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Development of an Ultra-Safe, Ultra-Low-Emissions Natural Gas-Fueled School Bus: Phase II, Prototype Hardware Development

J. Kubesh
*Southwest Research Institute
San Antonio, Texas*

MASTER

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
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J. Kubesh
Southwest Research Institute
San Antonio, Texas

NREL technical monitor:
C.Colucci

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Executive Summary

This report summarizes work done on Phase II, "Prototype Hardware Development," of Southwest Research Institute (SwRI) Project No. 03-6871, "Development of an Ultra-Safe, Ultra-Low-Emissions Alternative-Fueled School Bus." This work is sponsored by the National Renewable Energy Laboratory under Subcontract No. ZCF-5-13519-01.

A prototype school bus was designed and constructed. This bus incorporated many new technologies to increase the safety of the bus passengers as well as pedestrians boarding and leaving the bus. These technologies emphasized increased visibility between the bus driver and pedestrians or vehicles, and included the use of high intensity discharge lighting, pedestrian and vehicle detection systems, and remote-mounted cameras. Passenger safety was also stressed, with the application of seat belts and improved emergency exits and lighting.

A natural gas-fueled engine was developed for powering the bus. The development process focused primarily on improvements to the lean operation of the engine and control system advancements. The control system development included investigations into alternative control algorithms for steady-state and transient operation, various fuel metering devices, as well as new methods for wastegate control, knock and misfire detection, and catalyst monitoring.

Both the vehicle and engine systems represent state-of-the-art technologies. Integration of the vehicle and engine is planned for the next phase of the project, followed by a demonstration test of the overall vehicle system.

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Elizabeth Green of Blue Bird, who was the project manager in charge of the prototype bus design and construction. Ms. Green provided a great deal of support and was responsible for the excellent work done on the prototype bus.

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Table of Contents

	<u>Page</u>
List of Illustrations	vi
1.0 Vehicle Development	1
1.1 NREL Bus Body Features	5
1.2 Bus Safety Features	5
1.2.1 Visibility	5
1.2.2 Occupant Safety	5
1.2.3 Pedestrian/Vehicle Safety	6
1.2.4 Lighting Systems	7
1.2.5 Other Features	7
1.2.6 NREL Bus Chassis Features	9
2.0 Fuel System Development	10
3.0 Engine Development	12
3.1 Engine Modifications	12
3.2 Turbocharger/Exhaust System Optimization	12
4.0 Engine Controls Development	19
4.1 Air-Fuel Ratio Control Investigation	19
4.2 Fuel Metering Investigation	19
4.3 Humidity Compensation	23
4.4 Wastegate Control Investigation	23
4.5 Surge Suppression Control Development	26
4.6 Gas Composition Sensing	26
5.0 Engine Diagnostics Development	28
5.1 Knock Detection and Control	28
5.2 Misfire Detection	28
5.3 Catalyst Monitoring	28
6.0 Engine Development Results	35
7.0 Presentations	39
8.0 Conclusions	40

List of Illustrations

<u>Figure</u>	<u>Page</u>
1 NREL ultra-safe, ultra-low-emission natural gas school bus	2
2 Deere CNG engine mounted in rear engine compartment	3
3 Flexible rear wheel well safety skirts	4
4 Front view of bus with holographic "STOP" sign activated	8
5 Schematic of bus chassis and CNG storage tank placement	11
6 Original 8.1L engine configuration	13
7 Modified 8.1L engine configuration with RPECS unit	14
8 Pumping work versus engine speed for two turbine housing configurations	16
9 Prototype low restriction exhaust manifold	17
10 Pressure differential across cylinder head versus speed for turbine housing and exhaust system changes	18
11 Schematic of advanced control system features	20
12 Equivalence ratio control comparison at various control algorithms: 1200 rpm, 0.1 sec tip-in, tip-out, min-max load	21
13 Equivalence ratio control comparison—various fuel metering devices	22
14 Increase in lean misfire limit because of intake air humidity increase	24
15 Efficiency improvements resulting from true "Delta-P" wastegate control	25
16 Effect of turbocharger surge suppression compensation	27
17 Typical data from knock detection and control system	29
18 Typical data from misfire detection system	30
19 Exhaust gas oxygen measurements before and after catalyst—2200 rpm, 100% load	31
20 Change in UEGO voltage output across catalyst—2200 rpm, 100% load	32
21 Exhaust gas CO measurements before and after catalyst—2200 rpm, 100% load	34

List of Illustrations (Cont'd.)

