ADA

INVESTIGATION OF NON-PETROLEUM BASED FUELS

INTERIM REPORT
TFLRF No. 381

by
Douglas M. Yost
Matthew E. Schulman

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
U.S. Department of Energy
Office of Transportation Technologies
1000 Independence Avenue, SW
Washington, D.C. 20585

Under Contract to
U.S. Army TARDEC
Petroleum and Water Business Area
Warren, MI

Contract No. DAAE-07-99-C-L053 (WD24)

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September 2005

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A complex fully flexible engine test stand for light-duty diesel engine fuels research has been configured using Variable Valve Actuation by Sturman Industries. Due to the complexity of integrating the control systems, and the need to develop engine maps for all the control parameters, attaining a reliable and controllable test apparatus was the primary result of the effort. Exploration of the available control authority showed the promise in altering engine emissions by varying sources of EGR and controlling fuel injection events. The Variable Valve Actuation engine test stand allows such vast flexibility that fuel/engine optimizations can be performed together. Future efforts should look at the effects of the variable ignition qualities of selected test fuels.

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Fuel Injection	Light-duty	Diesel	Engine	Variable Valve Actuation

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EXECUTIVE SUMMARY

A complex fully-flexible engine test stand for light-duty diesel engine fuels research has been configured using Variable Valve Actuation by Sturman Industries. Due to the complexity of integrating the control systems, and the need to develop engine maps for all the control parameters, attaining a reliable and controllable test apparatus was the primary result of the effort. Exploration of the available control authority showed the promise in altering engine emissions by varying sources of EGR and controlling fuel injection events. The Variable Valve Actuation engine test stand allows such vast flexibility that fuel/engine optimizations can be performed together. Future efforts should look at the effects of the variable ignition qualities of selected test fuels.

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TABLE OF CONTENTS

Section **Page**

1.0 OBJECTIVE 1

2.0 INTRODUCTION AND BACKGROUND 1

3.0 APPROACH 2
- 3.1 Engine Installation 4
- 3.2 Control Techniques 9
- 3.3 Operations 11
- 3.4 Test Fuels 15
- 3.5 Ignition 16
- 3.6 EGR Flow 18
- 3.7 Valve Timing Conditions 20
  - 3.7.1 Control Condition A 20
  - 3.7.2 Control Condition B 20
  - 3.7.3 Control Condition C 21
  - 3.7.4 Control Condition D 21
  - 3.7.5 Control Condition E 22
  - 3.7.6 Control Condition F 23

4.0 CONCLUSIONS AND RECOMMENDATIONS 24

5.0 REFERENCES 24

LIST OF TABLES

Table **Page**

1. Proposed Test Matrix for Fischer-Tropsch Type Fuels 15
2. Control Parameters and Performance, Emission, and Combustion Response to VVA Approached for EGR 19

LIST OF FIGURES

Figure **Page**

1. Gas Flows and Instrumentation 4
2. View of Added Common-Rail Fuel System and Valve Control Connectors 5
3. Handshaking Schematic for Determining Injection Cycle 8
4. Camless VW 1.9L TDI Engine Test Stand with Integrated Valve and Engine Controllers 10
5. Comparison of Sturman VVA Valve Lift with VW Ground Cam 14

LIST OF FIGURES (continued)

Figure **Page**

6. Boiling Range and Cetane Number of Proposed Fuels 16
7. Temperature Effects on Ignition Delay of 310 psig for Fuels Matrix 17
8. Fuels Matrix Arrhenius Plots 17

SYMBOLS AND ABBREVIATIONS

ATDC	After Top Dead Center
CAN	Controller Area Network
CIDI	Compression Ignition Direct Injection
CO_2	Carbon Dioxide
DC	DaimlerChrysler
DI	Direct Injection
DOE	Department of Energy
EGR	Exhaust Gas Recirculation
EVC	Exhaust Valve Close
F-T	Fischer Tropsch
FPGA	Field Programmable Gate Array
FTP	Federal Test Procedure
HCCI	Homogeneous Charge Compression Ignition
HVA	Hydraulic Valve Actuation
HVA-VDM	Hydraulic Valve Actuation – Valve Drive Module
IQT	Ignition Quality Tester
IVO	Intake Valve Open
L	Liter
MAF	Mass Air Flow
mm	Millimeter
N·m	Newton meter
NOx	Oxides of Nitrogen
NREL	National Renewable Energy Laboratory
PCCI	Premixed Charge Compression Ignition
PM	Particulate Matter
ppm	Parts per Million
PW	Pulse Width
R&D	Research and Development
RPECS	Rapid Prototyping Engine Control System
rpm	Revolutions per Minute
SAE	Society of Automotive Engineers
SI	Spark Ignition
SwRI	Southwest Research Institute
TARDEC	United States Army Tank-Automotive RD & E Center
TDC	Top Dead Center

SYMBOLS AND ABBREVIATIONS (continued)

TDI	Turbocharged Direct Injected
TFLRF	United States Army TARDEC Fuels and Lubricants Research Facility
US	United States
VVA	Variable Valve Actuation
VW	Volkswagen

1.0 OBJECTIVE

This project sought to investigate Non-Petroleum Based Fuels and Lubricants for Advanced CIDI Automobile Engines, in two phases.

The project began with a Planning Phase to provide assistance to the DOE in planning an overall evaluation of non-petroleum based fuels and lubricants applicable to a light duty CIDI passenger car engine. Planning was to include defining the research necessary for future transitional non-petroleum fuel components that could also be used in producing hydrogen.

The subsequent Engine Phase involved installing a government-furnished 1.9L turbocharged, direct injection diesel engine equipped with variable valve actuation (VVA) in an engine dynamometer test cell. Electronic control of the VVA, fuel injection events, and other engine control parameters was devised and implemented. Baseline engine and fuel economy performance and petroleum-based fuel exhaust emissions were to be determined. The advanced engine and fuel formulations containing non-petroleum-based components were to be evaluated for improved fuel economy and reduced exhaust emissions at engine control conditions unique to having variable valve actuation architecture.

2.0 INTRODUCTION AND BACKGROUND

A meeting was held in October 2003, at the Volkswagen (VW) facility in Wolfsburg, Germany, to review the overall status of the Volkswagen in-house HCCI engine and fuels program, and to develop a test plan for the 1.9-liter camless engine. Parties involved were Sturman Industries, VW, National Renewable Energy Laboratory (NREL). SwRI staff prepared a briefing on the non-petroleum based fuels project for presentation to VW. The briefing outlined the information required by NREL, Sturman, and SwRI in order to initiate the project. Earlier discussions with VW indicated cooperation to begin the program.

