ACAP system are installed in a standard 19-inch instrumentation cabinet. The cabinet acts as a Faraday Cage preventing instrumentation from Electro-Magnetic Interference. The actual setup is shown in Figure 3-5. The top parts are the quick connection panels connected on the back of the ACAP system, which are used for BNC connections. The bottom part of Figure 3-5 is the ACAP combustion analysis system. Different modules are mounted on a power frame to power up the system. The modules used in the system are listed in Table 3-1.

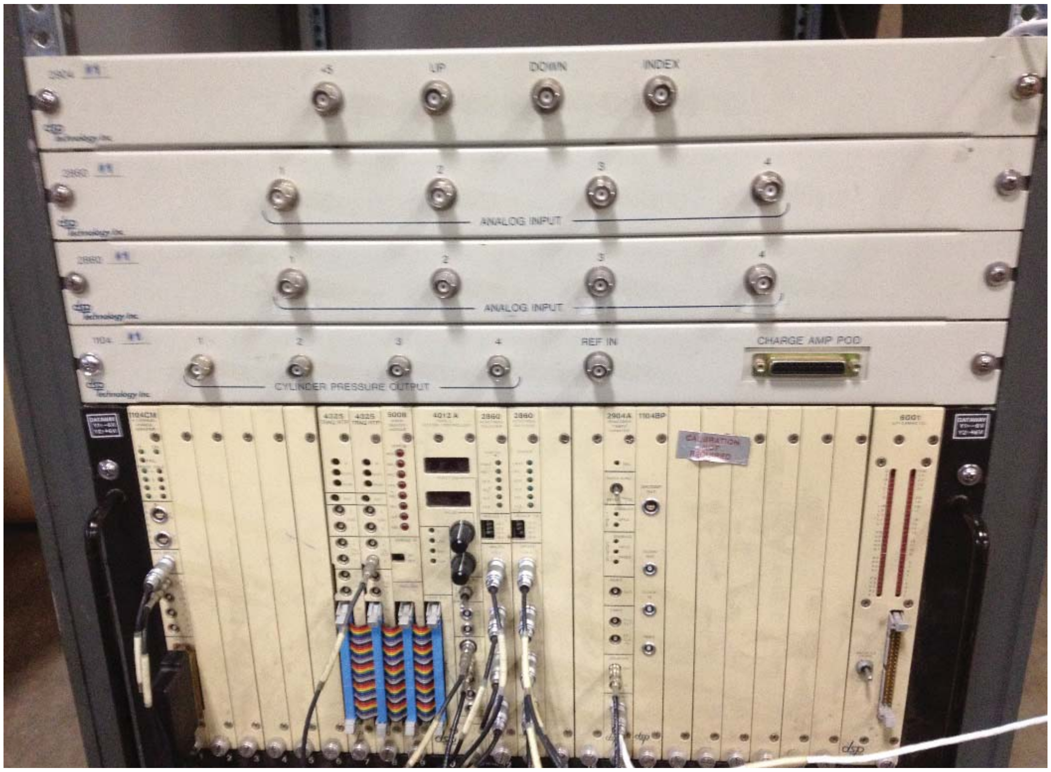

Figure 3-5: Test Cell ACAP System in 19 inch Cabinet

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[3] REDLINE ACAP, User Manual Version 4.0, DSP Technology Inc.

To run a minimum real combustion analysis package in ACAP, several modules are required in the power frame, including module 4325 Real Time Processor (RTP), 4012 TRAQ Controller, TRAQ ADC modules, 2904 SPINCODER and either model 6001 or 6002 crate controller[3]. TRAQ stands for transient and signal acquisition. The modules used are listed in Table 3-1, with information collected through the manual. The modules chosen are based on the module inventory and the requirements for running the ACAP system. The model number in Table 3-1 is ordered through the actual setup.

Table 3-1 Test Cell ACAP Modules[3]

Model NO.	Name	QTY	Description
1104CM	Signal Conditioning Modules	1	Four channel charge amplifier for conditioning and scaling cylinder pressure transducers (piezo-electric type).
4325	Real Time Processor	2	Model4325 Real Time Processor is a high speed processing unit using the Texas Instrument TMS320C25 digital signal processing chip capable of 10 million instructions per second.
5008	Memory Module	2	Memory Module, 8 Mega-sample memory module.
4012A	TRAQ Controller	1	TRAQ Controller, the "brains" for the control of the acquired data flow and for the communications between the host computer and the TRAQ system.
2860	ADC Modules	3	ADC Module, 4 channels, 12 bit resolution, maximum 1 Mega sample per second per channel conversion rate. ±5 Volt input range.
2904A	SPINCODER	1	SPIN CODER encoder counter/timer used to condition encoder signals, time stamp the encoder pulses, and provide position information from a pulse counter.
1642	Knock Module	1	Four-input knock filter/amplifier with knock peak detection and knock intensity integration.
6001	Crate Controller	1	Communicate link between the TRAQ crate and the host computer.

According to the manual, “4325 RTP is installed to the left of the 500x memory module. 500x memory modules are installed to the immediate left of the 4012. Model 4012 is installed at a location in which all the signal input modules (2812, 2814, 2860, 2904, etc.) may be placed to its right and all memory modules and RTPs may be placed to its left. The CRATE Controller (6001, 6002, or CC488) is always installed in slots 24 and 25”[3]. These rule must be followed to avoid connection damage to the ACAP system. The actual modules are installed as shown in Figure 3-6. For further information about each module, please refer to the REDLINE ACAP User Manual.

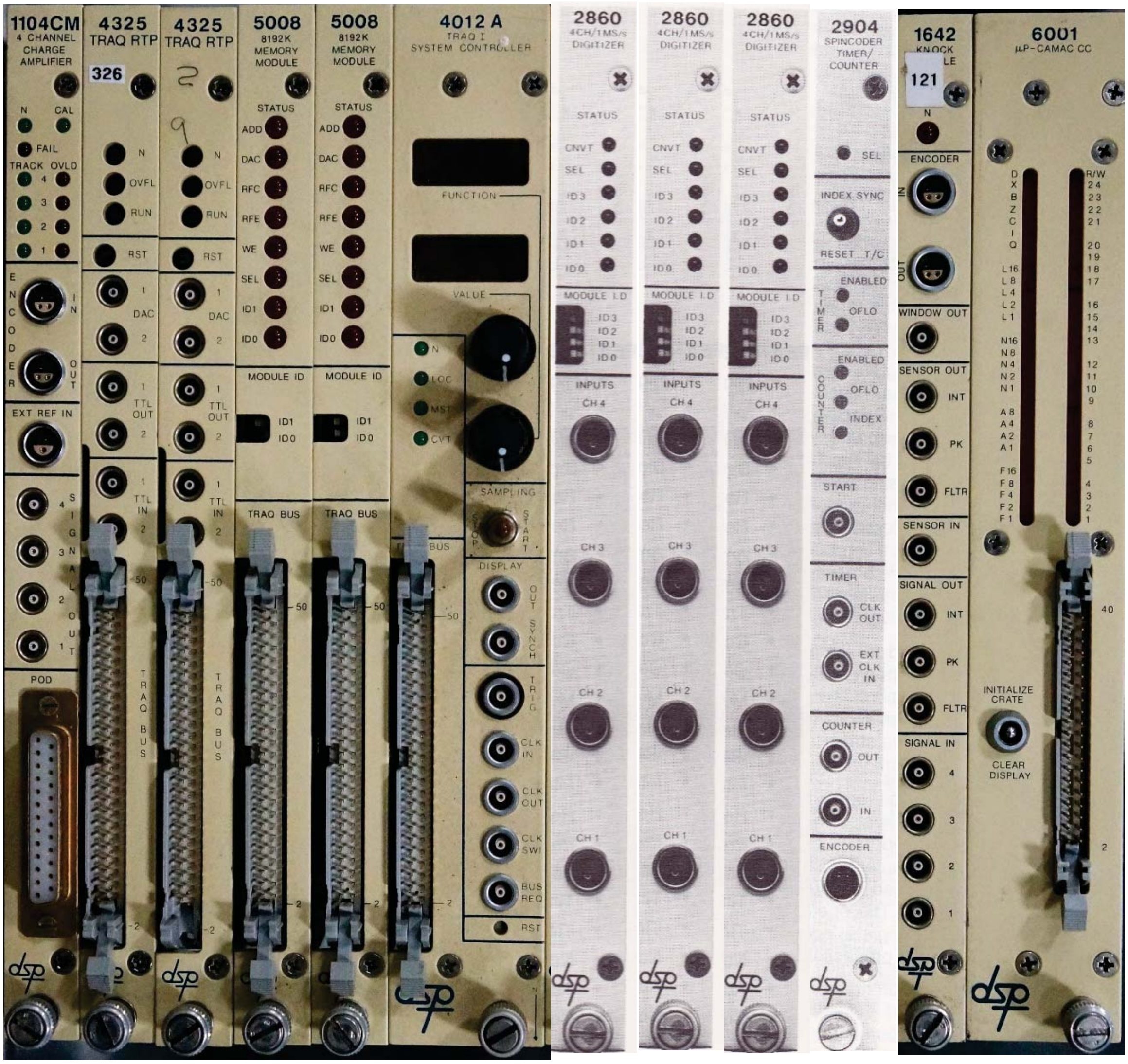

Figure 3-6: Test Cell ACAP System Modules

Table 3-2: Test Cell ACAP Modules Channel Connections

Model No.	Channel	Connection	Cable
1104CM Signal Conditioning Modules	Encoder In	1642 Encoder Out	LEMO FFA-0S 4 Pin Cable
	Encoder Out	2904 Encoder	LEMO FFA-0S 4 Pin Cable
	EXT Ref In	1104 Front Panel Ref	LEMO FFA-0S 2 Pin Cable
	Signal 4	1104 Front Panel Cylinder Pressure 4	CD International Inc. L00L00F-174LN-1
	Signal 3	1104 Front Panel Cylinder Pressure 3	CD International Inc. L00L00F-174LN-1
	Signal 2	1104 Front Panel Cylinder Pressure 2	CD International Inc. L00L00F-174LN-1
	Signal 1	1104 Front Panel Cylinder Pressure 1	CD International Inc. L00L00F-174LN-1
	POD	1104 Front Panel POD	POD Connector
4325 Real Time Processor	TTL Out 2	4012A TRIG	CD International Inc. L00L00F-174LN-1
4012A TRAQ Controller	TRIG	4325 TTL Out 2	CD International Inc. L00L00F-174LN-1
	CLK In	2904 Counter Out	CD International Inc. L00L00F-174LN-1
2860 ADC Modules	CH4	2860 Front Panel	LEMO FFA-0S 2 Pin Cable
	CH3	2860 Front Panel	LEMO FFA-0S 2 Pin Cable
	CH2	2860 Front Panel	LEMO FFA-0S 2 Pin Cable
	CH1	2860 Front Panel	LEMO FFA-0S 2 Pin Cable
2904A SPINCODER	Counter Out	4012 CLK In	CD International Inc. L00L00F-174LN-1
	Encoder	1104CM Encoder Out	LEMO FFA-0S 4 Pin Cable
1642 Knock Module	Encoder In	Encoder Front Panel with A, Z Output Chanel	LEMO FFA-0S 4 Pin Cable
	Encoder Out	1104CM Encoder Out	LEMO FFA-0S 4 Pin Cable
	SINGAL Out INT	1104 Front Panel	CD International Inc. L00L00F-174LN-1
	SINGAL Out PK	1104 Front Panel	CD International Inc. L00L00F-174LN-1
	SINGAL In 4	1104 Front Panel Cylinder Pressure 4	CD International Inc. L00L00F-174LN-1
	SINGAL In 3	1104 Front Panel Cylinder Pressure 3	CD International Inc. L00L00F-174LN-1
	SINGAL In 2	1104 Front Panel Cylinder Pressure 2	CD International Inc. L00L00F-174LN-1
	SINGAL In 1	1104 Front Panel Cylinder Pressure 1	CD International Inc. L00L00F-174LN-1
6001 Crate Controller	BUS	Host Computer	40 Pin Flat Ribbon Bus

The module 1104CM is a four-channel charge amplifier module for piezoelectric type pressure transducer signal. Most of the channels on 1104CM are connected to the 1104 quick connection front panel, which is connected to the engine cart panel with BNC cables. The Encoder In and the Encoder Out channel are wired to the 1604 module and the 2904 module as shown in Table 3-2.

The RTP module 4325 is connected to the memory module 5008 and the control module 4012A through the 50 pin Flat Ribbon Bus with several connectors on it. For the current setup, the two RTP 4325 modules, two memory 5008 and one 4012A in Figure 3-6 are connected through the 50-pin bus with 5 connectors. Data acquired from the signal input modules by 4012A is transferred through a private bus to the local memory storage 5008 which is an 8 mega sample memory module and to the RTP 4325. A jumper cable is used to connect one of the two 4325 modules TTL Out 2 channel with the TRIG channel on 4012A. In addition, the CLK In channel is wired to the Counter Out channel of the 2904 SPINCODER module as shown in Table 3-2. The encoder signals from the engine are connected to the system through a multiple-pin connector on the 2904A. The encoder pulse signal is used to “clock” the system. Three 2860 ADC modules are used according to Figure 3-6, which have four channels with 12-bit resolution each. This module is used for input and acquisition of analog data. LEMO FFA-0S 2-pin cables are used to connect module 2860 to the amplifier and later to the engine for data acquisition. All the channels on these three 2860 modules are connected to the quick connection front panels.

For 1642 Knock Module, the Encoder In is connected to the quick connection encoder panel, which has two channels including encoder A and Z signals. These will be connected to the engine cart interface panel. The Encoder Out is wired to the 1104CM Encoder Out channel. The rest of the channels connect to the 1104 quick connection front panel.

The crate controller 6001 communicates with the TRAQ crate and host computer through a 40-pin Flat Ribbon Bus. Since this ACAP system is an old combustion system, it requires a special module Industry Standard Architecture (ISA) slot on the host computer motherboard. The motherboard purchased is an ADEK MS-98A9 Ivy Bridge Industrial ATX motherboard; the quote for the motherboard is attached in the **APPENDIX 1**.

3.3.2 National Instrument (NI) Data Acquisition System

Besides the ACAP combustion analysis system, the National Instrument (NI) system serves as the main control system supporting the dynamometer control and electronic sensors power. In the test cell, the NI data acquisition system is mounted on one side of the test cell wall and could easily slide backward and forward. The whole system is shown in Figure 3-7, which includes an Uninterrupted Power Supply (UPS) unit, NI PXI system, harness, power fuse and an emergency stop button on the panel. The NI PXI system uses PXIe-1078 chassis and several modules for data acquisition. The PXIe-1078 supports a maximum of 9 slots and has up to 1.75 GB/s data transfer rate. The modules installed on the chassis are listed in Table 3-3. For further information about each module, please refer to NI website.