<u>Figure</u>	<u>Page</u>
22 COV _{imep} and Hc contour maps for lean limit determinations for original engine configuration—2200 rpm, 30 psia MAP	36
23 COV _{imep} and Hc contour maps for lean limit determinations for modified engine configuration—2200 rpm, 30 psia MAP	37
24 BSNO _x contour map for modified engine configuration—2200 rpm, 30 psia MAP	38

1.0 Vehicle Development

Blue Bird devoted a considerable amount of time to design, development, and construction of the prototype bus. The bus is a departure from conventional bus designs. A photograph of the new bus is shown in Figure 1.

The front portion of the body was redesigned to lower the windshield for improved visibility. Designs of the rear and center body sections were also enhanced. The center section design was changed to a heavy-duty structure with transit bus-type sliding windows. The design of the rear section, or davenport, was changed to allow improved access to the engine compartment.

New high intensity lighting technology, not currently available in the automotive industry, was incorporated for improved visibility. Discussions with Blue Bird also led to plans for incorporating new features such as a passenger restraint system and a rearview camera into the bus. Blue Bird also incorporated a Heads Up Display (HUD) unit for the bus instrumentation and rearview monitor. More advanced technologies, such as hologram warning signals and video learning centers, were also incorporated into the design of the bus.

Development work on the chassis included modifications to the frame rails so that the compressed natural gas (CNG) tanks can be removed more easily. Also, a new four wheel, anti-lock disc brake system was designed for use on the bus. Tests proved that this system provided superior braking performance.

A more complete summary of the bus features is provided in the next three sections. These three sections give details on the various innovative body, chassis, and safety features present on the bus.

1.1 NREL Bus Body Features

The bus body front section has an aerodynamic fiberglass cap with recessed strobe warning lamps. The bottom of the windshield is located approximately 12 in. above the floor line to provide maximum direct vision area. The shape of the driver's window also provides increased visibility. A wrap-around dash gives the driver easy access and visibility to instrumentation and controls. The body switch panel is to the left, chassis instruments to the front, and safety equipment monitors to the right of the driver.

The rear cap is constructed of fiberglass with recessed warning lamps. The engine door is top-hinged and provides easy access to the engine, as shown in Figure 2. The exterior lighting has been updated as well. The one-piece, fiberglass composite davenport is bonded and bolted to a steel side wall. The davenport was fabricated using a balsa core with fiberglass on both sides to provide a strong, rigid, relatively lightweight structure. A ceramic coating inside the engine compartment provides high temperature resistance to approximately 2000 °F. A large access door is provided in the center of the davenport for engine service. Two seals on the access door ensure that dust and fumes do not enter the bus body.

The body also includes skirt panels made of formed fiberglass, which extend downward from the body and cover the rear wheel wells. These skirts can be seen in Figure 3. The ground clearance of the skirt was reduced to minimize the possibility of students getting under the body. The rear wheel wells are covered by skirts to prevent students from being run over by the rear wheels.

The passenger compartment is 96 in. wide, which provides room for 39 in. school bus seats, (3 passengers per seat) with an 18 in. wide center aisle. This wider aisle allows better access to exits. The square roof bow design and 79 in. headroom provides comfortable interior space for larger students. The windows include an 11 in. high horizontal sliding sash at the top of the window for ventilation.

Figure 1. NREL ultra-safe, ultra-low-emission natural gas school bus

Figure 2. Deere CNG engine mounted in rear engine compartment

Figure 3. Flexible rear wheel well safety skirts

The passenger seat upholstery is composed of Athol Fire Block material with an aramid (Kevlar) backing. The vinyl has added fire inhibitors that reduce smoke. The bus has a vinyl floor covering with silicon carbide and aluminum oxide grains mixed throughout the vinyl, providing a slip-resistant surface. The edge trim in the stepwell is the same material, but is colored "safety yellow" to draw attention to the steps.