VW had concerns on authoring an agreement for the two-way disclosure of data and information. All parties agreed to have guidelines in writing. Information discussed at VW suggested the current state of combustion development at VW is similar to PCCI, not truly HCCI. VW indicated that variable valve actuation is required for internal/hot EGR, to extend the operating range of premixed combustion. It was felt that the range of premixed combustion needed to be extended to both higher and lower loads, and to engine speeds greater than 2000 rpm. VW had characterized the European driving cycle and was able to reduce the cycle to a series of steady-state points that represented significant contributions to Oxides of Nitrogen (NOx) and Particulate Matter (PM) emissions. The same approach was tried with the US FTP-75 drive cycle, and the cycle could not be reduced to a manageable number of data points that resulted in significant NOx and PM emissions contributors.

In conjunction with the meeting, SwRI personnel visited a laboratory in the VW engine R&D center to witness the operation of a Sturman camless cylinder head that had been previously delivered to VW on an unrelated project. Sturman personnel demonstrated the camless head and the capabilities of the control system and interface. A similar system was delivered to SwRI for the project. A test cell for a parallel VW fuels/combustion effort in the VW engine laboratory was also visited.

3.0 APPROACH

The project was initiated with teleconferences among NREL, Sturman Industries, and SwRI representatives to develop a project outline for the engine-testing phase of the work. A series of email drafts, as well as coordination followed this on the status of the 1.9L engine to be provided to SwRI. As Sturman-developed fuel injectors would not be complete in time for the project,

other fuel injection system options were evaluated. Eventually VW supplied the hardware for a Bosch High-Pressure Common-Rail fuel injection system. Sturman Industries integrated the fuel injection system to the production engine block via a cog belt drive that drives the common-rail pump at ⅔ crankshaft speed.

Sturman Industries also integrated the VVA hardware. The Sturman VVA cylinder head uses a production two-valve cylinder head, with the camshaft removed. The Sturman valve drive blocks and digital hydraulic valves are mounted in place of the camshaft. The overall height of the engine with the VVA does not exceed the height of the production engine.

An additional engine build task provided by Sturman Industries was modifications of the serial production piston combustion chamber geometry to lower the numeric compression ratio. The serial production 1.9L TDI engine has a compression ratio of 19.5:1, however VW recommended lowering the compression ratio to 16.5:1 for HCCI combustion work. The 16.5:1 compression ratio compares favorably with the Nissan MK [1] process compression ratio.

A confidentiality agreement was negotiated between Volkswagen and SwRI, with the expectation that Volkswagen's previous HCCI research on the same engine would be used as a starting point for this work. Lawrence Livermore National Laboratory was contacted about the capabilities of existing HCCI ignition and combustion models, for use in guiding the engine development work.

3.1 Engine Installation

When the 1.9L VW engine with VVA head was received from Sturman, the engine was installed on a quick-change cart then connected to the cell when the DaimlerChrysler (DC) OM611 test engine was removed. The dyno stand was calibrated and readied for engine operation. The diagram in Figure 1 illustrates the gas flows through the engine system, and data acquired:

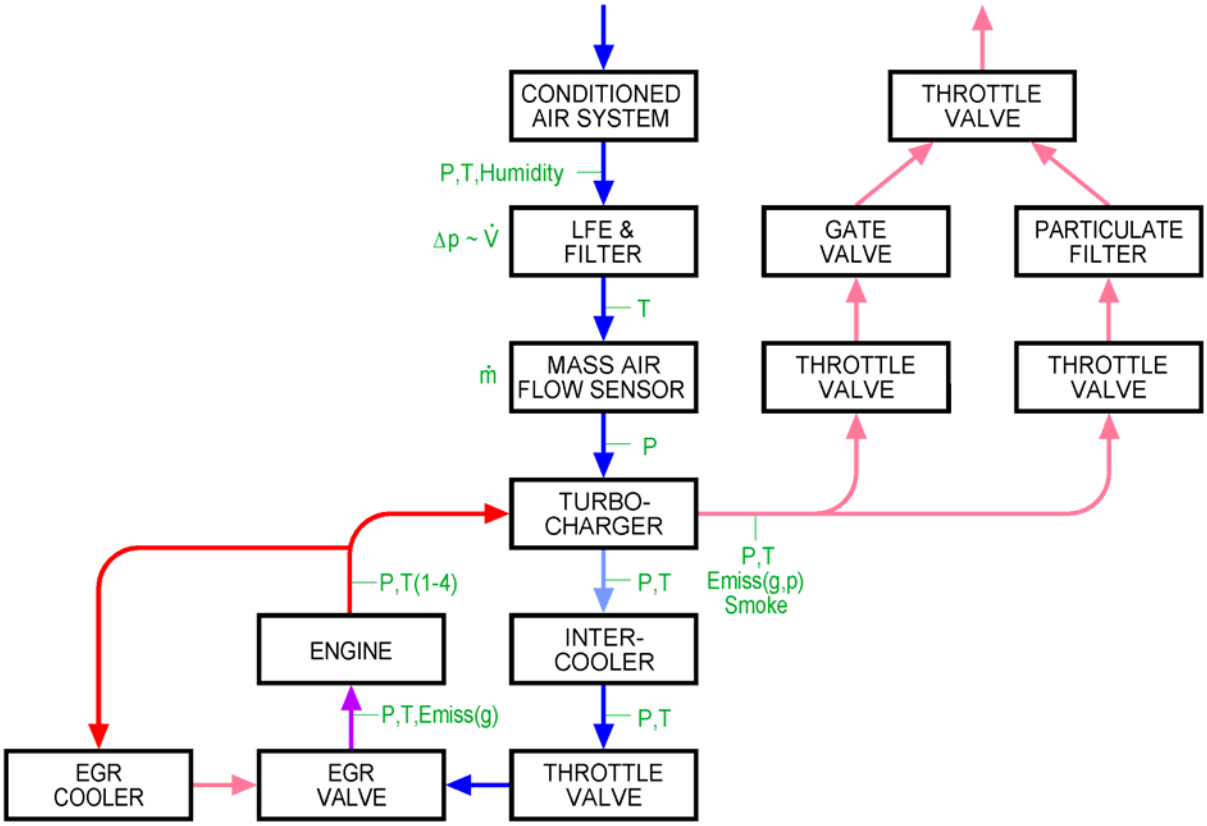

Figure 1. Gas flows and Instrumentation

The VW wiring harness was bypassed, as it did not support the common rail fuel system installed on the engine. The common-rail fuel system was a custom system for this engine, with the fuel injectors being non-production items. The common-rail fuel is non-production for VW

for the 1.9L TDI engine. The added common-rail fuel system and some of the Sturman digital valve control electronics are visible in Figure 2.