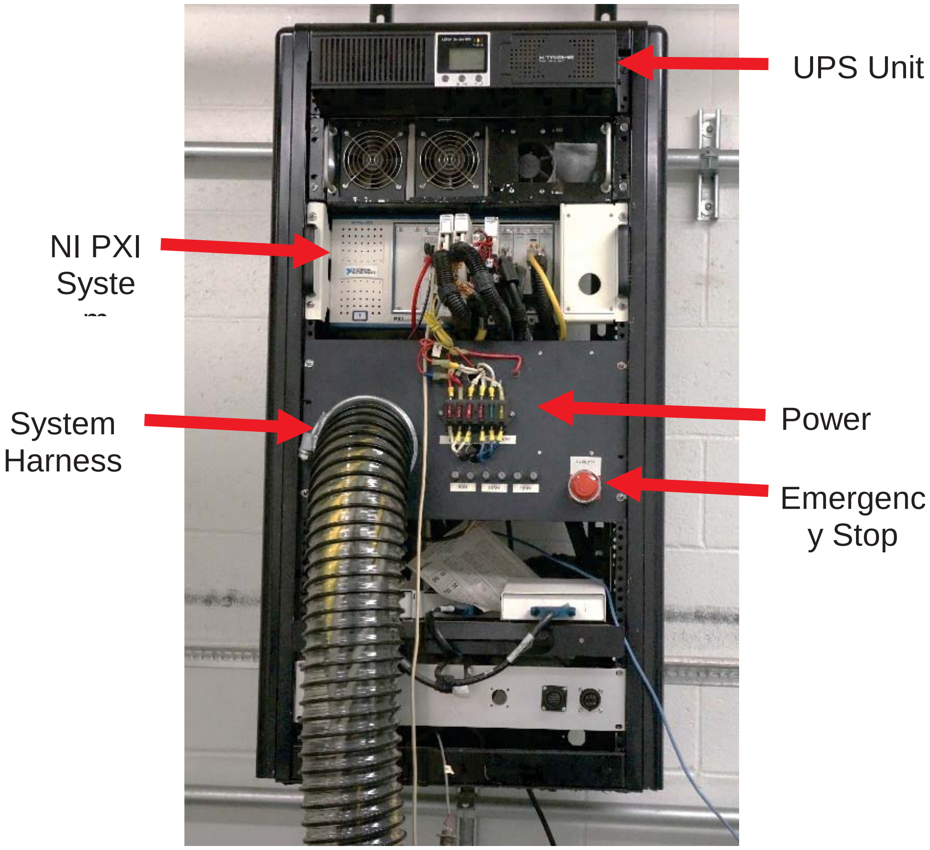

Figure 3-7: Test Cell National Instruments Data Acquisition System

Table 3-3: NI PXI System Modules Installed[4]

Chasis	QTY	Description
NI PXIe-1078	1	9-Slot 3U PXI Express Chassis With AC - Up to 1.75 GB/s
Module	**QTY**	**Description**
NI PXIe-8100	1	Deployment platform for LabVIEW Real-Time and LabWindows™/CVI Real-Time applications
NI TB-4353	2	thermocouple input module, a front mounting isothermal terminal block,12 CH Thermocouple
NI TB-2706	1	Direct Connectivity Terminal Block, 70 screw terminals, and a metal enclosure with strain relief hardware
NI PXI6225	1	16-Bit, 250 kS/s, 80 Analog Input Multifunction DAQ
NI PXI6722	1	Static and Waveform Analog Output -- 13-Bit, 8 Channels
NI PXI-8513	1	1-Port Software-Selectable/FD NI-XNET CAN Interface
NI PXIe-8430/8	1	High Performance, 8-Port Serial Interface

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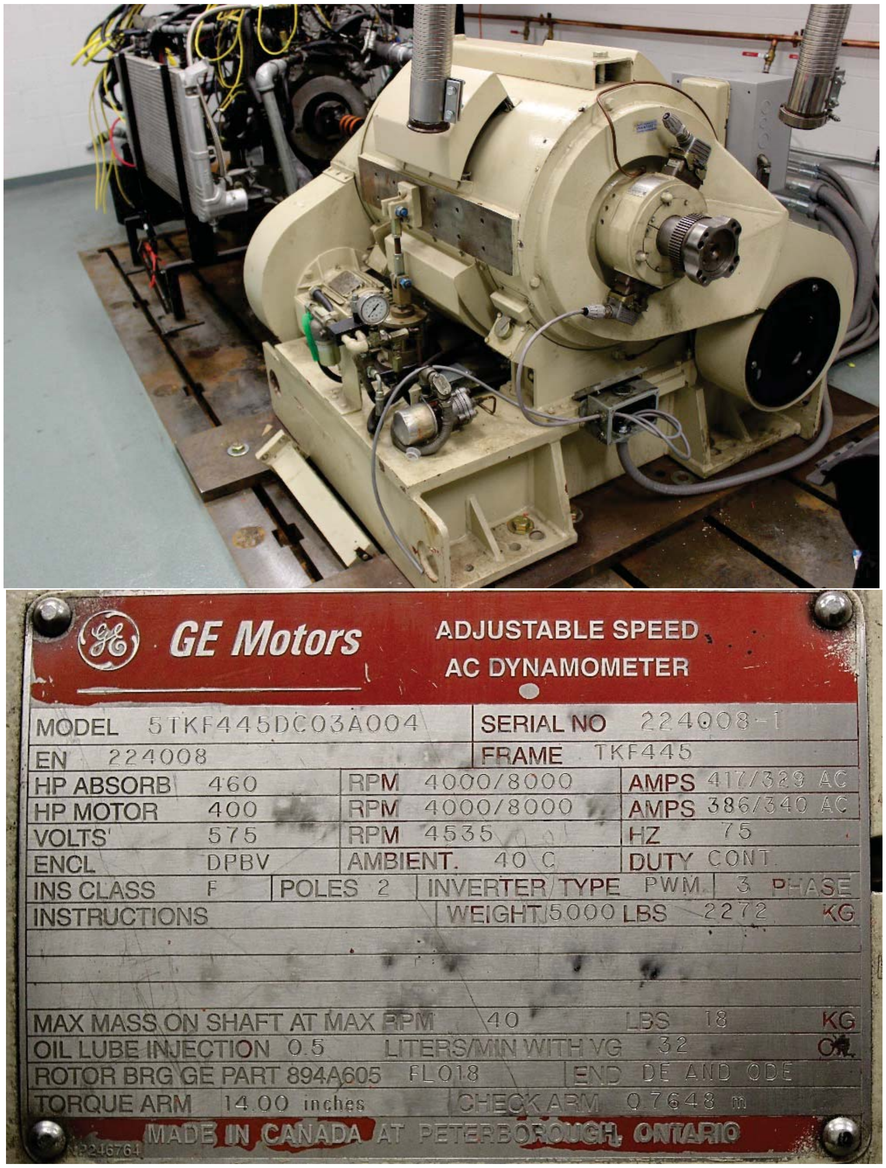
[4] www. Ni. com

3.4 Dynamometer System

A GE Motors Adjustable Speed AC Dynamometer 5TKF445DC03A004 shown in Figure 3-8 is used to measure the power output of the engine. The absorbing capacity of the dynamometer is 460 Hp and motoring capacity is 400 Hp. Also, the maximum speed for the dynamometer is 8000 RPM.



GE Motors

ADJUSTABLE SPEED
AC DYNAMOMETER

MODEL 5TKF445DC03A004
SERIAL NO 224008-1
EN 224008
FRAME TKF445
HP ABSORB 460
RPM 4000/8000
AMPS 417/329 AC
HP MOTOR 400
RPM 4000/8000
AMPS 386/340 AC
VOLTS 575
RPM 4535
HZ 75
ENCL DPBV
AMBIENT 40 C
DUTY CONT
INS CLASS F
POLES 2
INVERTER TYPE PWM
3 PHASE
INSTRUCTIONS
WEIGHT 5000 LBS 2272 KG
MAX MASS ON SHAFT AT MAX RPM 40 LBS 18 KG
OIL LUBE INJECTION 0.5 LITERS/MIN WITH VG 32 OIL
ROTOR BRG GE PART 894A605 FL018
END DE AND ODE
TORQUE ARM 14.00 inches
CHECK ARM 0.7648 m
MADE IN CANADA AT PETERBOROUGH, ONTARIO
P246764

Figure 3-8: GE Motors Adjustable Speed AC Dynamometer

CHAPTER 4 Optical Engine Setup

4.1 Optical Engine Specification

The optical engine provided by MAHLE Powertrain is an engine based on a 2013 Ford Escape 2.0L EcoBoost 4 cylinder spark ignited direct injection (SIDI) production engine. For the Ford Ecoboost engine, the detail geometry parameters are listed in Table 4-1 from the service manual. These parameters could be used to set up the engine control unit, DSP-ACAP combustion analysis system.

Table 4-1: Ford Ecoboost Engine and Optical Engine Geometry Parameters[5][6]

Engine Type	EcoBoost 2.0L	Optical Engine	**Unit**
No. of Active cylinders	4	1	-
Bore	87.5	87.5	mm
Stroke	83.1	100	mm
Displacement	2	0.6	L
Firing Order	1-3-4-2	NA	-
Connecting Rod Length	155.87	155.87	mm
Compression Ratio	9.3:1	10.24:1	-
Spark Plug	NGK T4025R	NGK T4025R	-
Spark Plug Gap	0.8	0.8	mm

According to the information from MAHLE Powertrain, though the optical engine is modified based on the Ecoboost engine, there are some differences between these two engines. Compared with the Ecoboost engine, the optical engine's stroke is 100mm, engine displacement is 0.6L for the single cylinder and compression is 10.24:1 instead of 9.3:1. In addition, the optical engine utilizes customized connecting rod and pistons, whose piston

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[5] 2013 Escape Workshop Manual Section 303-01B Engine-2.0L GTDI Specifications

[6] MAHLE Powertrain 01735 DOE Optical Engine

has a flat top and four threaded holes. These four threaded holes are used to mount the Bowditch elongated piston, showing in Figure 4-1^{6}.

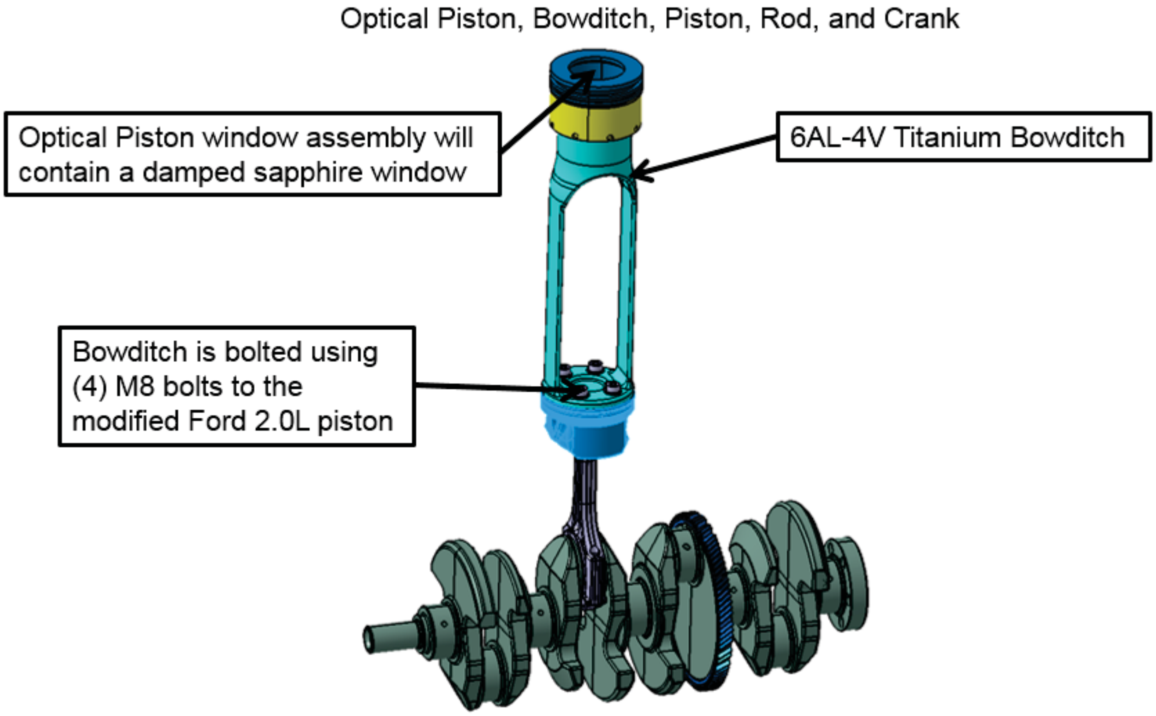

Figure 4-1: Optical Engine Bowditch Assembly [10]

In Figure 4-1, the optical piston window is now equipped with a transparent pent-roof top shape optical grade quartz liner upper window, which is clamped between the cylinder head and hydraulic deck through hydraulic pressure. The window is shown in Figure 4-2. The gray layer is the gasket to seal the combustion chamber and the quartz ring.

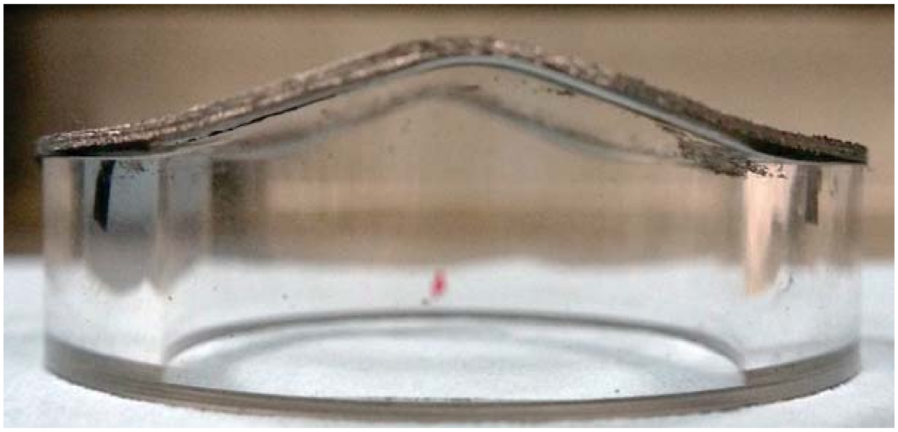

Figure 4-2: Optical Engine Pent-Roof Shape Optical Grade Quartz Liner Upper Window

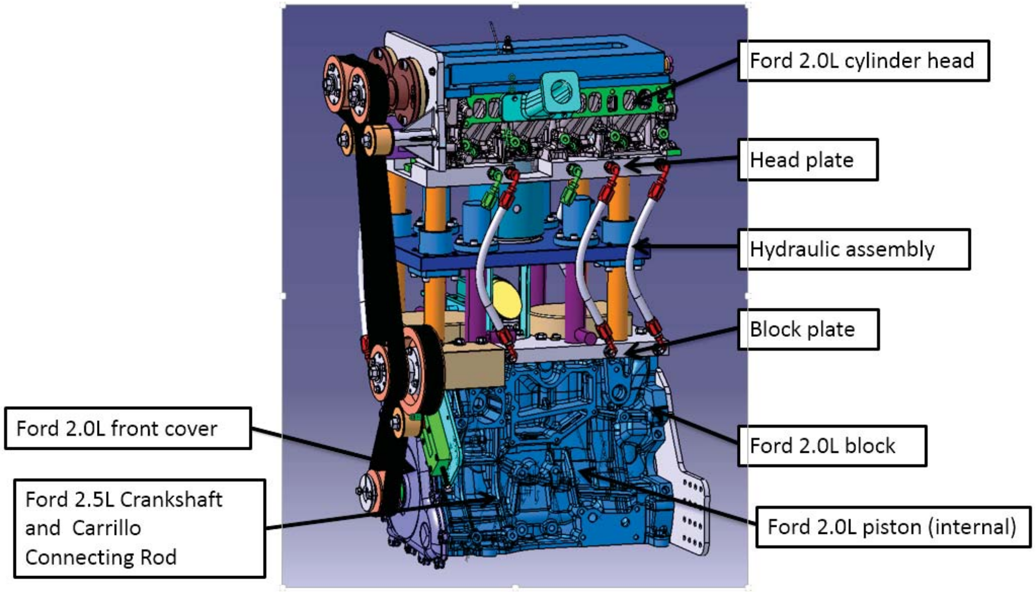

Figure 4-3: MAHLE Powertrain 3D CAD Design Concept Overview of Optical Engine[6]

The full assembly of the optical engine in Figure 4-3[6] from MAHLE Powertrain shows the design overview. For the optical engine at Michigan Technological University, the cylinder head is the 2.0L Ecoboost production cylinder head machined for the pent-roof optical access accommodating a standard production spark plug.

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4.2 Hardware Setup

4.2.1 Engine Mounting

The engine is mounted on a universal cart shown in Figure 4-4. The left side shows the original optical engine without any instrumentation. On the right side, the optical engine is mounted on a universal cart, which provides mobility to move the engine to the test cell. Because there are different engine platforms in the test cell, it is easy to move the engine out of the test cell after the experiment. Moreover, from the right side of Figure 4-4, the engine is jacked to a specified height of 78.9 cm (31.0625 inch) to mate with the dynamometer shaft.

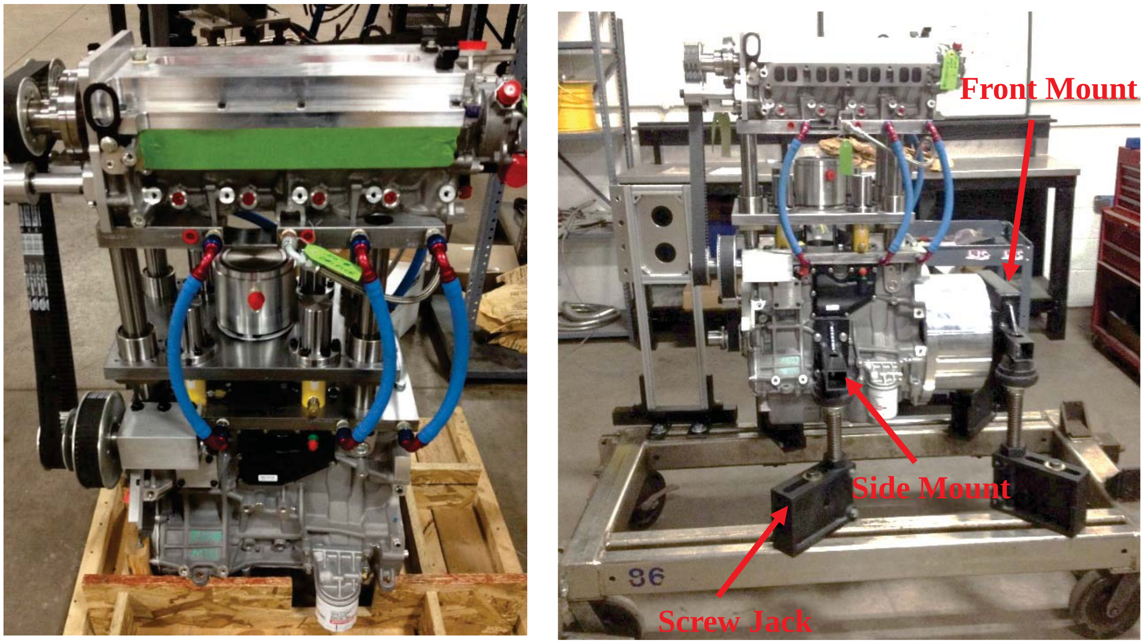

Figure 4-4: Optical Engine (Left) and Optical Engine Mounting on Engine Cart (Right)

To mount the engine on the cart, several accessories are required and some of them are designed and fabricated. The mounting process of each component is presented in the block diagram in Figure 4-5. These components include front mount frame, side mount welded by two inches square tube, four screw jacks for engine support, bell housing, screw jack adapters and ranger mount to reduce vibration.