1.2 Bus Safety Features

1.2.1 Visibility

1.2.1.1 Data Vision

The Data Vision System is a HUD unit that projects pertinent information onto the windshield so that drivers do not have to divert their eyes from the road. Both video and instrumentation information can be displayed.

The video information will include the following:

Curbside - This will display on the HUD screen a view of the door side of the bus and curb from a camera mounted in the curbside mirror. This presentation will automatically display when the bus is stopped and the entrance door is opened. This video will be displayed for 20 seconds after the door is closed so the driver can ensure that students have cleared the side of the bus.

Rearview - The rearview video will be displayed from a camera at the rear of the bus. This presentation will automatically display when the bus is in reverse.

Interior - This video will be displayed from an interior camera and will be displayed by manual selection.

The HUD will also display several parameters from the bus instrumentation. The vehicle speed is displayed in large numbers when the bus is in operation. Warning indicators are also displayed if emergency exits are opened. The HUD also has the capability of showing other warning indicators across the bottom, such as low oil pressure, high temperature, and low air pressure.

1.2.1.2 Holograms

Several holographic technologies are employed to increase visibility. A holographic lookdown strip on the windshield will increase the driver's viewing area by allowing him/her to view a portion of the space below the windshield that is normally in his/her blind spot. Also, a holographic "STOP" sign is mounted to the right front windshield and the rear window. This sign will flash the word "STOP" when the warning lamps are on to provide greater visibility of the vehicle when stopped.

1.2.2 Occupant Safety

1.2.2.1 Passenger Restraint System

The passenger seats are 39 in. Blue Bird high-back school bus seats that meet FMVSS 222 (Federal Motor Vehicle Safety Standard #222). The seat frame is anchored to the body to withstand a 15,000-lb pull test. The seats include 3 emergency locking lap and shoulder belts integrated into the seat padding. Also, two of the seats have integrated child safety seats for small children.

1.2.2.2 Fire Suppression and Gas Detection

Protection is provided through a fire and gas detection system that uses signals from sensors strategically located in the bus and engine compartment. The driver is alerted immediately by visual and audible alarms if an overheat condition occurs and/or the air is contaminated with natural gas. The fire suppression system extinguishes a fire in its earliest stages, before it spreads into passenger areas.

1.2.2.3 Emergency Exits

Several emergency exits have been designed into the bus. Two pushout windows on each side of the body provide large openings hinged at the top. Two roof hatches provide an emergency exit route through the roof in the event the bus has rolled on its side. These roof hatches also pop up to provide fresh air ventilation during normal operation. A side emergency door is provided in the center section of the body on the driver side of the vehicle. Also, a large emergency window is provided in the rear center of the vehicle. Actuation of the exit handle releases gas cylinders that automatically open the window. Back-up lamps are also activated on opening of this window exit to provide area lighting.

1.2.3 Pedestrian/Vehicle Safety

1.2.3.1 Side Detection System

An automotive radar system detects and informs the driver of other vehicles traveling in the blind spot region of the vehicle. Driver information is provided by a visual indicator and an audio reminder when turn signals are engaged. A digital signal processor eliminates false alarms caused by objects such as trees, signs, and guardrails.

1.2.3.2 Forewarn

The Forewarn system is a proximity sensor that alerts the driver to children moving within its detection areas. One sensor monitors the area around the stepwell and the front of the bus. A second sensor located on the curbside monitors the area around the rear axle. The system is active while the bus is stopped and the door is open. If a pedestrian moves into one of the detection zones, a warning alarm sounds and a visual indicator is illuminated on the Forewarn system screen.