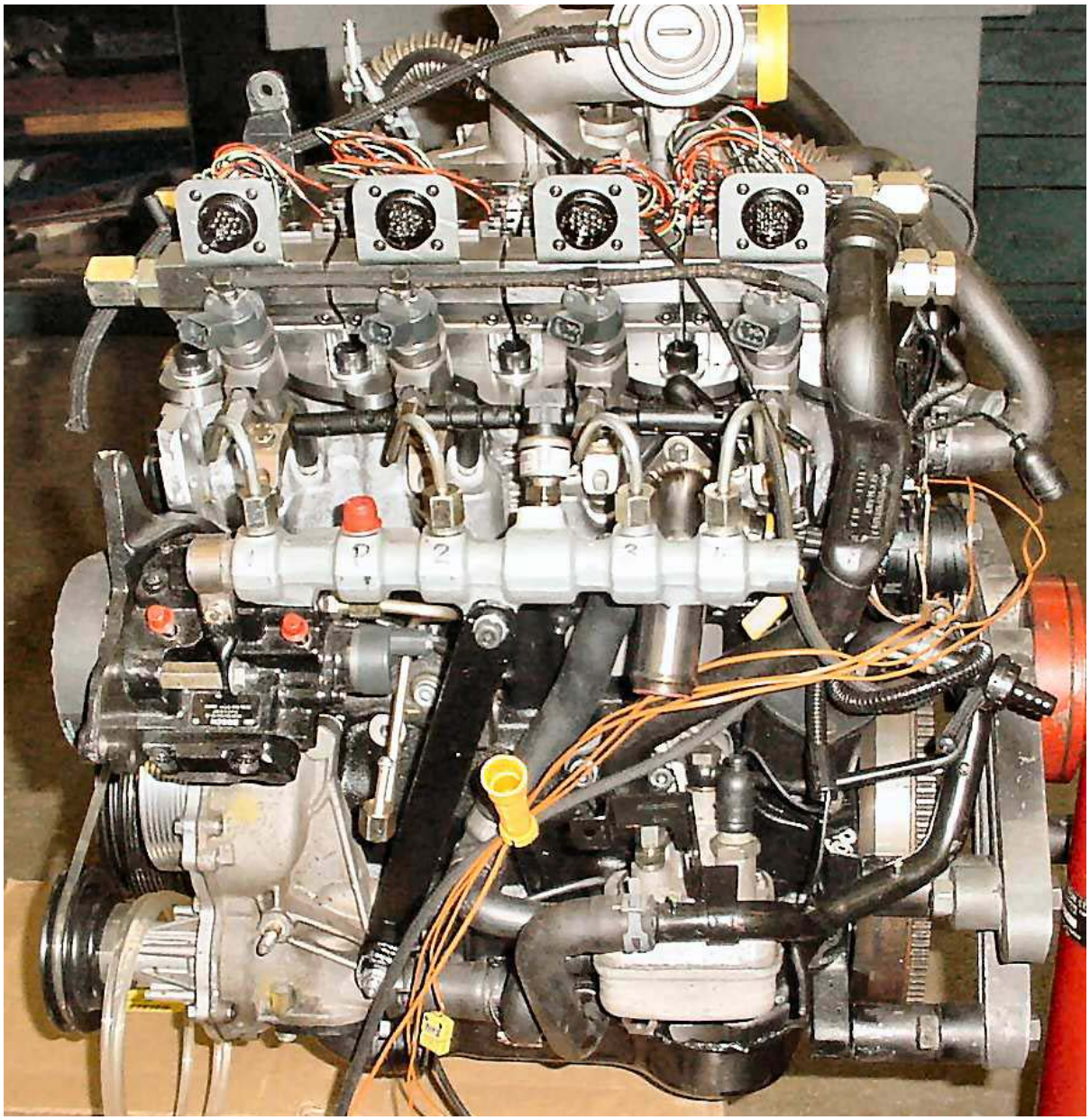

Figure 2. View of Added Common-Rail Fuel System and Valve Control Connectors

A SwRI Rapid Prototyping Engine Control System (RPECS) used for previous Department of Energy work in a common-rail DC engine was used in this program [2,3,4]. An RPECS was

required because the engine did not have an Electronic Control Module, because the fuel injection system was unique for this engine build and control maps were not available. Substantial alterations of the control code and wiring harness were required for adaptation to the current test stand due to the differing configurations of the VW and DC engines. However, the VW test engine had the same type of fuel injection system as the DC OM611 engine and that portion of the wiring harness and control code was used with modifications.

Injector drivers and software changes to allow multiple fuel injections and to synchronize the engine control, fuel injection, data acquisition, and VVA systems were required. The project obtained from Sturman a high speed, four-channel peak and hold driver for powering the coils of the electronic fuel injectors. The Sturman injector driver allowed faster rise times and faster cycle times than the previous in-house built driver. The previous injection control section used a custom built timing board with a chip that was no longer in production. The custom board was swapped for a FPGA (Field Programmable Gate Array) board, which allows over a million programmable digital operations. The FPGA board can be reconfigured in software. The FPGA board controls the timings for the fuel injectors, handles the Pulsewidth Modulated (PWM) control parameters, reads the hot wire Mass Air Flow (MAF) frequency, counts the flywheel teeth, detects TDC, monitors the Sturman "cam" signal, and monitors the 360 count encoder. The RPECS controlling the system currently has the capability of performing four fuel injection events per cylinder, per cycle. The fuel injection timing events are open loop control based on timings calculated from the flywheel teeth, TDC marker, and Sturman "cam" signal.

The PWM vacuum controllers for the turbocharger wastegate and the EGR valve were also borrowed from the DC engine setup. Other PWM signals included the fuel rail pressure control and the intake throttle control. The fuel rail pressure control is closed loop for the inlet metered common-rail pump with pressure transducer feedback from the fuel rail. The common rail pump has the capability of 1500-bar injection pressure. The intake throttle is used to bias the EGR circuit, and is closed looped based on the MAF sensor.

Cylinder pressure transducer adapters that fit the glow plug passages were designed, machined and installed. A 720 pulse per revolution shaft encoder was installed on the engine for clocking the high-speed cylinder pressure data acquisition

Two Hall effect sensors were installed; one to sense the 133-tooth flywheel for the RPECS timing and fuel injection event control; and another to sense TDC for cylinder number one. The signal from a 360 pulse/revolution shaft encoder is supplied to the Sturman HVA controller and the RPECS. The signal from the shaft encoder and the 133-tooth flywheel signal will be compared to validate the 133/360 ratio. If the observed ratio deviates from 133/360, a "stop engine" signal to the Sturman HVA controller can be generated within ¼ of an engine cycle. Use of the 133/360 ratio signal will attempt to avoid any coupling failures that could occur with an externally mounted encoder which could result in valve timing errors or piston-to-valve collisions. The 360 pulse/revolution encoder signal and the TDC signal are passed to the Sturman controller. The Sturman controller determines which cycle is compression and returns a 360° high/360° low signal back to RPECS to synchronize fuel injection as shown in Figure 3.