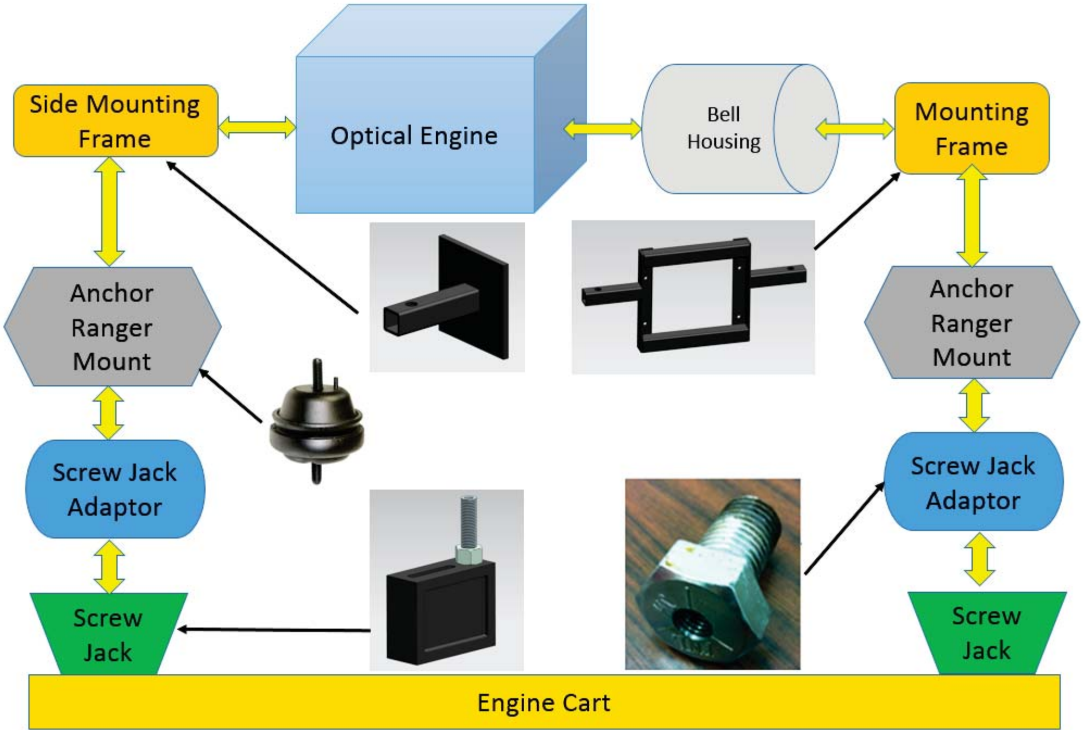

Figure 4-5: Engine Mounting Components Connection Block Diagram

Basically, the engine on the cart is supported by the four heavy duty screw jacks, which makes it adjustable and easy for positioning the height of the optical engine. Then four ranger mounts are connected to the screw jacks through screw jack adapters, which are machined from 7/8-9 hex bolts with 12 mm diameter, 1.75 pitch, 35 mm depth threaded holes at the center to fit the ranger mount threaded stud. The detailed CAD drawings are attached in APPENDIX 2.

On the end of the ranger mount, front mount frame and side mount frames are supported. The ranger mounts act as dampers to balance the vibration while the engine is running. For the front side of the engine, the bell housing connects the engine flywheel with the dynamometer shaft. Then the housing is mounted on the front mount frame through four bolts as shown in Figure 4-6. The front frame is made of 2-inch carbon steel square tubing with 0.25 inch thickness. By cutting and welding the tube, the front frame is built. The holes on the tube are used to connect to the ranger mount. The bell housing has a four screw holes square pattern to fit with the engine rear end.

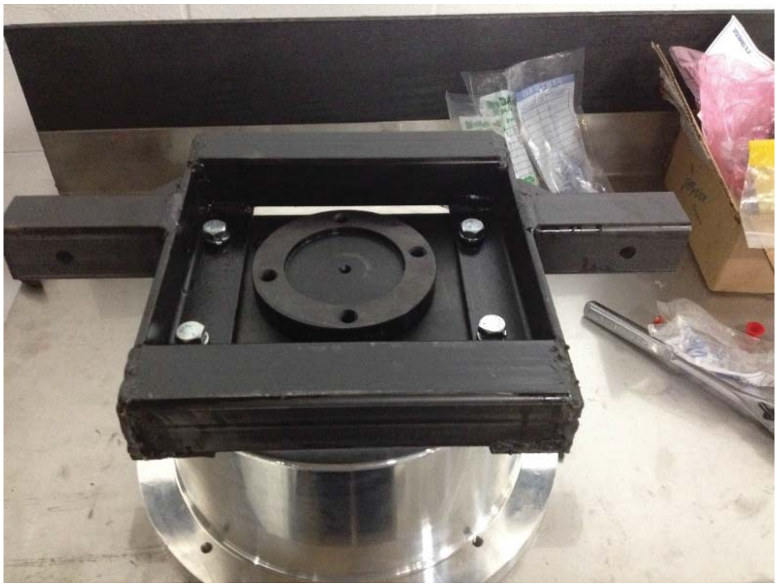

Figure 4-7: Bell Housing Mounted with Front Mount Frame

There are two side mounting frames on the left and right sides of the optical engine. Their setup is similar to the front mounting frame, except that the 2 inch square tube is welded on a metal plate as shown in Figure 4-7. Then, several holes are drilled according to the optical engine side screw pattern. Above all, the engine is supported and mounted on the universal cart.

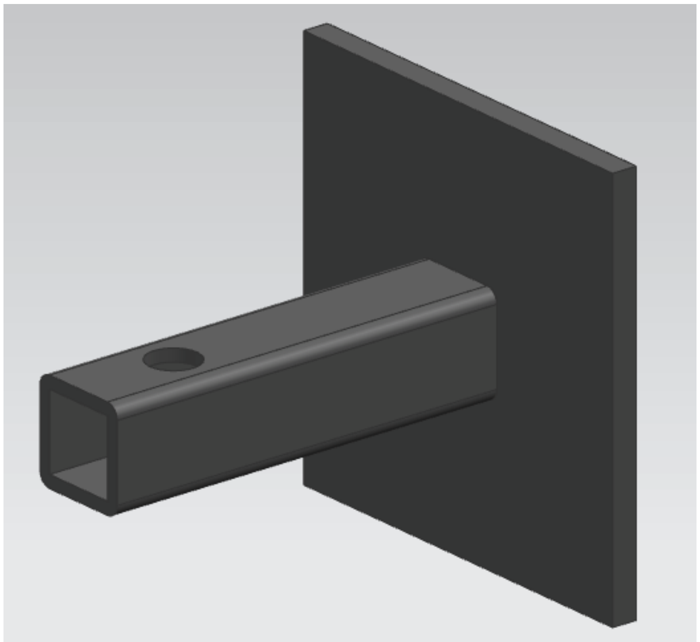

Figure 4-6: Side Mount CAD Model

4.2.2 Cart Interface Panel Design

Interface panel mounting on the universal cart provides easy and fast connections between the engine harness and data acquisition system. The interface panel includes mounting holes for different flange receptacles, BNC, USB and Ethernet connectors. Two panels are designed as shown in Figure 4-8. Both of them are machined from ASTM B209 aluminum sheets. One is the coolant and fuel line panel and the other one is the connector panel. The design of the panels is standardized for all APS LABS research engines, and some features are not used by the optical engine, for example, the AUX WATER ports on the coolant and fuel line panel.

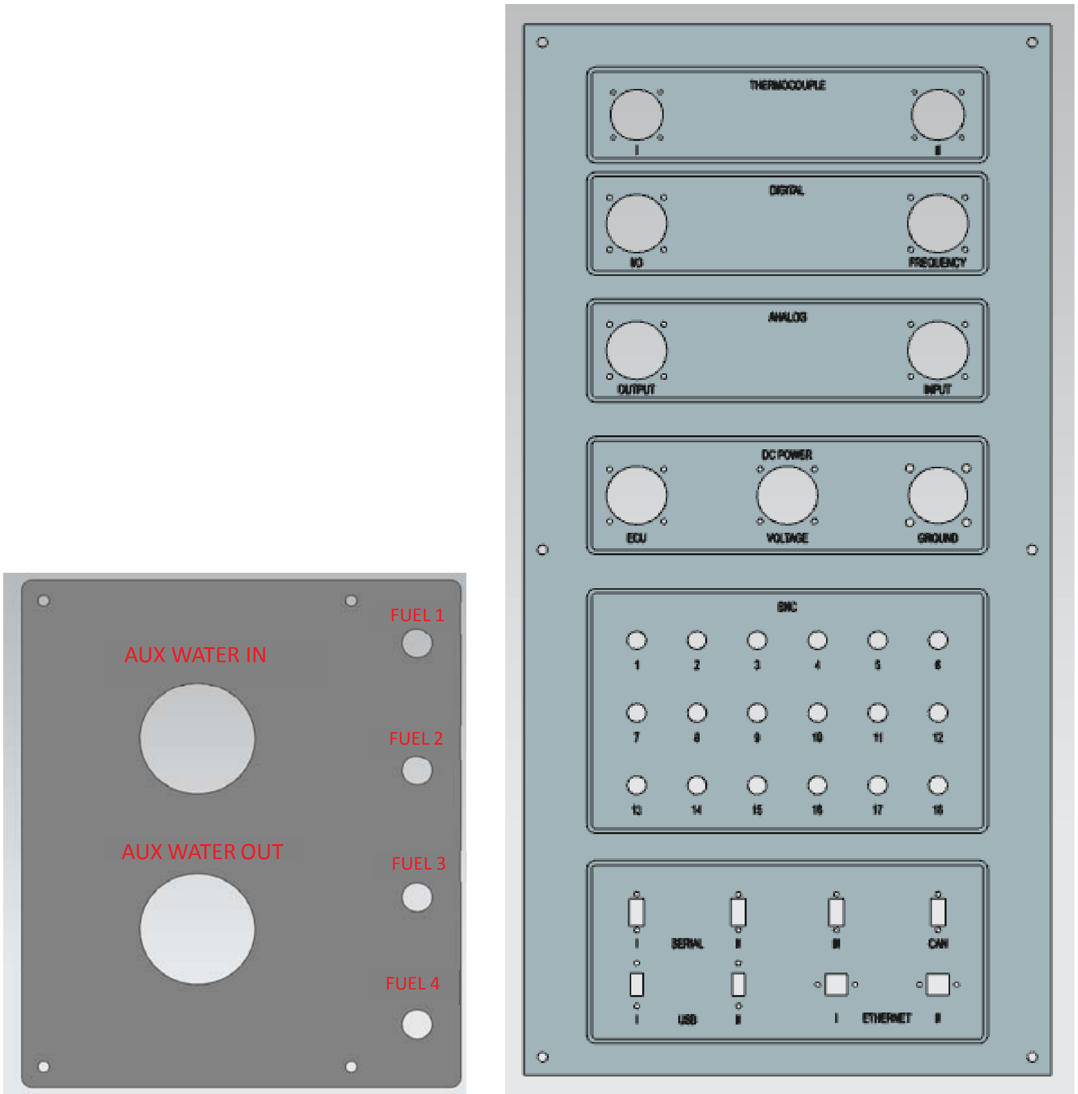

Figure 4-8: Interface Panel: Coolant and Fuel Line Panel (left); Connector Panel (Right)

The coolant and fuel panel includes coolant inlet, outlet and four fuel line connectors. The connector panel is designed to have spare holes for additional connectors. The connector panel is separated into six sections including two thermocouple connectors, two digital input or output connectors, two analog connectors, three DC power connectors, 18 BNC connectors and one section for USB and Ethernet connectors. These two panels are mounted separately on different sides of the universal cart through 80/20 frame. Figure 4-9 shows the machined panels with connectors on it, which shows the connectors being used for current setup. The connectors could be easily changed based on the test requirement for future research. The detailed dimensions CAD drawings of these two panels are attached in APPENDIX 3 and 4. Moreover, the detail connections are listed as follows including thermocouple connection, analog connection and ECU power supply.

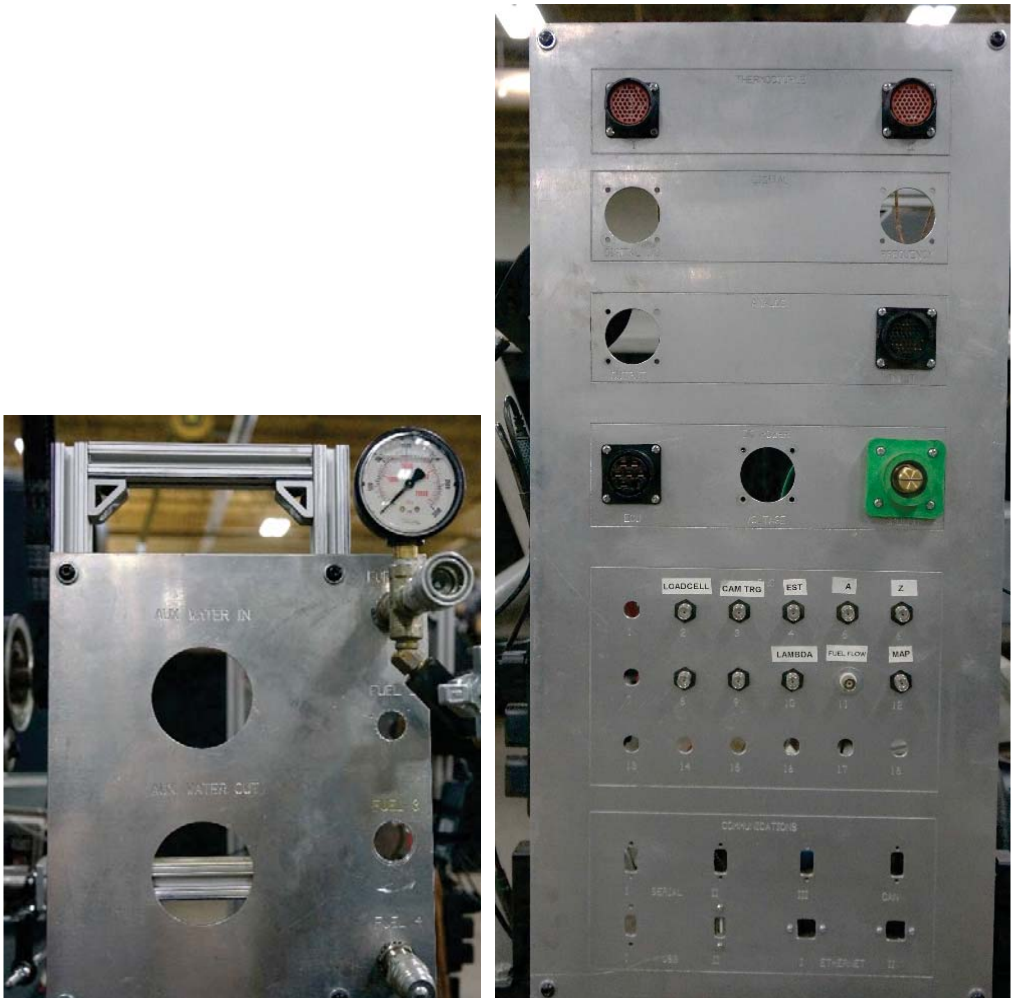

Figure 4-9: Machined Interface Panels: (1) Coolant and Fuel Line Panel (left); (2) Connector Panel (Right)

4.2.2.1 Thermocouple Connection

There are two thermocouple connectors mounted on the interface panel, which are the 55-pin female flange thermocouple connectors. These connectors are shown in Figure 4-10. Pin socket number one is located in the center of the connector, and the last pin socket is located on the outside boundary of the connectors, counting counterclockwise.