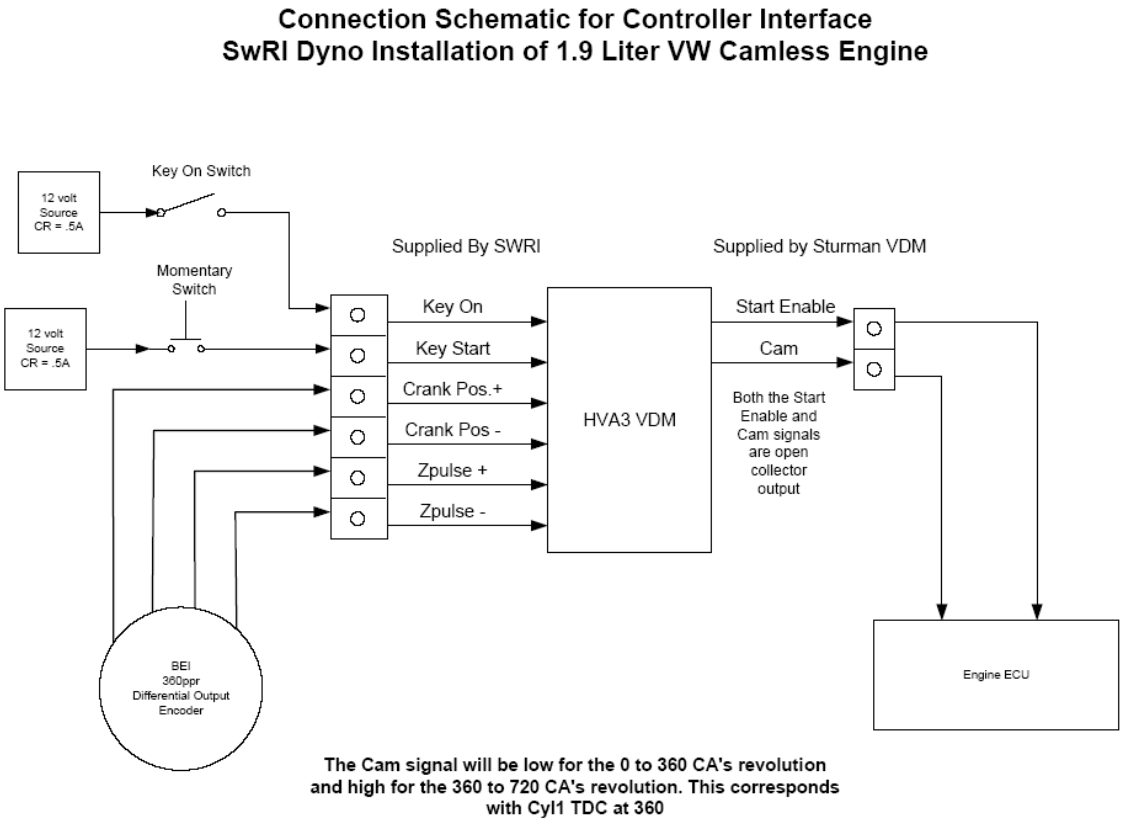

Figure 3. Handshaking Schematic for Determining Injection Cycle

The HVA control system electronics was completed by Sturman and shipped to SwRI, for installation. HVA controller and RPECS handshaking were accomplished to determine the proper cycle for injection. Due to the interdependence of the electronic controls, SwRI could not run the engine prior to integration of the HVA controller to troubleshoot wiring and control loops. Likewise, the HVA needed feedback from RPECS to time and activate the valves. The engine was operated with variable valve control. Valve lift, timing, and duration can be varied. Another feature of the Sturman HVA system is a secondary valve event, such as opening the exhaust valve during the intake event. Opening the exhaust valve during the intake event can be used for internal, uncooled EGR due to rebreathing of the exhaust gases during the intake stroke. Monitoring cylinder pressures, and combustion duration, the effects of the secondary exhaust

valve event could be seen, in fact sufficient EGR could be passed using the secondary valve event to stall the engine.

The completed engine installation with integrated SwRI RPECS controller and Sturman HVA-VDM is shown in Figure 4. Due to the electrical control cables for the valve controller, RPECS and fuel injection control, and hydraulic hoses for the valve drive mechanism the actual engine is barely visible in Figure 4.

3.2 Control Techniques

Toward the goal of conceiving control techniques for the engine system, requests were made to VW to obtain data from their HCCI program with the 1.9L TDI engine. The plan included utilization of VVA and non-petroleum based fuels to expand the HCCI region of operation for the 1.9L engine. Pertinent literature was continuously reviewed on the latest HCCI and HCCI fuels research.

A SwRI staff member attended a SAE-sponsored HCCI symposium. The symposium reviewed some of the latest research and development on Homogeneous Charge Compression Ignition engines. Although HCCI is seen as a bridging technology for future clean diesel engines, the majority of the work presented dealt with SI engine applications of HCCI. The reactivity of current distillate fuels does not lend itself well to HCCI operation; thus it appears the fundamental work is being done with SI fuels. However, to meet future diesel engine emission requirements HCCI combustion, defined as simultaneous low NOx and low PM emissions, will

be required over a large portion of an engines operating range. Although aftertreatment can be utilized, HCCI operation is seen as a way to reduce aftertreatment size and cost.

Figure 4. Camless VW 1.9L TDI Engine Test Stand with Integrated Valve and Engine Controllers

Many of the presentations dealt with the variable valve activation as a means to control HCCI start of reaction. Generally, the CA50, or crank angle of 50% burn, was used as a measure to control HCCI combustion. Most control routines tried to hold CA50 between TDC and 10 degrees ATDC, with a CA50 at 5 degrees after TDC appearing to be the most common metric for HCCI. One variable valve timing approach discussed involved negative valve overlap; early EVC combined with late IVO, sometimes called recompression. Fuel reformation by injection during negative valve overlap appeared to offer promise for HCCI operation. Late IVC or Miller

cycling was also discussed, but extensive research efforts were not being made with late IVC. The approach that appears to provide more promising results is rebreathing, using a second exhaust valve event during the intake valve event. Rebreathing is an approach that can be utilized using the Sturman HVA variable valve system for the DOE advanced non-petroleum based fuels program. SwRI reviewed all data presented on rebreathing in order to sketch out an operating condition test matrix for use with the VW engine.

Active control of the valve events appears to be the only suitable means to control HCCI engines. Some of the work presented on model-based controls showed excellent combustion stability while varying valve events to maintain a stable CA50 location [5]. Unfortunately the Sturman HVA system as initially configured had a manual interface, which would not work for active control. Discussions with Sturman were initiated to determine if an interface for active control can be added to the HVA, possibly through a CAN interface.

3.3 Operations

The VW 1.9L VVA engine was operated using calibration tables from the previous DOE work using a DC OM611 engine. Although the maps let the engine run, none of the control loop tuning parameters were properly set for the VVA engine. Substantial effort was required to get to stable engine operation, specifically when speed changes and load were made. After exploratory operation at several test conditions it became obvious that fuel control, EGR, and intake air control parameters were not at the optimal settings for efficient, low emission engine operation. Without VW input excessive efforts would be required to map the engine to achieve baseline performance. A conference call between VW, Sturman, NREL, and SwRI resulted in an

agreement on data to be exchanged. The VW-VVA engine will be operated at 2060 rpm, and fuels and VVA will be used to extend the region of HCCI operation, both high-load limit and low-load limit. VW has supplied engine-specific data that had been presented in Germany to SwRI, Sturman, and NREL. Also included in that data was maps for injection timing and EGR. The data received was reviewed and used to formulate a test matrix. Unfortunately information not included in the supplied data was fuel rail pressure maps as a function of engine speed and fuelling rate. Fuel rail pressure is critical with a common-rail fuel system because it determines the injection duration at a given fuelling quantity, thus can impact emissions greatly.

The VW-VVA engine was operated at 1600 rpm and 100 N·m load to validate data supplied by VW. This point was chosen because it included the most complete set of data for engine operation and response. The data suggests using 25-30% EGR at the operating condition. Efforts to meet the EGR, using CO_2 tracer in the exhaust and intake manifold, resulted in poor combustion and heavy smoke at half the EGR shown on the maps. Further investigation indicated the default VVA valve timings had 60° of negative overlap, which was resulting in a large residual, or internal EGR. VW was contacted and supplied the valve timings used for their work, which had a smaller negative overlap. The incorrect EGR measurements also suggested CO_2 ratio would not be the best approach for setting EGR with the experimental setup. The intake mass flow at manifold conditions, and VW cam timings, was used as the reference for calculating EGR. Any external EGR or VVA changes that result in a mass flow change from the reference value for a speed/load condition will be considered EGR.

Sturman was contacted about using the CAN interface built into the HVA-VDM module to communicate with the RPECS CAN so that valve timings could be set from the RPECS, to

enable using of the RPECS for active valve control by adding model-based control algorithms. Engineers from Sturman Industries and SwRI Controls collaborated to enable control of the Sturman VVA system by SwRI's RPECS controller via implementation of the CAN interface built into the HVA-VDM. Several technical issues were identified and worked out, though some calibration work will be necessary to fully enable active control of the VVA system.

While on site, Sturman acquired valve motion data under a variety of engine conditions comprising variations in commanded lift, commanded valve open/close timing, and hydraulic system pressure. The data was examined by Sturman to ensure the system is functioning correctly. The data was to be shared with SwRI for use in calibrating control aspects of the system. The control calibrations were used to ensure valve/piston parameters so that collisions do not occur. In attempts to duplicate VW data it had become apparent that the valve lift profiles, and valve lift were sufficiently different for the camless engine. The VVA engine has a lower lift, but has higher opening and closing velocities, and a longer dwell at maximum lift. Figure 5 shows the valve profile differences between the Sturman VVA and the VW cam engine.