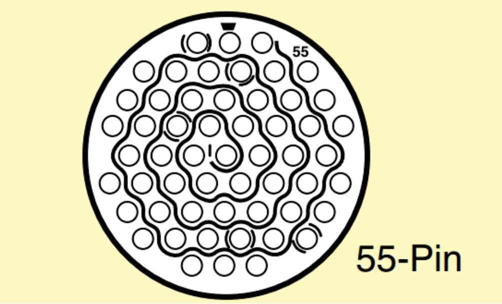

Figure 4-10 : Omega MTC-55-FF Series 55-Pin Thermocouple Connectors

For optical engine setup, not all the pins in the connectors are used. The pin connections are chosen based on the optical engine research requirements. The thermocouples' connections are listed in

Table 4-2, taking the left side connector mounting on the panel as the connector No.1, the other as No.2. K type thermocouples are used for whole setup in the research. For normal K-type thermocouples, the red wire is made of nickel-aluminum, which is the negative terminal (-). The yellow wire is made of nickel-chromium, which is the positive terminal (+). The detail components for the connectors are listed in **APPENDIX 5**.

Table 4-2: MTC 55-Pin Thermocouple Wire Connections

Connector No.1		
Socket No.	**Thermocouple Wire**	**Description**
5	K Type Red (-)	Oil In Temperature
6	K Type Yellow (+)	
7	K Type Red (-)	Oil Out Temperature
8	K Type Yellow (+)	
29	K Type Red (-)	Intake Temperature
30	K Type Yellow (+)	
33	K Type Red (-)	Exhaust Temperature
34	K Type Yellow (+)	
Connector No.2		
29	K Type Red (-)	Cylinder Liner Temperature
30	K Type Yellow (+)	

4.2.2.2 Analog Connection

A 63 pin amp series 2 flange receptacle shown in Figure 4-11 is mounted on the interface panel connecting the engine sensors to the data acquisition system. The first socket starts from the left side of the first row as shown in Figure 4-11.

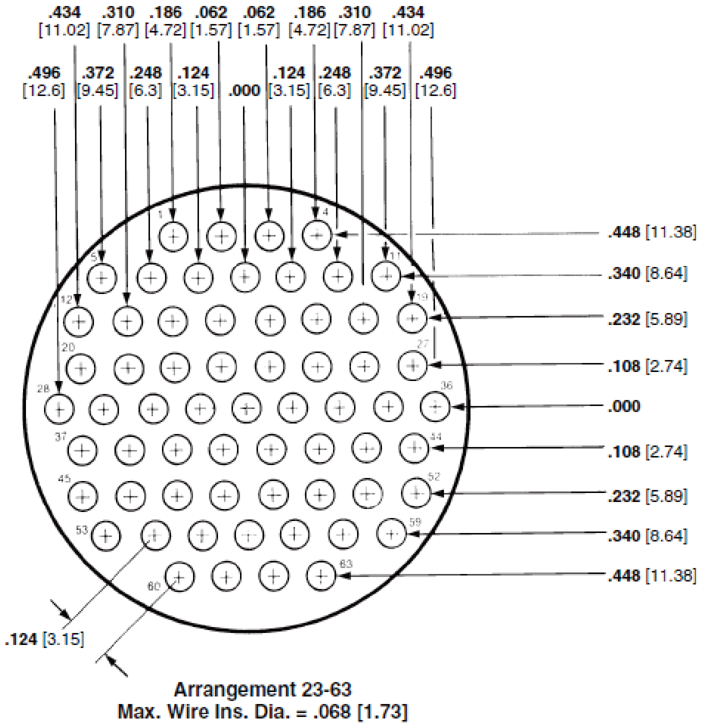

Figure 4-11: 63 pin AMP Series 2 STD Flange Receptacle

Table 4-3: Analog Wire Connections to NI DAQ

Socket No.	Wire Color and Polarity	Description
7	White Wire (+)	Omega PX209-030A MAP sensor
8	Black Wire (-)	
44	Green Wire (+)	Left Bank Lambda Sensor
45	Black Wire (-)	
46	Red Wire (+)	Fuel Flow (g/s) Meter
47	White Wire (-)	
54	Yellow Wire (+)	GP50 211D Oil Pressure Sensor
55	Black Wire (-)	
58	Orange Wire (+)	Optical Deck Hydraulic Pressure
59	Black Wire (-)	

For current setup, there are five sensors connected, including an Omega PX209-030A5V manifold absolute pressure (MAP) sensor, a lambda sensor, a fuel flow meter sensor, a GP50 211D oil pressure sensor and an optical deck hydraulic sensor. More sensors may be needed depending on future research. The pin connections are listed in Table 4-3. The MAP sensor installed on the engine here is the sensor in Figure 4-12.

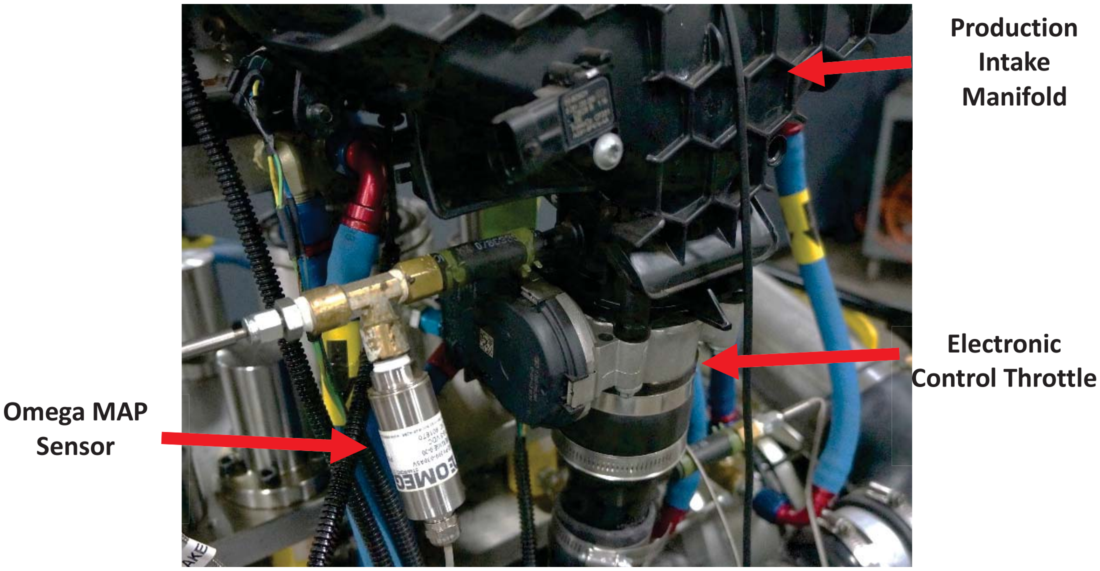

Figure 4-12: Omega PX209-030A5V Manifold Absolute Pressure (MAP) Sensor Position

4.2.2.3 Engine Control Unit (ECU) Power Supply

The ECU is powered by a 14 V power supply from the data acquisition system. A seven-pin amp series 3 reverse flange receptacle on the interface panel is used to connect the ECU to the DAQ system shown in Figure 4-13. The specified socket connections of this connector are listed in Table 4-4.

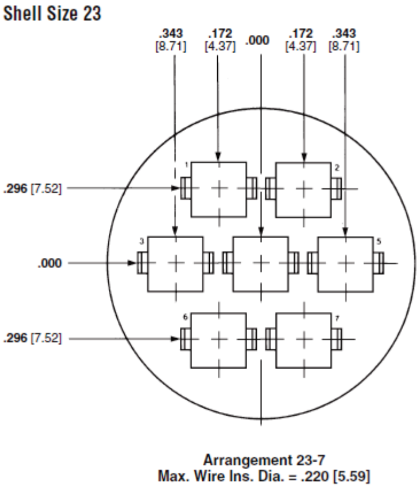

Figure 4-13: Circular Plastic Connectors Series 3 7-Pin

In Table 4-4, both clean 14V and dirty 14V are from the DAQ power supply system. The difference between them is that the clean 14V is more noise resistive and used to power the sensors sensitive to the noise. The dirty 14V connects to the components which are more noise tolerant such as the power for the GDI injector and ignition coils. “GND” represents the ground connections.

Table 4-4: ECU Power Connection

Socket No.	Description
1	ECU Battery
2	ECU Key Switch
3	Clean 14V
4	Lambda Sensor Power (Dirty 14V)
5	Dirty 14V Power
6	GND
7	GND

4.2.3 Oil Circulation System

The engine oil system for the optical engine is similar to the production engine, which provides a thin film of oil lubricating and removing heat from the engine moving parts. Beside this purpose, the engine oil in the optical engine is also used to heat up the piston liner shown in Figure 4-3. The engine oil system consists of an electronic pump to pressurize the engine oil to circulate around the engine. In addition, an oil heater is also connected downstream to the oil pump to maintain the oil temperature around 45°C. These two components are mounted on a metal plate which is secured on the universal cart as shown in Figure 4-14. The simplified block diagram is shown in Figure 4-15.

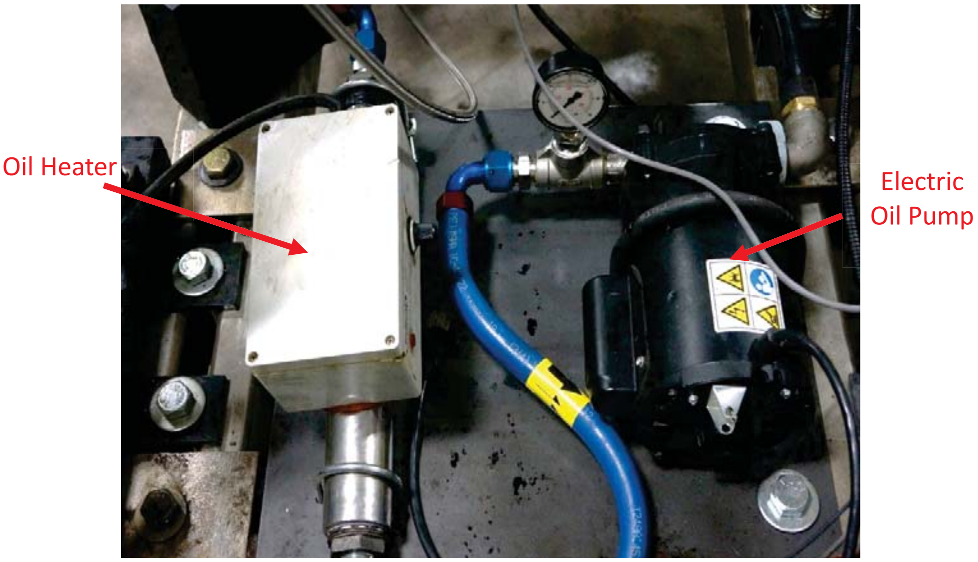

Figure 4-14: Oil Heater and Pump Mounted on Universal Cart

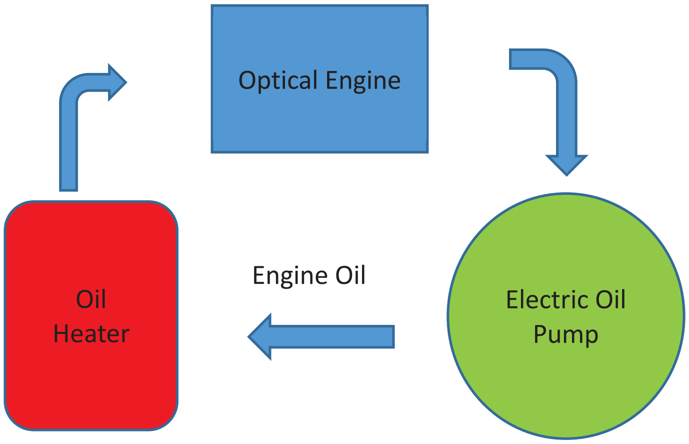

Figure 4-15: Block Diagram of Engine Oil System

4.3 Engine Control Unit (ECU) and Wiring

Since the optical engine is customized based on the Ford Ecoboost 2.0L spark ignited direct injection engine, the production engine control unit from Ford could not satisfy the control requirement for the optical engine. Therefore, MotoHawk ECM-5554-112-0904-C/F 112-pin engine control unit is chosen to meet control requirements for the optical engine. This module can support up to 33 analog input channels, 8 high impedance injector output signals and 8 Electric Spark Trigger (EST) output signals[7].

For the optical engine, throttle control, ignition control, speed limiter control, skip fire control and trigger signal for optical synchronization are carried out through this MotoHawk engine control unit. For skip firing control strategy, the engine does not fire continually, and it has only specified cycle combusted during the testing operation. In addition, the fuel injection of the optical engine is controlled through an individual driver, which is a Bosch ES-HDEV-1 GDI driver. These two components are shown in Figure 4-16. The detail information of the MotoHawk ECM and Bosch fuel injector is attached in **APPENDIX 6**.

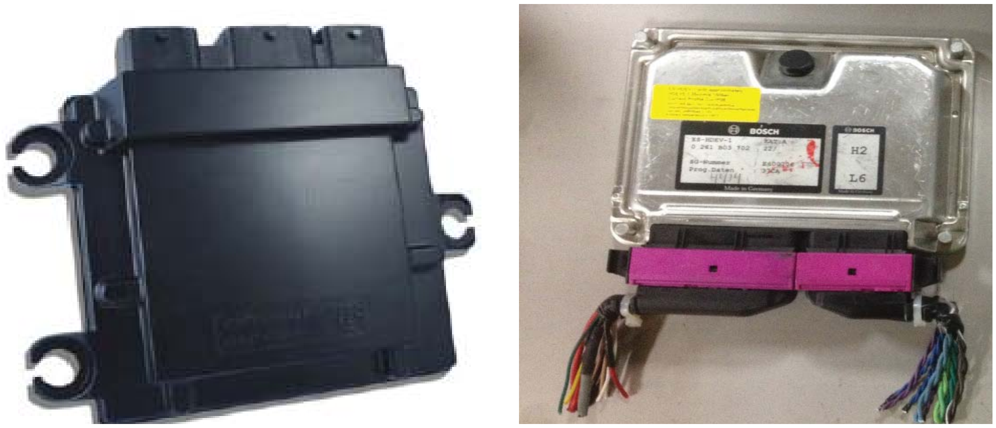

Figure 4-16: MotoHawk ECM 0554 (Left) and Bosch ES-HDEV-1 Fuel Injector Driver (Right)

Since the ECU harness is purchased with the MotoHawk ECU, which is independent of the optical engine harness. To connect both of them, a Hoffman A24N24ALP 24" x 24" x

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[7] Woodward Datasheet 36350, MotoHawk Control Solution ECM-5554-112-0904-C/F

6.62" Medium Type NEMA 1 enclosure is installed on one side of the universal cart as shown in Figure 4-17.

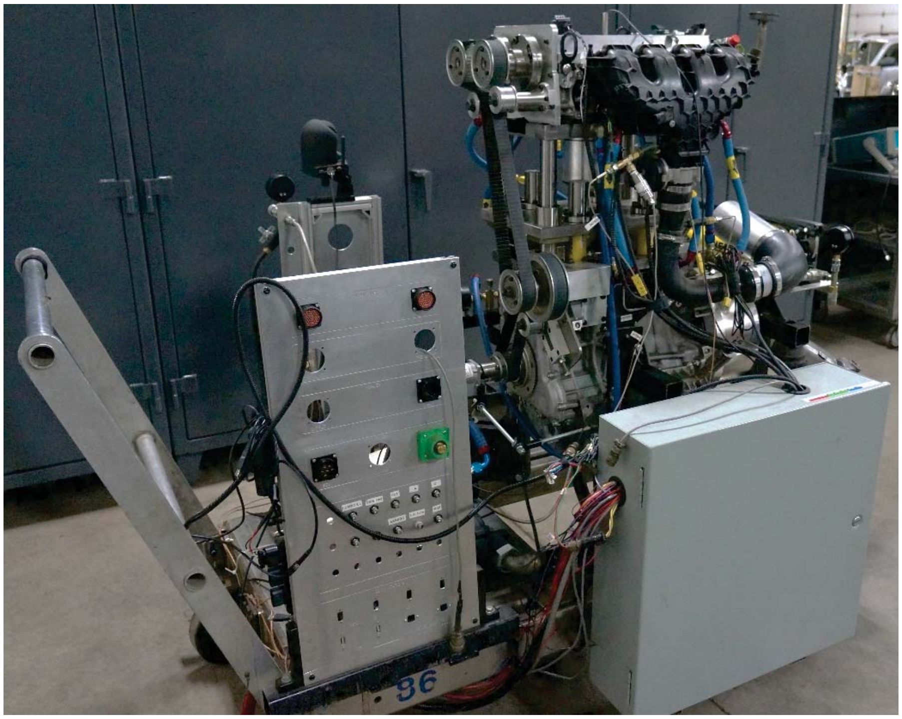


Figure 4-17: Enclosure Mount on One Side of Universal Cart

Inside the enclosure, ECU, din rails and terminal blocks are mounted on the panel. In Figure Figure 4-18, two din rails are mounted on the enclosure panel. On the left side of each din rail, the terminals are connected to the harness from the MotoHawk ECU. On the right side, the din rail terminals are connected to the optical engine harness. The ECU is connected with the optical engine. The detail of the ECU harness is on the harness manual from MotoHawk. For current setup, not all harnesses from ECU are useful and connected with the optical engine. The connected wires are listed in Table 4-5 which shows the current connection inside the enclosure. In Table 4-5, the optical engine harness connections are almost the same as the ECU harness except for some analog input signals such as an acceleration paddle, a MAP sensor, a fuel rail pressure, a Universal Exhaust Gas Oxygen (UEGO) sensor and an Electronic Control Throttle (ECT) components signals. Based on the research requirements, additional sensor wirings could be added to the ECU's default harness. The wire colors listed in Table 4-5 provide a reference for checking harness connections.