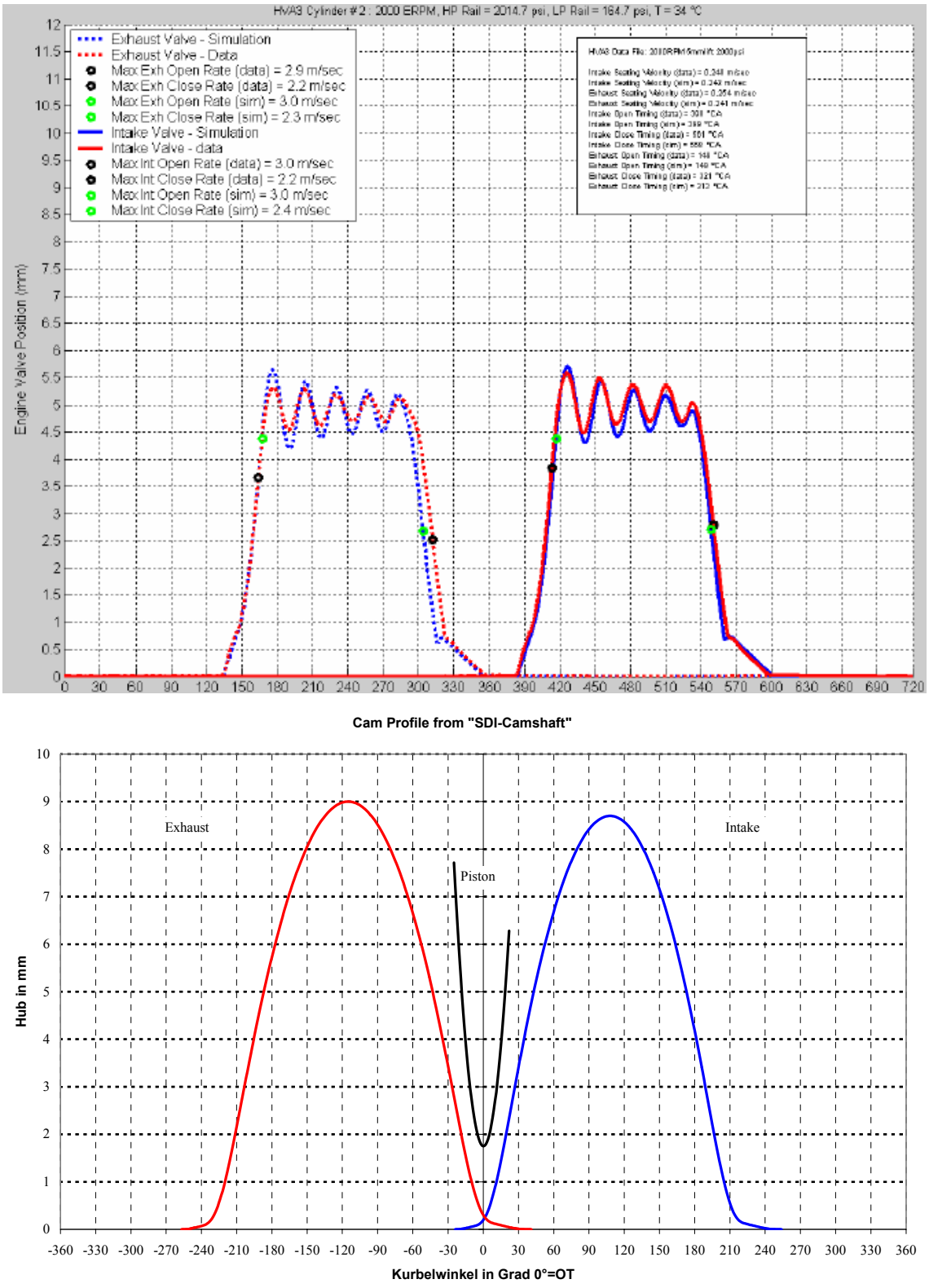

Figure 5. Comparison of Sturman VVA Valve Lift with VW Ground Cam

3.4 Test Fuels

Josh Taylor of NREL defined a series of test fuels. In addition to the base fuel, the other fuels are all narrow boiling mixtures of n-alkanes and isoalkanes and are meant to simulate synthetic fuel properties and structure. The fuel matrix as proposed is shown in Table 1. The matrix was set up with 3 different boiling ranges and three (3) cetane levels. The lowest boiling range is the synthetic naphtha from Syntroleum. The other fuels are blends of components. Two options were given for Fuel #5. Discussions were directed towards the "Alt. 5" fuel in which the matrix would look more like a cross with three (3) boiling ranges at the same cetane number, and three (3) cetane number for the same boiling range. A plot of the cetane number versus boiling range is shown in Figure 6 for the matrix of fuels.

All of the proposed fuels are essentially zero sulfur (<15 ppm), zero aromatics fuels. VW mentioned that aromatics might be an interesting property worth looking into. Chevron-Phillips has several aromatics that can be blended into these fuels to pursue aromatic effects in the future. However, since the emphasis is on fuels that could be produced from Fischer Tropsch (F-T), the fuel matrix was considered to be adequate.

Table 1. Proposed Test Matrix for Fischer-Tropsch Type Fuels

Fuel #	Description	IBP (°C)	FBP (°C)	CN
1	Soltrol 100 (C9-C11 isoalkanes)	160	167	30.4
2	Syntroleum FC-2 (synthetic naphtha)	76	134	38.8
3	65% Soltrol 100 + 35% n-decane	160	174	39
4	Soltrol 170 (C12-C14 isoalkanes)	223	244	39.3
5	72% Soltrol 170 + 28% n-dodecane	216	244	50
6	BP-15	165	347	50
Alt. 5	25% Soltrol 100 + 75% n-decane	160	174	50

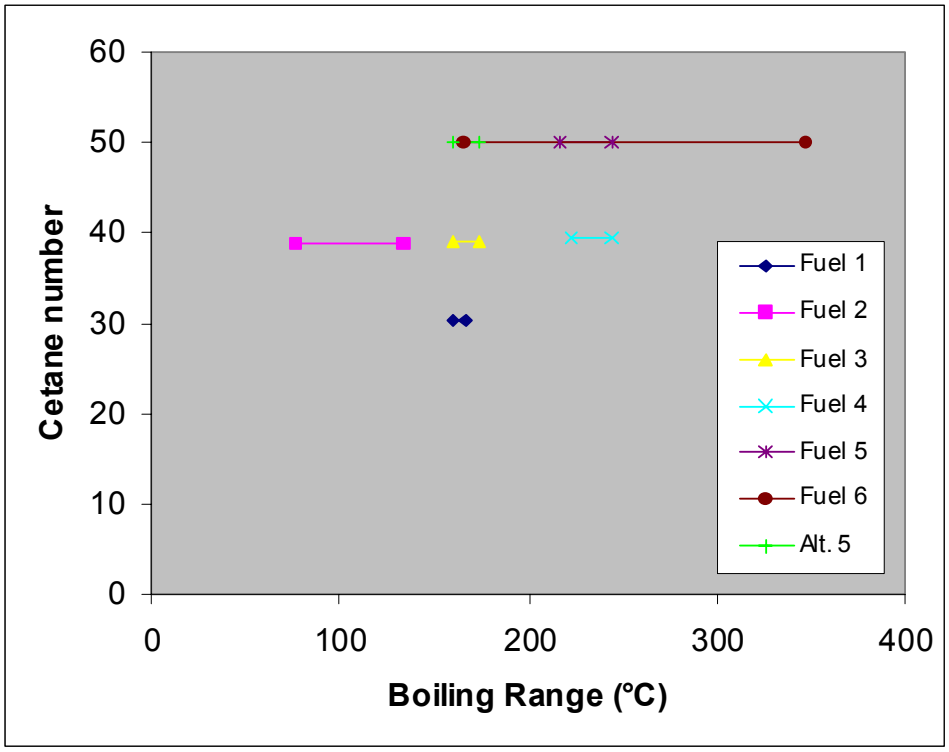

Figure 6. Boiling Range and Cetane Number of Proposed Fuels

The base fuel for testing and initial engine operation was BP15. BP15 is a 15 ppm sulfur diesel fuel prepared by processing straight-run distillate stocks through a commercial, single-stage hydrotreater employing a high-activity catalyst at maximum severity. This fuel was prepared in a commercial refinery unit (not a pilot plant), but cracked stocks were excluded from the feed because the specification sulfur level could not have been achieved with their inclusion. Year 2007 actual production will likely employ more advanced processing to allow the inclusion of cracked stocks.

3.5 Ignition

NREL determined the ignition characteristics of the proposed fuels using an Ignition Quality Tester (IQT). Figure 7 shows the ignition delay of the matrix of fuels for a constant pressure and

varying temperatures. Figure 8 shows an Arrhenius type plot of natural log ignition delay versus reciprocal temperature for the proposed fuels.

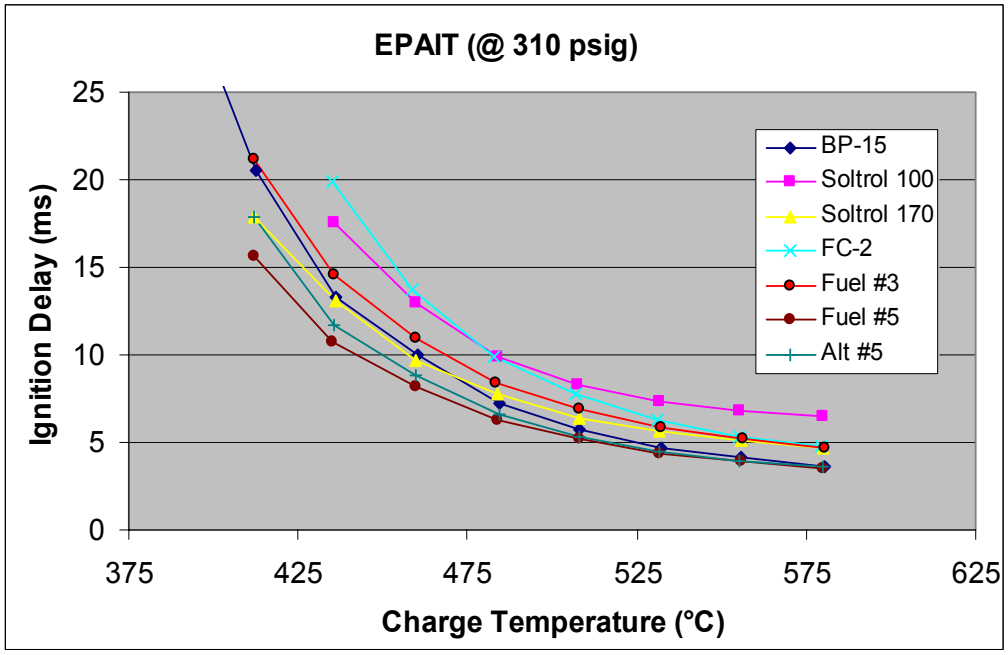

Figure 7. Temperature Effects on Ignition Delay at 310 psig for Fuels Matrix

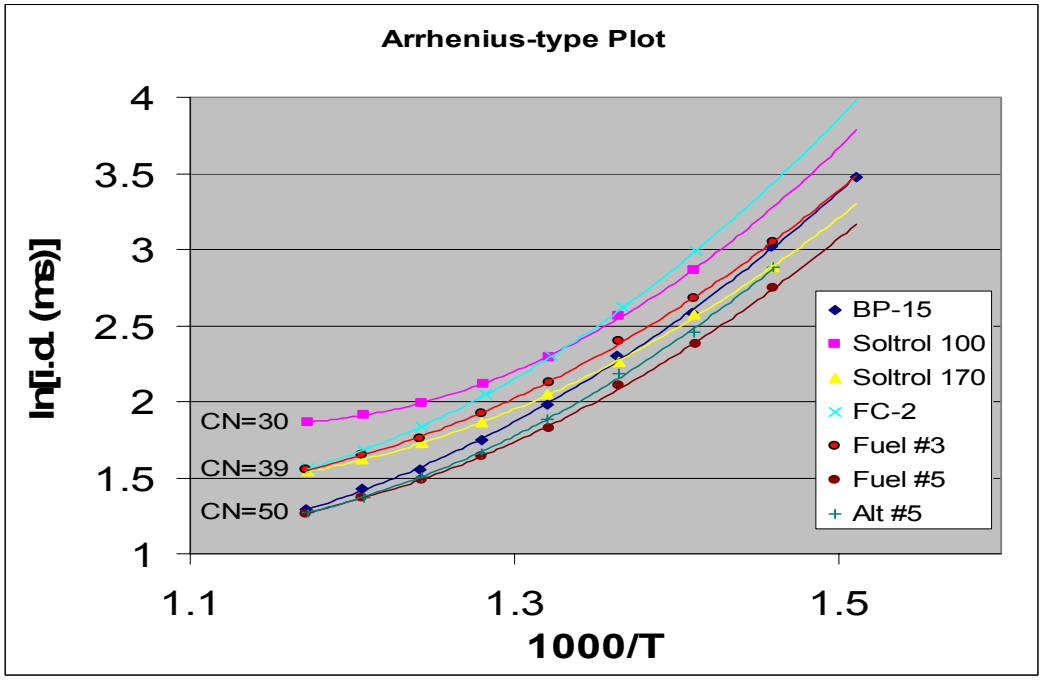

Figure 8. Fuels Matrix Arrhenius Plots

The ignition quality data for the fuels is valuable for helping to determine fuel injection timing, manifold conditions, and valve timings for controlling combustion with the various proposed test fuels.

3.6 EGR Flow

A series of test conditions were run and the settings recorded, to examine the effect of different techniques for achieving the same EGR flow. The conditions were performed using BP15 fuel. A baseline point without EGR established an airflow value. A 6-mm valve lift was used for all primary valve events. External-loop EGR flow was then added until the baseline airflow was decreased by 25%. The same airflow was then targeted using a second exhaust valve event to "rebreathe" gases from the exhaust manifold back into the cylinder. Finally, the same airflow was achieved by advancing the exhaust valve closing and retarding the intake valve opening, to retain the desired quantity of exhaust gas in the cylinder between combustion cycles. An additional run was made using a 10% pilot fuel injection during the negative valve overlap period. Additional runs using secondary valve events for EGR and a combination of internal and external EGR was investigated. The exhaust valve opening and intake valve closing timings were not varied for these runs. Data from these experiments are shown in Table 2. Unfortunately an error in the high-speed data acquisition system configuration resulted in loss of the actual pressure traces, but the statistics for the cylinder pressure and burn data was retained.

Table 2. Control Parameters and Performance, Emission, and Combustion Response to VVA Approaches for EGR

Control	EVO(1/2) [°]	EVC(1/2) [°]	IVO [°]	IVC [°]	Pilot SOI [°BTDC]	Main SOI [°BTDC]	EGR [%]	BSFC [g/kW-h]	Smoke	HHC [ppm]	CO [ppm]	CO2 [%]	NOX [ppm]	CA05 [°]	CA50 [°]	ΔCA [°]
A	140	350	370	565		14.5	0%	232	0.19	115.9	120.1	7.51	1750	-0.238	2.750	2.988
B	140	350	370	565		14.5	25%	231	0.17	119.7	159.5	9.57	1013	-0.470	2.615	3.085
C	140	306	414	565		14	25%	240	0.27	118.2	111.1	9.78	1315	-0.370	2.618	2.988
D	140	306	414	565	360	14	25%	242	0.18	182.1	214.1	9.76	1347	-0.515	2.550	3.065
E	140/415	350/450	370	565		14	25%	233	0.37	153.6	216.6	9.95	972	0.005	3.060	3.055
F	140/425	325/445	395	565		14	24%	236	0.23	137.6	162.8	9.75	1165	-0.105	2.895	3.000

3.7 Valve Timing Conditions

3.7.1 Control Condition A

Control condition A in Table 2 represents the valve timing condition with the VVA system that was similar to the metal cam, and was used as our reference mass airflow condition. All points were operated with the fuel injection pressure at 1350-bar, which should result in PCCI combustion similar to what VW used. A single injection event was used for Control A, and the fuel injection timing was adjusted to locate the crank angle of 5% burn (CA05) at TDC. It should be noted the crank angle of 50% burn (CA50) occurred around 3˚ ATDC, more advanced than would be desirable. The early CA50 timing, in conjunction with no-EGR results in a high NOx value. In fact the NOx value seems very high for this operating condition, which suggests at 1350-bar injection pressure the fuel is injected during the ignition delay period and is highly premixed when combustion begins.