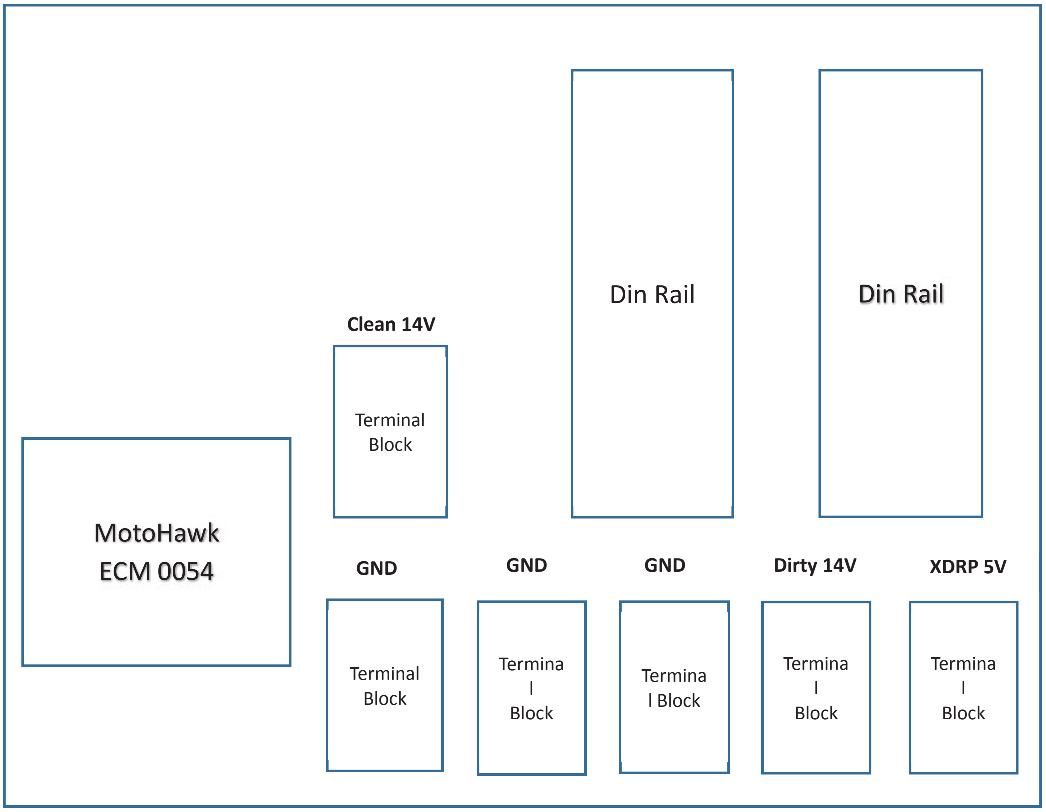


Figure 4-18: ECU Enclosure inside Components Block Diagram

Besides the din rails, six terminal blocks are also mounted on the panel of the enclosure. Their functions are similar to din rails, providing connections between the ECU, the optical engine and the interface panel connects. For a single block, all the terminals are actually connected with each other through a jumper panel. Half of the six blocks are used as power supplies for driving sensor including clean 14V, dirty 14V and XDRP 5V. “XDRP” is a 5V sensor power source provided by the ECU. The other three blocks are ground (GND) connectors. The dirty and clean 14V are from the data acquisition system. All these GND blocks connect to the test cell ground through the interface panel ground connectors (Joy Cooper Interconnect E1018-1704). The detail connections of these terminal blocks are in Table 4-6. The main components of the ECU instrumentation are attached in **APPENDIX** 7.

Table 4-5: Harness Connections between MotoHawk ECU and Optical Engine

ECU Harness					Din Rail			Optical Engine Harness			
No.	Detail Description	Wire Color						Wire Color			Description
1	Electronic Spark Timing 4	YEL	🟨	🟨	O	1	O	🟥	🟥	RED	Camera Trigger Signal
2	Electronic Spark Timing 3	YEL-ORG	🟨	🟧	O	2	O	🟪	🟪	PPL	Electronic Spark Timing (EST) 1
3	Electronic Spark Timing 2	YEL-RED	🟨	🟥	O	3	O	🟦	🟦	BLU	Coil 2
4	Electronic Spark Timing 1	YEL-PNK	🟨	🟪	O	4	O	⬜	🟪	WHT-PPL	Coil 1
20	Low Side Output 10	BRN-BLK	🟫	⬛	O	12	O	⬛	⬛	BLK	High Pressure Fuel Pump(HPFP) Solenoid Low Side Driver
27	Fuel Injector 3	GRN-ORG	🟩	🟧	O	17	O	⬜	⬜	WHT	Injector 3 Low Sider Driver Signal (Not In Use)
28	Fuel Injector 3	GRN-YEL	🟩	🟨	O	18	O	🟨	🟨	YEL	Injector 4 Low Sider Driver Signal (Not In Use)
29	Fuel Injector 1	GRN-BRN	🟩	🟫	O	19	O	🟫	🟫	BRN	Injector 1 Low Sider Driver Signal
30	Fuel Injector 2	GRN-RED	🟩	🟥	O	20	O	⬜	⬜	WHT	Injector 2 Low Sider Driver Signal (Not In Use)
51	Analog Input 1	BRN	🟫	🟫	O	29	O	🟥	🟥	RED	Acceleration Pedal Analog Signal
53	Analog Input 2	RED	🟥	🟥	O	30	O	🟧	🟦	ORG-BLU	Manifold Absolut Pressure(MAP) Sensor Signal
64	Crankshaft Sensor	WHT-BRN	⬜	🟫	O	37	O	🟦	🟦	BLU	Crankshaft Position Sensor Digital, Open Drain Strong Pull-up
76	EST Return	BLK-YEL	⬛	🟨	O	49	O	⬛	⬛	BLK	Electronic Spark Timing (EST) Return Signal
83	Analog Input 15	WHT-GRN	⬜	🟩	O	56	O	🟦	🟦	BLU	Fuel Rail Pressure Sensor
91	Analog Input 4	YEL	🟨	🟨	O	63	O	🟨	🟨	YEL	Universal Exhaust Gas Oxygen (UEGO) to NI DAQ system
			⬜	⬜			O	🟥	🟥	RED	Universal Exhaust Gas Oxygen (UEGO) to ACAP system
102	Analog Input 47	PPL	🟪	🟪	O	69	O	🟩	🟧	GRN-ORG	Throttle Position 2 Signal
108	H-Bridge Output 1	BLK-TAN	⬛	⬜	O	70	O	🟨	🟪	YEL-PPL	TACM+ (ECT Motor+) Electronic Control Throttle
112	H-Bridge Output 1	TAN-BLK	⬜	⬛	O	73	O	🟩	🟦	GRN-BLU	TACM- (ECT Motor-) Electronic Control Throttle

Table 4-6: Terminal Block Connections between MotoHawk ECU and Optical Engine

Clean 14 V			
Description	**Wire Color**		
Test Cell 14 V	RED	🟥	🟥
Encoder Power	RED	🟥	🟥
GP50 Power	RED	🟥	🟥
MAP Power	RED	🟥	🟥
GP50 Power	RED	🟥	🟥

Dirty 14V			
Description	**Wire Color**		
Ignition Power	RED	🟥	🟥
HPFP Power	RED	🟥	🟥
Coil 1 Power	PPL	🟪	🟪
Bosch GDI Driver Power	RED	🟥	🟥

XDRP 5V			
Description	**Wire Color**		
FP Sensor Power	GRN-RED	🟩	🟥
CRK REF	GRN-PPL	🟩	🟪
GDI Driver on	RED	🟥	🟥
ETC REF	YEL	🟨	🟨
XDRP 5V	PPL-YEL	🟪	🟨

GND			
Description	**Wire Color**		
GND bar	BLK	⬛	⬛
ECU GND	BLK	⬛	⬛
Encoder GND	BLK	⬛	⬛
Enclosure GND	BLK	⬛	⬛
LC1 GND	MIX	⬜	⬜
Lambda GND	BLK	⬛	⬛

GND			
Description	**Wire Color**		
GND bar	BLK	⬛	⬛
GP50 GND	BLK	⬛	⬛
Throttle Paddle GND	BLK	⬛	⬛
GP50 GND	BLK	⬛	⬛
PX209 GND	BLK	⬛	⬛

GND			
Description	**Wire Color**		
GND bar	BLK	⬛	⬛
Coil1 GND	BLK-RED	⬛	🟥
FP GND	GRN-YEL	🟩	🟨
XDRG	PPL-PNK	🟪	🟪
CNK GND	GRN-WHT	🟩	⬜
EST RTN	BLK	⬛	⬛
ETC GND	PNK-BLU	🟪	🟦

CHAPTER 5Experiment

5.1 Experiment: Motoring and Firing Cycle

After all the setup from previous chapters, the basic experiment on the optical engine has been performed. To obtain clean optics results from the optical engine, the engine is designed not to have any oil lubrication for the piston and rings. Instead of regular piston rings, the optical engine uses Torlon® PAI (polyamide-imide) piston rings because of their wear resistance and high strength for the thermal load. Even with these special piston rings, the engine could only operate under low load and run with a skip fire strategy due to the life cycle of the optical engine. Compared with a regular production engine continual fire strategy, the optical engine is controlled to fire at serval cycles and then motor for several cycles. One of the test results is used as an example here. The test condition is listed in Table 5-1. The manifold absolute pressure (MAP) is set as 33.5 kPa, which is a light load condition compared with the MAP under full open throttle condition. SA is the spark angle, and SOI is the start of injection, which is controlled by the ECU. FP is fuel pressure measured at the high-pressure fuel pump. In this test, the skip fire ratio is set as 10:15, which has 10 firing cycles and 15 motoring cycles. With the motoring cycle, the heat could dissipate out of the firing cycle to reduce the thermal load on the piston. The skip fire ratio could be adjusted through ECU.

With the gross indicated mean effective pressure (IMEPg) versus number of cycles in Figure 5-1, the skip fire strategy could be well observed. When the engine is firing, the IMEPg is around 150 kPa. Otherwise, the IMEPg is approximately stable at -25 kPa when the engine is motoring. Each dot on Figure 5-1 represents one cycle of the engine, during which the crankshaft rotates 720 degree. For this test, there are 4 firing groups, total 100 cycles. The last five combustion cycles of each group are recorded for later parameter calculations as shown in Figure 5-1 dash lines area. The purpose of recording the last five cycles is to reduce the motoring cycle effect on the combustion cycle.

Table 5-1: Test Condition for the Optical Engine

Test Date	2015-03-09
MAP (kPa)	33.5
Speed (rpm)	1000
Spark Angle (SA) (dBTDC)	29
Dwell Time (ms)	1.5
Start of Injection (SOI) (dBTDC)	330
Fuel Pressure (FP) (MPa)	9.5
Skip Fire Ratio	10:15
Lambda	1.07

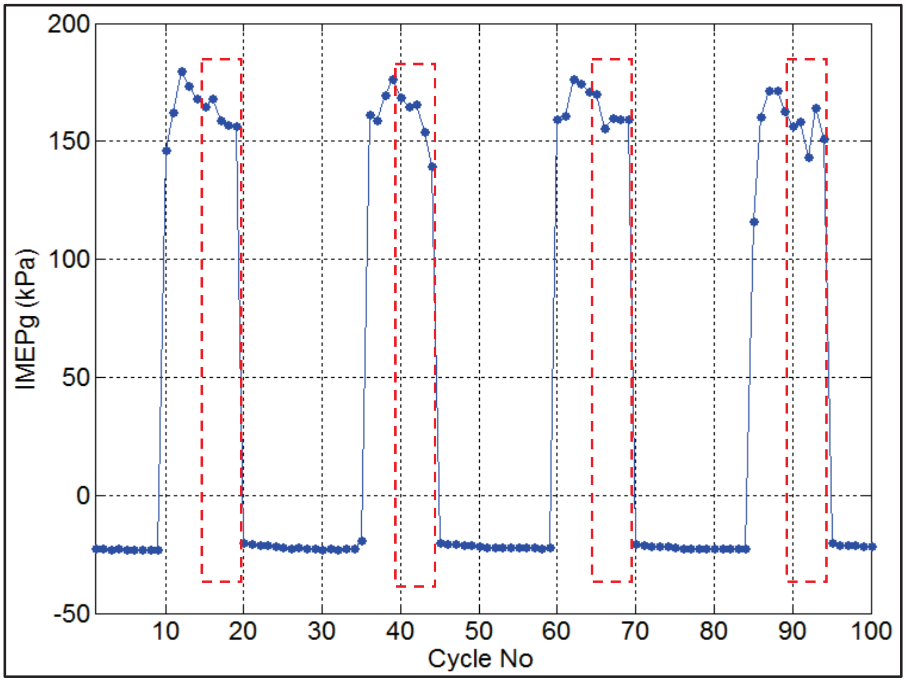


Figure 5-1: Optical Engine Skip Firing

During the test, the pressure trace of the optical engine could be monitored through the ACAP real time combustion analysis system. One motoring cycle and one firing cycle data from Figure 5-1 are used as an example. The pressure traces of these two cycles are displayed in Figure 5-2 and Figure 5-3. The engine reaches its peak pressure when the piston reaches its top dead center where crank angle is zero degree during the motoring cycle as shown in Figure 5-2.

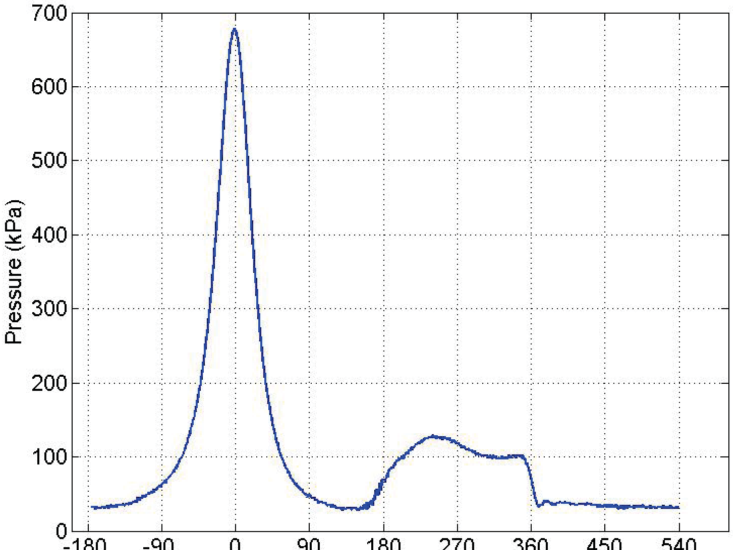


Figure 5-2: Optical Engine Pressure Trace for Motoring Cycle

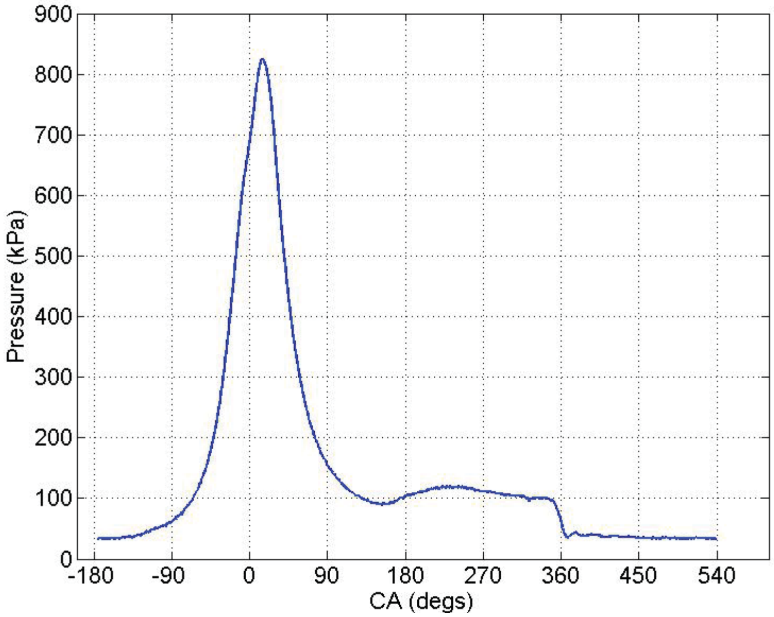


Figure 5-4: Optical Engine Pressure Trace for Firing Cycle

For the firing cycle, the spark timing is controlled, and the peak pressure is offset from the top dead center as shown in Figure 5-4. Through the data collected by the ACAP system, the Log P versus Log V diagram can be plotted as shown in Figure 5-3, which is used to check the quality of the cylinder pressure data. P is the in-cylinder pressure and V is the cylinder volume at any crank position.

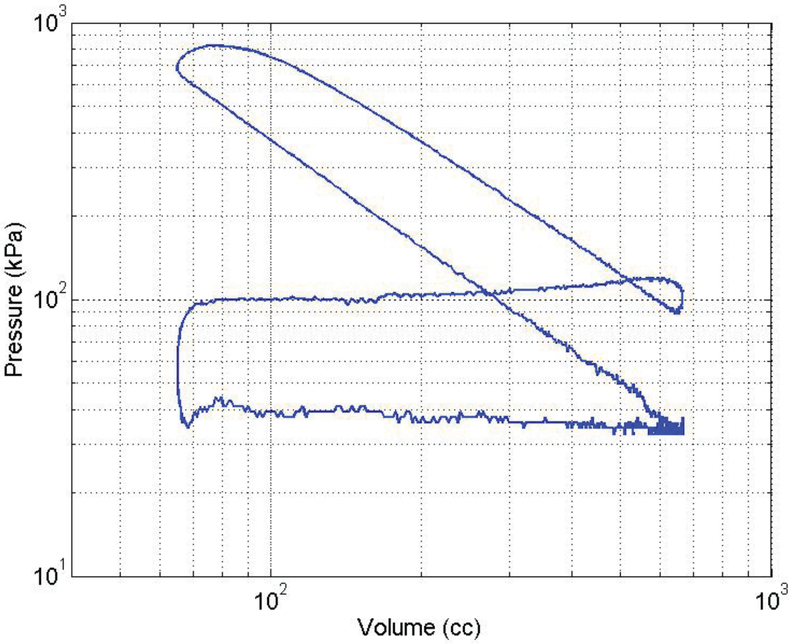


Figure 5-3: Optical Engine Log P-log V at Firing Cycle

5.2 Optical Instrumentation

The advantage of the optical engine is the visualization of the combustion chamber through the optical window. The current research under sponsorship by Ford Motor Company is to study the gasoline engine ignition system. The optical instrument setup is displayed in Figure 5-5. A LaVision Ultra Speed Star 16 high-speed camera is used for the test in Figure 5-5. The camera for the ignition research has not been decided yet. Different cameras will be examined by engine tests to achieve better images. The camera bridge shown in Figure 5-5 is supported by 2 tripods located outside the test cell bed to avoid vibration effect. A metal plate with holes to mount the high speed camera is clamped on the surface of the camera bridge. A Nikon 200mm lens is used in this test. With manual focus and aperture f4, the camera could focus on the area around the spark plug. The aperture f4 could be reduced for wider depth of field. The test condition is shown in Table 5-2.

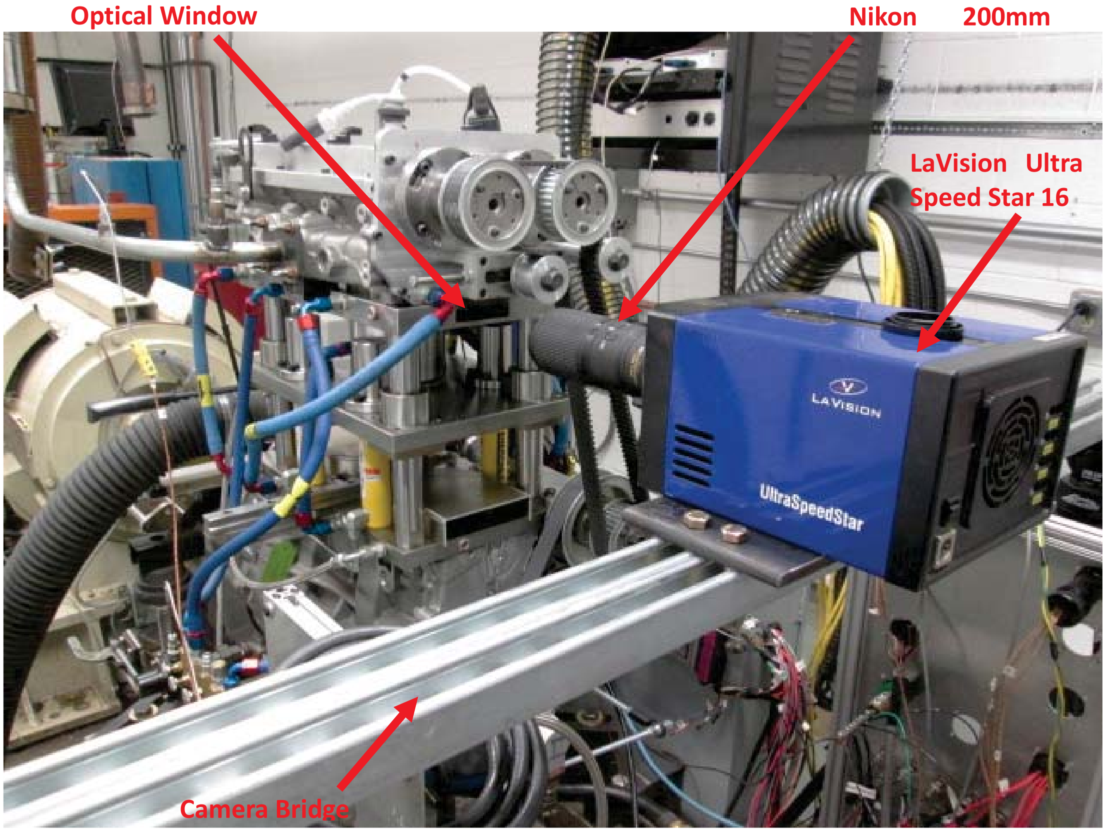


Figure 5-5: Optical Engine and Camera Setup

Table 5-2: Test Condition for the Optical Engine

Test Date	2015-02-19
MAP (kPa)	33
Speed (rpm)	1000
SA (dBTDC)	22
Dwell Time (ms)	1.5
Skip Fire Ratio	10:15

With MATLAB post processing, the post processed images captured by the LaVision Ultra Speed Star 16 is shown in Figure 5-6, which is just one engine cycle out of 20 combustion cycles. The frame rate and exposure time can be adjusted through the Ultra Speed Star software. Since the light sensitivity of this camera is low, the result is dark in Figure 5-6. The spark plug is visualized on the second row of the figure. The lens used in this test is a Nikon 200mm f4.0 D lens. The camera is set to capture an image every 1000 us, which is approximate to 6 crank angle degree with engine operating at1000rpm (167 us per crank angle). The exposure time is set by default through the software, which must be less than the time between two frames. Limited by the camera and lens, shortening the time between two frames to capture an image every crank angle leads to a darker image.

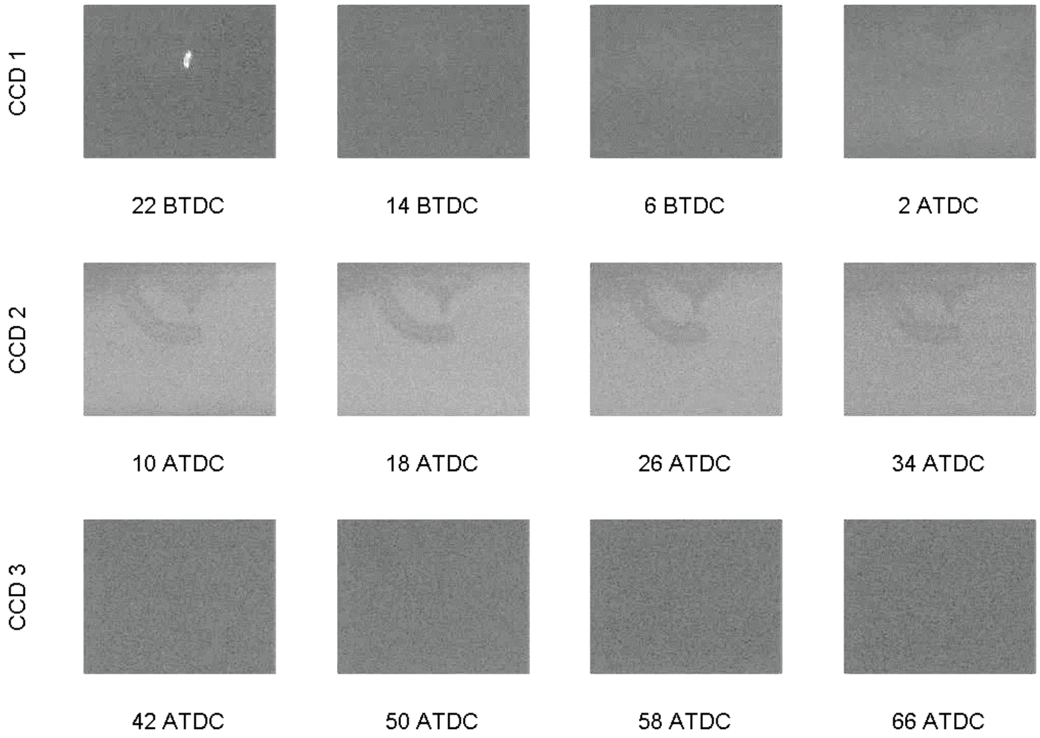


Figure 5-6: Optical Engine USS 16 Imaging Result with Nikon 200 Lens, 6 CA (1000 us) per Frame, F/4, Exp 975 us, Distance 2.75 ft

Besides the Ultra Speed Star 16 camera, a Canon 60D and Photron SA 1.1 high speed camera have been tried out to capture images for the optical engine under simila operation condition as shown in Figure 5-7. The images capture by Canon 60D covers almost one cycle, which could see the spark overlays with flame in Figure 5-7a because of the long exposure. The results recorded by Photron SA 1.1 is the best among these cameras since its ability to capture images for every crank angel degree. The white area in Figure 5-7b is the flame developed after ignition. The camera used for the optical engine research has not been decided yet. Different cameras will be used and compared to achieve best imaging results in the future.

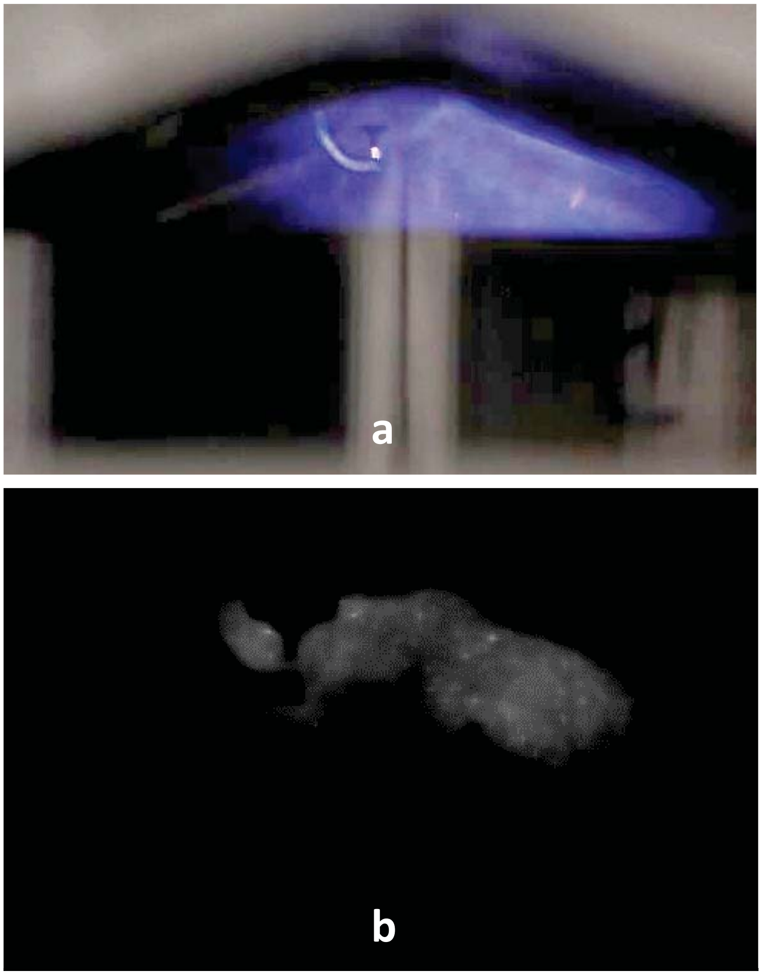


Figure 5-7: Optical Engine Image Results:

(a) Image Captured by Canon 60D DSLR f5.6, Exposure time 50000 us (300 CA), ISO 640, 33kPa MAP, 2ms Dwell Time;

(b) Image Captured by Photron SA 1.1, Nikon 85mm lens, f1.8, 12mm Extension Tube, Exposure time 100 us (1 CA), 33.5 kPa MAP, 1.5 ms Dwell Time

CHAPTER 6 Conclusion and Future Work

Above all, the optical access engine instrumentation is recorded in detail covering the test cell setup and optical engine setup, which serves as reference material for instrumentation update and experiment. Moreover, the experiment performed in CHAPTER 4 validates that the current optical engine setup operates normally and is prepared for optical instrument integration and engine research.

Future work on the optical engine is integrating the optical access engine with the diagnostic and optical measurement techniques and cooperating with Ford Motor Company in ignition research through the optical access engine. The future work is listed as follows.

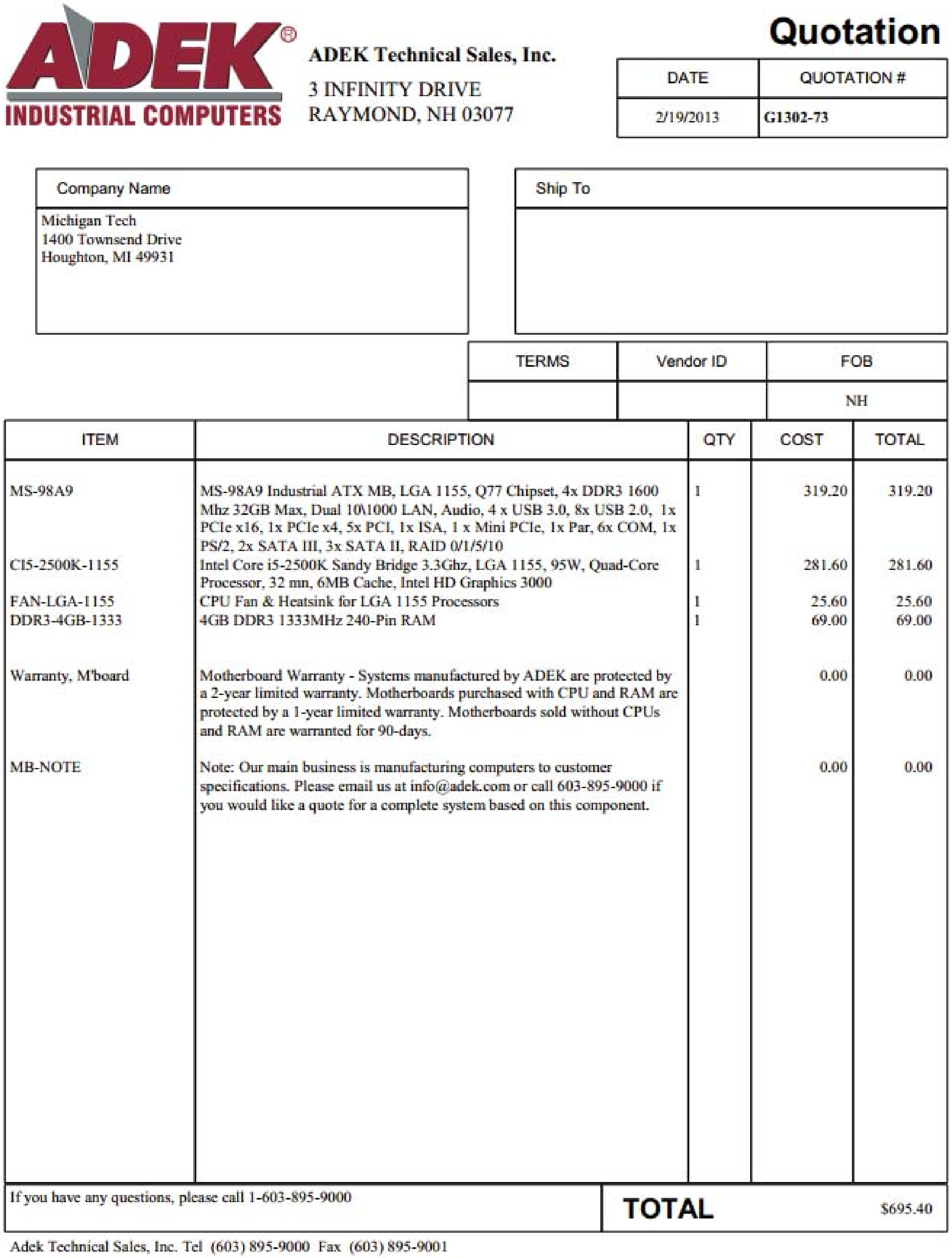
1. A high-speed camera will be chosen to have the ability to capture sharp images per crank angle degree while the optical engine operating under skip firing strategy.
2. Ignition research including spark plasma stretching and spark energy study on different spark plugs and ignition coils through optical access engine will be performed utilizing the diagnostic and optical measurement techniques
3. Particle image velocimetry (PIV) system will be instrumented to study flow condition inside the combustion chamber.