3.7.2 Control Condition B

Control condition B in Table 2 represents the valve timing condition with the VVA system that was similar to the metal cam. EGR was applied from the external cooled high-pressure EGR loop, and resulted in a reduction of 25-percent from the reference mass airflow condition. The point was operated with the fuel injection pressure at 1350-bar, which should result in PCCI combustion similar to what VW used. A single injection event was used for Control B, and the fuel injection timing was adjusted to locate the CA05 at TDC. It is noted the CA50 occurred near 3˚ ATDC, but is still more advanced than would be desirable. The early CA50 timing in conjunction with 25% EGR results in a high NOx value, but at a value which is substantially

lower than the Control A case. The ΔCA, the crank angle delta between CA05 and CA50, is slightly longer when EGR is added.

3.7.3 Control Condition C

Control condition C in Table 2 represents utilizing the VVA system to add internal EGR. The EGR was applied by closing the exhaust valve early, trapping residuals in the cylinder. The intake valve is then opened late to allow some expansion of the trapped residuals. This approach is called recompression and the valves were adjusted to result in a reduction of 25-percent from the reference mass airflow condition. The point was operated with the fuel injection pressure at 1350-bar. A single injection event was used for Control C, and the fuel injection timing was adjusted to locate the CA05 at TDC. It is noted the CA50 again occurred near 3˚ ATDC, and is still more advanced than would be desirable. The early CA50 timing in conjunction with 25% EGR results in a high NOx value, but the value lower than the Control A case, but higher than Control B.

3.7.4 Control Condition D

Control condition D in Table 2 represents utilizing the VVA system to add internal EGR, along with using flexibility of the fuel injection system. The EGR was applied by using recompression and the valves were adjusted to result in a reduction of 25-percent from the reference mass airflow condition. The point was operated with the fuel injection pressure at 1350-bar. Pilot and Main injection events were used for Control D. Ten percent of the total fuel was injected during the recompression period as a pilot fuel injection event. This fuel injection approach has been called reformation [6]. The Main fuel injection timing was adjusted to locate the CA05 at TDC.

It is noted the CA50 again occurred near 3˚ ATDC, and is still more advanced than would be desirable. The combination reformation fuel injection and recompression EGR resulted in NOx similar to just the recompression EGR, but had a sizable increase in hydrocarbon and carbon monoxide emissions.

3.7.5 Control Condition E

Control conditions E and F in Table 2 represent utilizing the unique capabilities of the Sturman VVA system to add an additional valve event for controlling internal EGR. The secondary valve event was on the exhaust valve as noted in the Table. The exhaust valve was opened during the intake stroke, at timing near maximum piston velocities, to induct residuals from the exhaust manifold (rebreathing). For Control E the secondary valve lift was 3-mm. The EGR by rebreathing was adjusted to result in a reduction of 25-percent from the reference mass airflow condition. The point was operated with the fuel injection pressure at 1350-bar. A single fuel injection event was used for Control E. The Main fuel injection timing was adjusted to locate the CA05 at TDC. It is noted the CA50 again occurred near 3˚ ATDC. The rebreathing EGR resulted in the lowest NOx emissions of the conditions run however there were concomitant increases in smoke, hydrocarbon, and carbon monoxide emissions.

3.7.6 Control Condition F

Control condition F in Table 2 utilized the unique capability of the Sturman VVA system to add an additional valve event for controlling internal EGR along with the addition of EGR from an external loop. The secondary valve event was on the exhaust valve as noted in the Table. For Control F the secondary valve lift was 2-mm, and the duration was 15 crank angle degrees shorter than Control E. The EGR by rebreathing and external loop was adjusted to result in a reduction of 25-percent from the reference mass airflow condition, with approximately 12.5-percent reduction coming from each EGR source. The point was operated with the fuel injection pressure at 1350-bar. A single fuel injection event was used for Control F. The Main fuel injection timing was adjusted to locate the CA05 at TDC. It is noted the CA50 again occurred near 3˚ ATDC. The combination rebreathing and external EGR resulted in a slightly higher NOx emission than Control E, but also resulted in lower levels of smoke, hydrocarbon, and carbon monoxide emissions than Control E.

The data discussed represented a single run for each of Control A through Control F operating conditions, so the results are by no means rigorous or statistically valid. The engine was run to see what effects large changes in how EGR is induced into the engine had on emissions and economy. As noted the injection pressure was quite high and the experiments revealed combustion was occurring too fast. These results suggest more EGR could be tolerated at this operating condition when using VVA to control CA50 to 5˚ ATDC. A fuel less reactive than the BP15 fuel could also be beneficial to control the timing of CA50 to occur later in the cycle.

4.0 CONCLUSIONS and RECOMMENDATIONS

Due to the complexity of integrating the control systems, and the lack of engine maps for all the control parameters, efforts were mostly involved in attaining a reliable and controllable test apparatus. Exploration of the available control authority showed the promise in altering engine emissions by varying sources of EGR and controlling fuel injection events. The VVA engine test stand allows such vast flexibility that fuel/engine optimizations can be performed together. Future efforts should look at the variable ignition qualities of the test fuels matrix suggested by NREL.

5.0 REFERENCES

1. Kimura, S., et al, "New Combustion Concept for Ultra-Clean and High-Efficiency Small DI Diesel Engines," SAE Paper 1999-01-3681.

2. Yost, D., Buckingham, J., and Frame, E., "Dimethoxymethane in Diesel Fuel: Chemical Characterization of Toxicologically Relevant Compounds From Diesel Emissions," TFLRF Interim Report No. 358, April 2001.

3. González, et al, "Impact of Engine Operating Conditions on Low-NOx Emissions in a Light-Duty CIDI Engine using Advanced Fuels," SAE Paper 2002-01-2884.

4. Yost, D., Schulman, M., and Frame, E., " Characterization of Toxicologically Relevant Compounds From Diesel Emissions: Phase II," TFLRF Interim Report No. 372, March 2004.

5. Gerdes, J.C., Shaver, G.M., and Roelle, M.J., Mechanical Engineering Department, Stanford University "Cycle-to-cycle Control of HCCI Engines With Variable Valve Actuation," SAE Homogeneous Charge Compression Ignition Symposium, Berkeley, CA, August 10-11, 2004.

6. Urushihara, T., Nissan Motor Co., "Compression Ignition Engine Strategies for Expansion in Operating Range in Gasoline Fueled Homogeneous Charge Compression Ignition Engine," SAE Homogeneous Charge Compression Ignition Symposium, Berkley, CA, August 10-11, 2004.