Reference

1. Lucchini, T., Fiocco, M., Onorati, A., Montanaro, A. et al., "Full-Cycle CFD Modeling of Air/Fuel Mixing Process in an Optically Accessible GDI Engine," SAE Int. J. Engines 6(3):1610-1625, 2013, doi:10.4271/2013-24-0024.
2. Gill, K. and Zhao, H., "In-cylinder Studies of Fuel Injection and Combustion from a Narrow Cone Fuel Injector in a High Speed Single Cylinder Optical Engine," SAE Technical Paper 2008-01-1789, 2008, doi:10.4271/2008-01-1789.
3. REDLINE ACAP, User Manual Version 4.0, DSP Technology Inc.
4. www. Ni. Com
5. 2013 Escape Workshop Manual Section 303-01B Engine-2.0L GTDI Specifications
6. MAHLE Powertrain 01735 DOE Optical Engine Specifications
7. Woodward Datasheet 36350, MotoHawk Control Solution ECM-5554-112-0904-C/F

APPENDIX

1. ADEK MS-98A9 Ivy Bridge Industrial ATX motherboard



ADEK Technical Sales, Inc.
3 INFINITY DRIVE
RAYMOND, NH 03077

Quotation

DATE	QUOTATION #
2/19/2013	G1302-73

Company Name
Michigan Tech 1400 Townsend Drive Houghton, MI 49931

Ship To

TERMS	Vendor ID	FOB
		NH

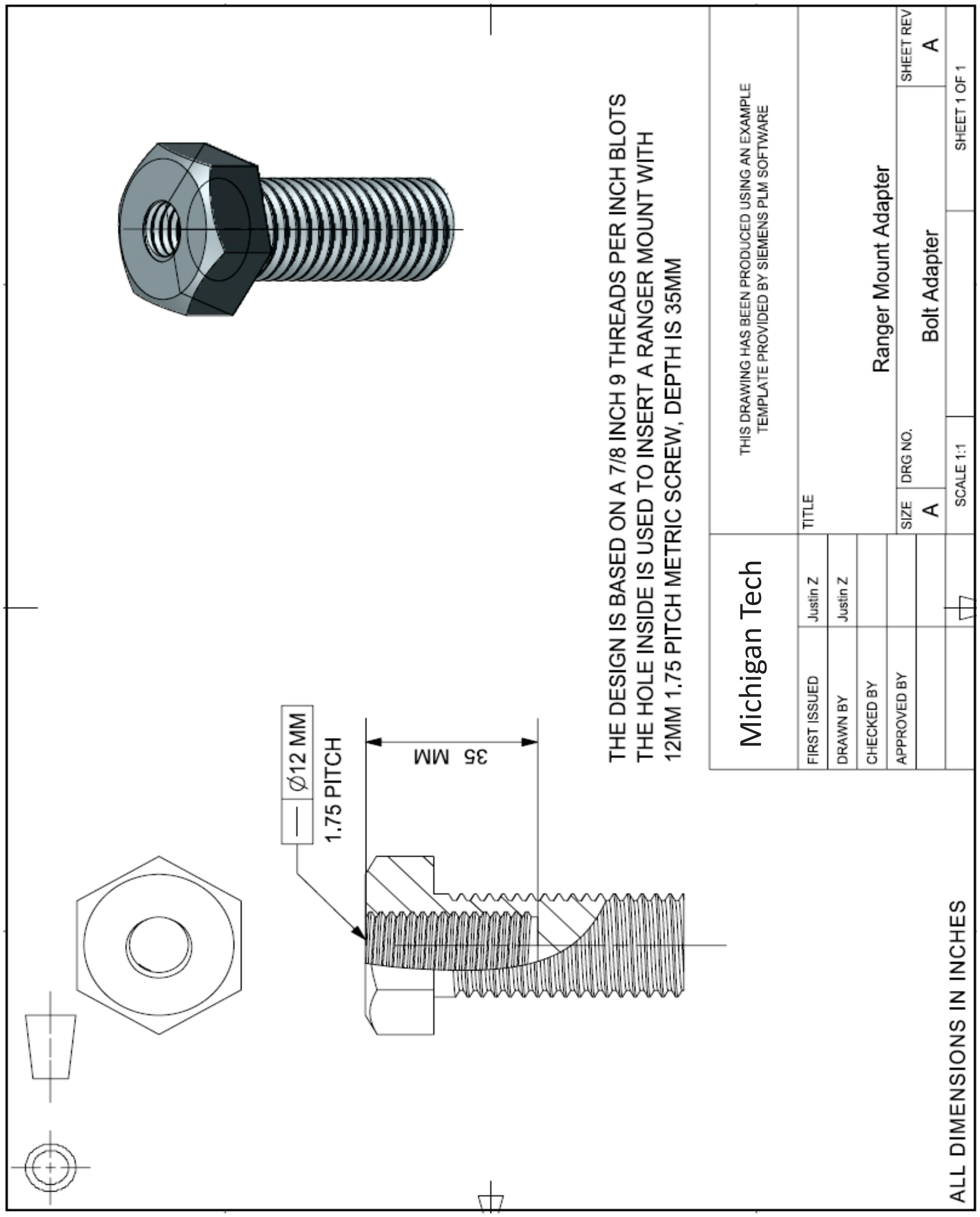
ITEM	DESCRIPTION	QTY	COST	TOTAL
MS-98A9	MS-98A9 Industrial ATX MB, LGA 1155, Q77 Chipset, 4x DDR3 1600 Mhz 32GB Max, Dual 10\1000 LAN, Audio, 4 x USB 3.0, 8x USB 2.0, 1x PCIe x16, 1x PCIe x4, 5x PCI, 1x ISA, 1 x Mini PCIe, 1x Par, 6x COM, 1x PS/2, 2x SATA III, 3x SATA II, RAID 0/1/5/10	1	319.20	319.20
CI5-2500K-1155	Intel Core i5-2500K Sandy Bridge 3.3Ghz, LGA 1155, 95W, Quad-Core Processor, 32 mn, 6MB Cache, Intel HD Graphics 3000	1	281.60	281.60
FAN-LGA-1155	CPU Fan & Heatsink for LGA 1155 Processors	1	25.60	25.60
DDR3-4GB-1333	4GB DDR3 1333MHz 240-Pin RAM	1	69.00	69.00
Warranty, M'board	Motherboard Warranty - Systems manufactured by ADEK are protected by a 2-year limited warranty. Motherboards purchased with CPU and RAM are protected by a 1-year limited warranty. Motherboards sold without CPUs and RAM are warranted for 90-days.		0.00	0.00
MB-NOTE	Note: Our main business is manufacturing computers to customer specifications. Please email us at info@adek.com or call 603-895-9000 if you would like a quote for a complete system based on this component.		0.00	0.00

If you have any questions, please call 1-603-895-9000

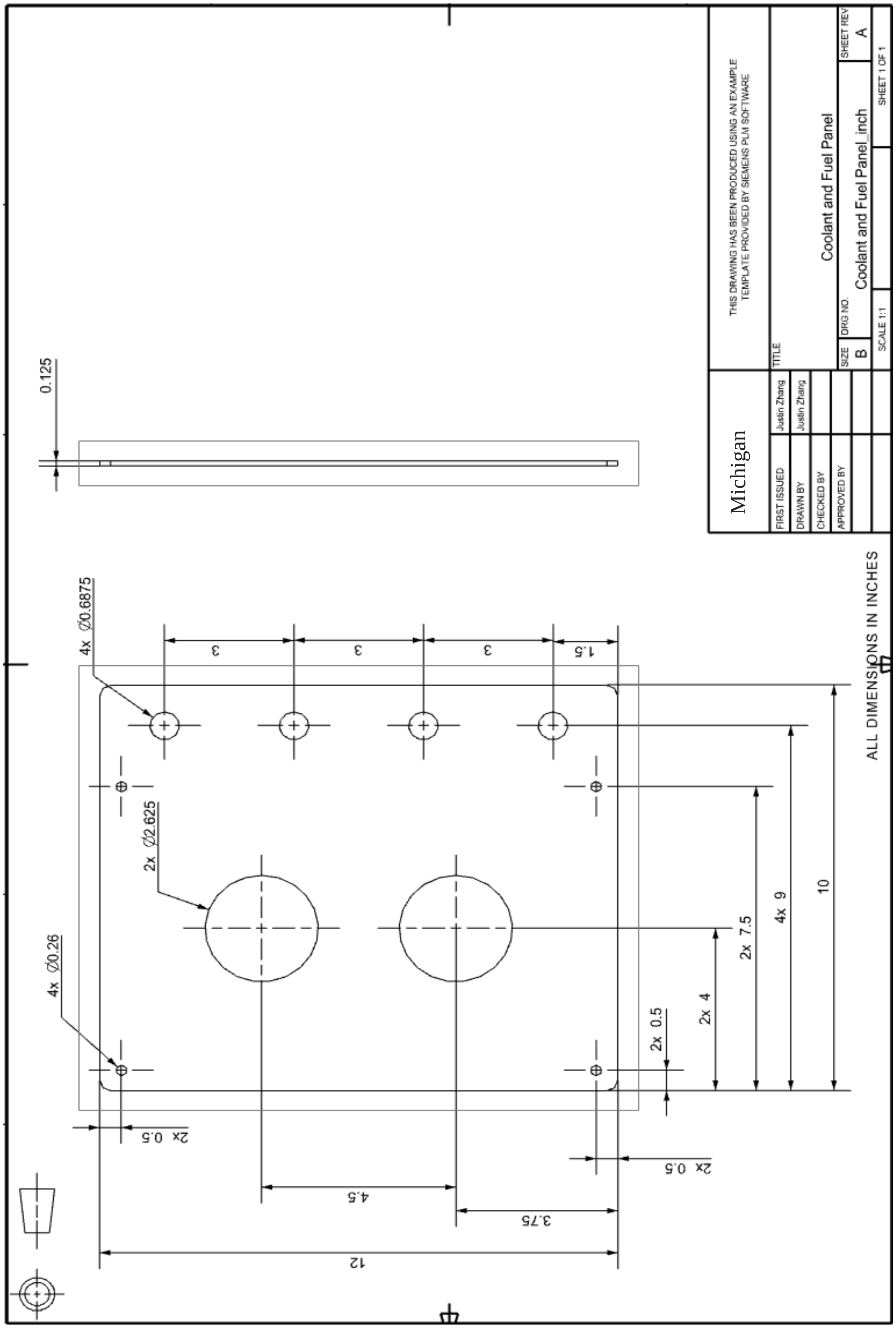
TOTAL $695.40

Adek Technical Sales, Inc. Tel (603) 895-9000 Fax (603) 895-9001

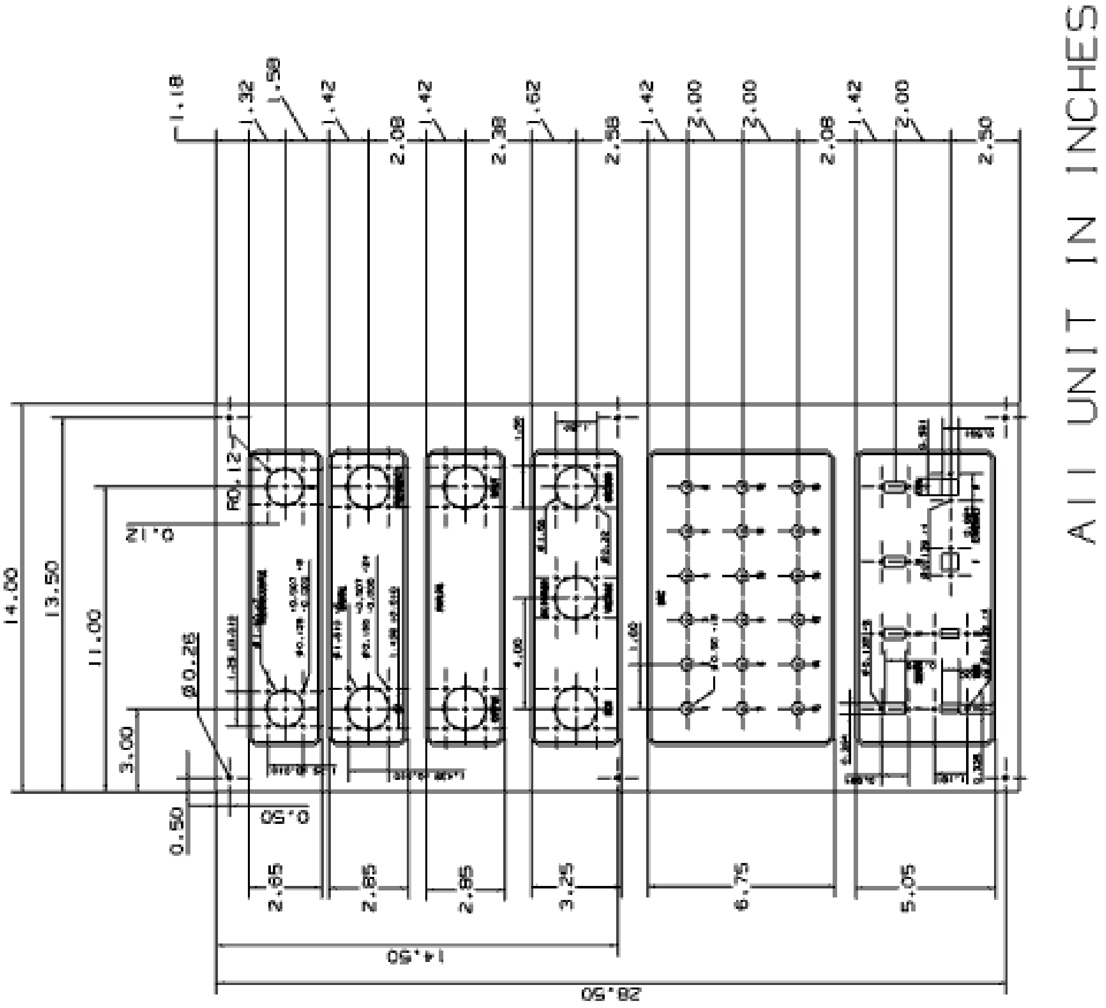
2. Engine Mount Components Drawing – Screw Jack Adapter



3. Coolant and Fuel Panel



4. Connector Panel



5. Cart Interface Components.

Item	Supplier	Vendor's P/N	QTY	Description
Thermocouple Connectors				
Type K TC Connector	Omega	MTC-55-FF	2	55 Pin Female Flanged TC Connector
Type K TC Pin	Omega	HPC-CH-S	3	Female Chromel Pin 20pk (+),WHT P
Type K TC Pin	Omega	HPC-AL-S	3	Female Alumel Pin 20pk (-),GRN R
Type K TC Backshell	Ebay	MTC-55-SHL	2	Thermocouple Male Backshell cable clamp 55 cavities
Analog Connectors				
Analog In	Newark	46F1137	1	63 pin AMP Series 2 STD Flange Receptacle
Analog In	Newark	46F1117	1	Series 2 Multimate Gold Pins (28-24 AWG) 100 pk
ECU Power Connectors				
ECU Power	Newark	46F1151	1	7 Pin AMP Series 3 Reverse Flange Receptacle
ECU Power	Newark	90F7240	14	Series 3 Type XII Gold Power Sockets (16-12 AWG)
80/20 Frame				
80/20 Frame Accessories	McMaster	47065T101	2	80/20 Aluminum T-Slotted Framing Four-Slot Single, 1" Solid Extrusion, 10ft
80/21 Frame Accessories	McMaster	47065T216	12	90 Degree Brace, Single, 2 Hole, for 1" Extrusion
80/22 Frame Accessories	McMaster	47065T139	20	90 Degree Brace Required Fasteners
80/23 Frame Accessories	McMaster	47065T65	4	Floor-Mounting Brackets Single, 2-Hole, for 1" Extrusion
80/24 Frame Accessories	McMaster	47065T142	3	Floor-Mounting Brackets Required Fasteners
10 series 80/20	Price Engineering	1010	20	10 series 80/20 (in feet)
80/24 Frame Accessories	Price Engineering	4132	10	2-hole gusset corner
80/25 Frame Accessories	Price Engineering	3393	60	1/2" slide in T-nuts
80/26 Frame Accessories	Price Engineering	3321	15	slide in T-nuts for 1/4" plate
80/27 Frame Accessories	Price Engineering	4107	3	2-hole joining strip
80/28 Frame Accessories	Price Engineering	14000	4	Floor Mounting Brackets

6. MotoHawk ECM (from Datasheet 36350)

WOODWARD

Datasheet
36350

MotoHawk Control Solutions

ECM-0554-112-0904-C/F

Engine Control Modules
Calibratible / Flash

(0904-C: 1751-6455)
(0904-F: 1751-6454)

Description

Presenting the ECM-5554-112-0904-C/F engine control modules from Woodward's MotoHawk Control Solutions product line. These rugged controllers are capable of operating in harsh automotive, marine, and off-highway applications. The module and its connector system are environmentally sealed and suitable for engine mounting in many applications.

This unit provides 112 connector pins with inputs, outputs, and communications interfaces that support a wide variety of applications.

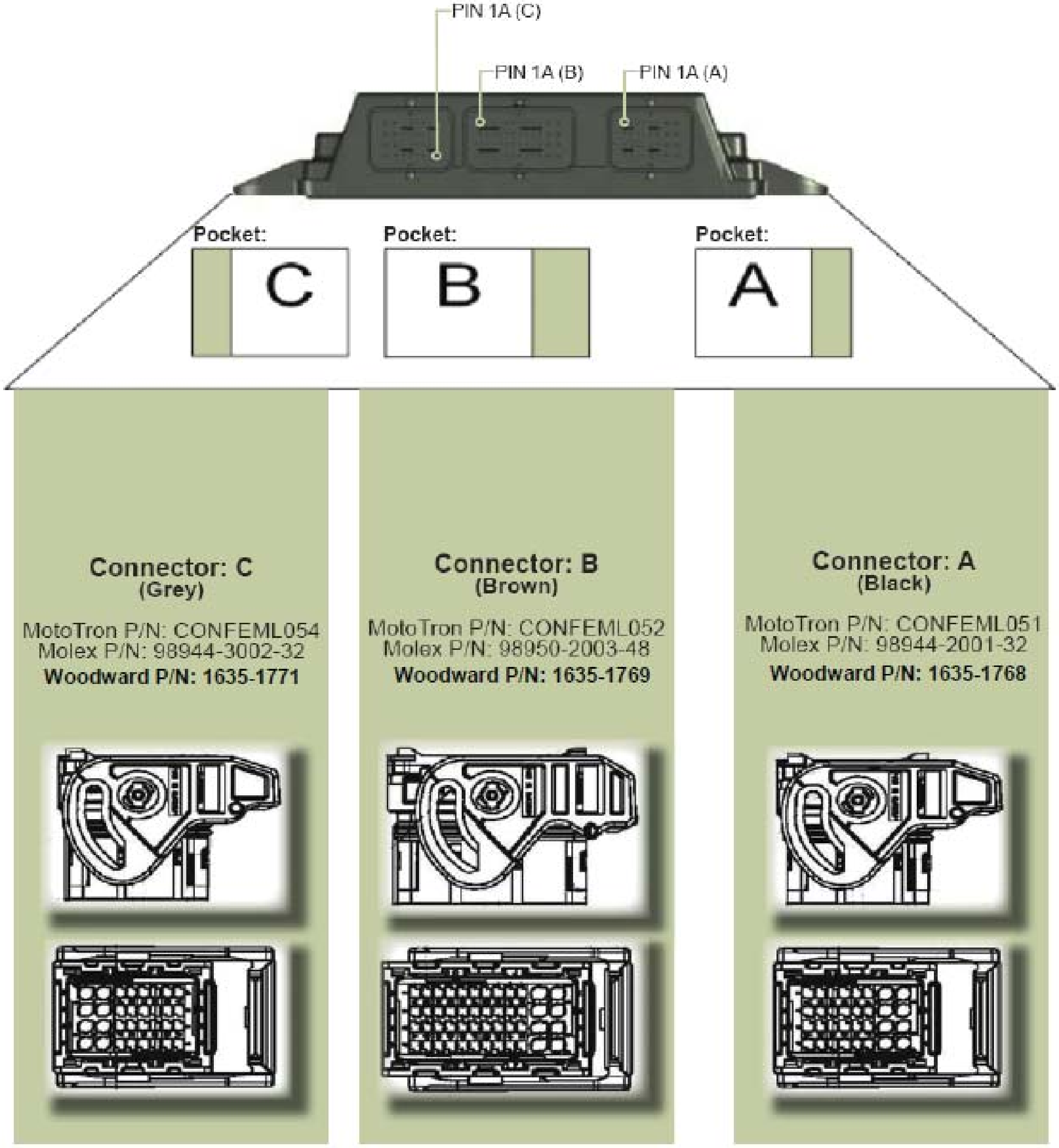
The ECM-5554-112-0904 is part of the ControlCore® family of embedded control systems. The ControlCore operating system, MotoHawk® code generation product, and MotoHawk's suite of development tools enable rapid development of complex control systems.

Each controller is available in ‘F’ (Flash) or ‘C’ (Calibratible) versions. Flash modules are typically used for production purposes. Calibratible modules are typically for prototyping/development only; they can be calibrated in real time using MotoTune®.

Physical Dimensions

- 112-pin platform
- **Microprocessor:** Freescale MPC5554, 80 MHz
- **Memory:** 2MB Flash, 64K RAM, + 32K Cache, 32K EEPROM
- **Calibratible Memory:** 512K (256K x2) RAM
- **Operating Voltage:** 9–16 Vdc, 24 V (jump start), 4.5 V (crank)
- **Operating Temperature:** –40 to +105 °C
- **Inputs:**
  VR and Digital Engine Position Sensor (crank and cam) Inputs
  33 Analog
  4 Oxygen Sensor
  3 Speed (digital)
  2 Knock Sensor
  1 Emergency Stop
- **Outputs:**
  8 Injector (high impedance)
  8 Electronic Spark Trigger (5 V)
  1 Tachometer or Link Interface
  14 Low Side Driver Outputs
  1 Digital Output
  1 Main Power Relay Driver Output
  2 H-Bridge Outputs
- **Communications:**
  3 CAN 2.0B Channels
  1 RS-485 Channel

Connector/Pocket Definitions



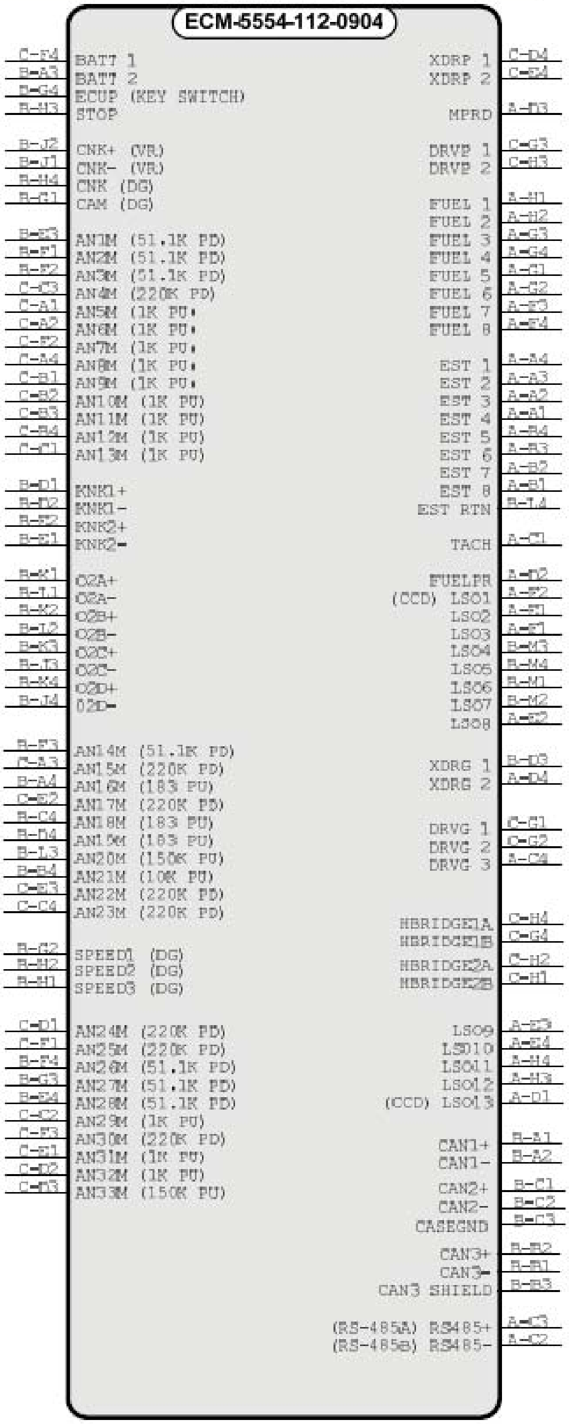
Connector: C
(Grey)
MotoTron P/N: CONFEML054
Molex P/N: 98944-3002-32
Woodward P/N: 1635-1771

Connector: B
(Brown)
MotoTron P/N: CONFEML052
Molex P/N: 98950-2003-48
Woodward P/N: 1635-1769

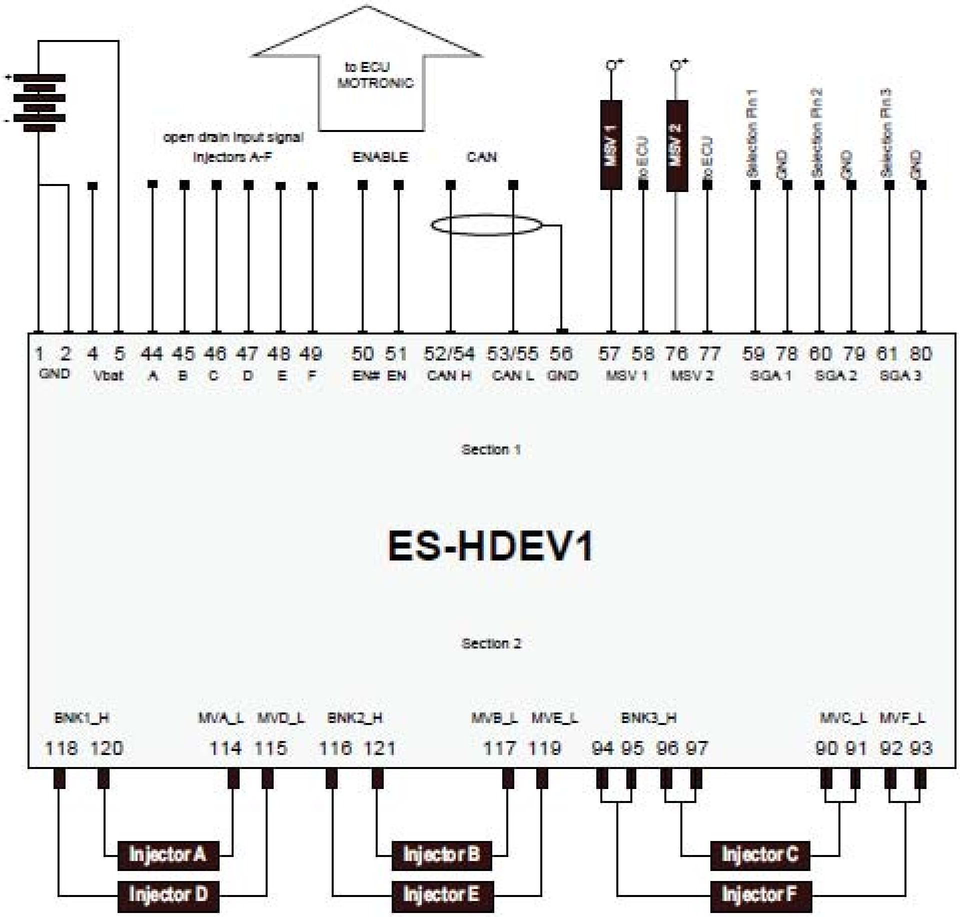
Connector: A
(Black)
MotoTron P/N: CONFEML051
Molex P/N: 98944-2001-32
Woodward P/N: 1635-1768

Woodward 36350 p.4

Block Diagram



7. BOSCH ES-HDEV1 Fuel Injector Driver Information



5 PINNING

Type of connector: BOSCH K3-MK 121 pol.

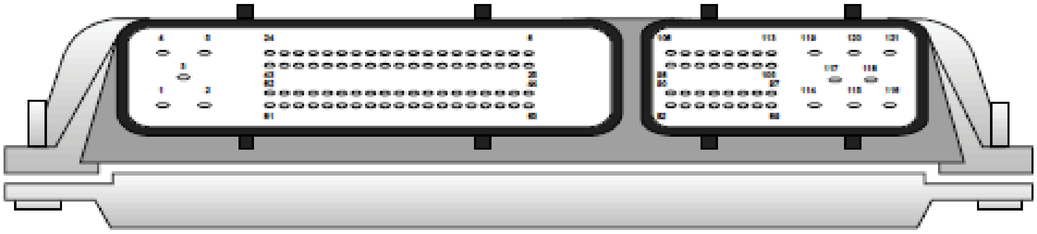


Figure 7: View to edge connector

Section 1	Signal	Description	Remark
1 / 2	GND	BAT- connection	
4	$V_{BAT}1$	BAT+ connection	(*) optional
5	$V_{BAT}2$	BAT+ connection	
44	MV_A	input signal injector A	low-active
45	MV_B	input signal injector B	low-active
46	MV_C	input signal injector C	low-active
47	MV_D	input signal injector D	low-active
48	MV_E	input signal injector E	low-active
49	MV_F	input signal injector F	low-active
50	ENABLE#	enable not powerstage	low-active
51	ENABLE	enable powerstage	high-active
52 / 54	CAN-H	CAN High	
53 / 55	CAN-L	CAN Low	
56	GND shield	CAN Ground	
57	MSV OUT 1	output decay diode for quantity control valve 1	
58	MSV IN 1	input decay diode for quantity control valve 1	
59	SGA 1	ECU selection pin 1	
60	SGA 2	ECU selection pin 2	
61	SGA 3	ECU selection pin 3	

76	MSV OUT 2	output decay diode for quantity control valve 2	
77	MSV IN 2	input decay diode for quantity control valve 2	
78	GND SGA 1	ECU selection ground 1	
79	GND SGA 2	ECU selection ground 2	
80	GND SGA 3	ECU selection ground 3	

Section 2	Signal	Description	Remark
94 / 95 96 / 97	BNK3_H	Common connection Highside injector C, F	
90 / 91	MVC_L	Output Lowside injector C	HDEV31
92 / 93	MVF_L	Output Lowside injector F	HDEV32
118 / 120	BNK1_H	Common connection Highside injector A, D	
114	MVA_L	Connection Lowside injector A	HDEV11
115	MVD_L	Connection Lowside injector D	HDEV12
116 / 121	BNK2_H	Common connection Highside injector B, E	
117	MVB_L	connection Lowside injector B	HDEV21
119	MVE_L	connection Lowside injector E	HDEV22

8. ECU Instrumentation Components

Source	Part No.	QTY	Unit Price	Price	Description
WOODWARD	ECM-5554-112-0904-C00-M,8923-1629	1	840	840	5554-112 PIN CALIBRATABLE ENGINE CONTROL MODULE Green Hills Version 4.2.1 or GNU required
	HARN-P112-002,5404-1216	1	657	657	DEVELOPMENT HARNESS ECM554112090X
	CON-JBOX-002-01,1626-1116	1	35.97	35.97	6-WAY JUNCTION BOX
	CON-TERM-002-00,1649-1078	1	7.17	7.17	120 OHM CAN1 & CAN2 TERMINATOR (CD, JK) - BLUE CAP
	ASM-TUNE-40000-00,8928-1208	1	1317	1317	MOTOTUNE - NO USB TO CAN CABLES,MOTOTUNE CD,MOTOTUNE DONGLE
	HARN-DC-004-00,5404-1103	1	38.97	38.97	KEY POWER TO BUS
	ASM-INTR-013-00,5404-1259	1	286.8	286.8	SINGLE CHANNEL USB-CAN KVASER LEAF-LITE CABLE
Newark	26M4924	150	0.666	99.9	TERMINAL BLOCK, DIN, 2POS, 26-10AWG;
	SPC10576	1	7.92	7.92	DIN Mounting Rail 35MM, STEEL 1M Length x 35MM Width x 7.5MM Height
	72K2057	7	3.06	21.42	MOLEX 38760-0108 TERMINAL BLOCK, BARRIER, 8 POSITION, 24-12AWG
	72K3623	7	4.14	28.98	MOLEX-7233/10-TERMINAL BLOCK JUMPER
Midwest Equipment	A24N24ALP	1	246.9	246.9	Hoffman A24N24ALP, 24" X 24" X 6.62" Medium Type 1 Enclosure
	A24N24MPP	1	63.8	63.8	Hoffman A24N24MPP, Sub Panel, NEMA 1, Perforated 21.00" X 22.50