1.2.3.3 Vectra Safety-Vox Annunciator

The Vectra Safety-Vox Annunciator delivers several audible pre-recorded messages. These messages can be activated automatically or manually. The automatic messages include:

"Caution, this bus is backing up."	(Automatically played when bus is shifted to reverse)
"Please stand clear of doors."	(Automatically played when doors are opened)
"This bus is leaving, please stand back."	(Automatically played when doors are closed)
"Caution, this bus is turning right."	(Automatically played when the right turn signal is engaged)
"Stand clear, engine start."	(Automatically played when bus is started)

The following messages can be played manually at the driver's discretion:

"Please exit the bus now."
"Please sit down and be quiet."
"Traffic danger - please stay on the curb"
"Safe to cross in front of the bus"

1.2.4 Lighting Systems

1.2.4.1 High Intensity Discharge Lighting (HID)

HID lighting has been incorporated in the bus design because it provides a greatly expanded light pattern, increased service life, and more light output for a 20% reduction in power requirements.

Low beam headlamps are HID white lamps that illuminate the road surfaces and markings clearer and at a greater distance than traditional lighting. *Entry door lighting* is provided to illuminate the entryway. These lights are switched on automatically when headlamps are on and the entrance door is opened. *Side pedestrian safety lighting* will illuminate both side areas of the bus for pedestrians when at a stop. These lights are also switched on when the headlamps are on and the entrance door is opened. *Rear wheel safety lighting* is provided to illuminate the area in front of and to the side of each rear wheel. These lights are switched on when headlamps are on and directional, backup, or warning lamps are on.

Increased lighting is also provided in cases of emergency. *Emergency door lighting* will provide illumination in the vicinity of the emergency exit. This illumination will cover the exit doorway and the outside surrounding area. These lights are switched on when the emergency door is opened. *Interior fiberoptic emergency aisle lighting* is used to illuminate the aisle during emergencies.

1.2.4.2 Hologram "STOP" Warning Signs

Two floodlit holographic signs will be mounted to the right front windshield and the rear window. These signs will flash the word "STOP" when the warning lamps are on. This warning sign replaces the traditional STOP arm, and provides greater visibility of the vehicle when stopped. The photograph of the front of the bus in Figure 4 clearly shows this sign, as well as some of the other lighting systems.

1.2.4.3 Whelen Strobe Warning Lights

The Whelen Strobe Warning Lights are the red and amber warning lamps located at the top of the bus. These lamps are strobe lights, which give the vehicle greater visibility.

1.2.4.4 Daytime Running Lights

The bus is equipped with daytime running lights (DRL), which are headlights that turn on with the ignition. The lamps provide greater visibility to other drivers and reduce the potential for accidents. The DRL have shown to be effective in preventing collisions involving a vehicle pulling out in front of another vehicle, lane changing collisions, and head-on collisions.

1.2.5 Other Features

1.2.5.1 Global Positioning System (GPS)

The global positioning system uses precise vehicle location and data communications to enhance fleet information distribution. This system consists of a base station and vehicle unit, linked together with on-board communication equipment. The base station may be used to send messages to the driver or monitor vehicle operation. The driver can send messages back to the base station, send an emergency call with the touch of a button, and is provided with route information. The driver information is displayed on a monitor, as well as on the HUD.

Figure 4. Front view of bus with holographic "STOP" sign activated

1.2.5.2 Learning Center

The bus is equipped with a VCR, monitors, and speakers to keep children occupied and prevent them from being disruptive. The system also includes a radio and PA system.

1.2.5.3 Video Recording

Roadside, curbside, rear and interior video is recorded on a quad-screen while the bus is in operation. A security feature utilizes a motion detector to activate the interior camera when the bus is not in operation.

1.2.5.4 Cellular Phone

In addition, the vehicle is equipped with a cellular phone for emergency calls.

1.2.6 NREL Bus Chassis Features

The bus body is mounted on a 270-in. wheelbase frame. The frame consists of two C-channel rails that are one-piece and full depth from bumper to subframe. These rails are 9.62 in. high with 3 in. flanges, and the frame width is 34 in., which provides adequate space for mounting and removal of the CNG fuel storage cylinders. The chassis is equipped with a new, 4-channel Bendix ABS anti-lock brake system.

Prior to the engine development work, the bus was originally powered by a John Deere PowerTech 8.1L engine. This engine is an 8.1L, inline, six-cylinder engine. The engine develops 250 hp at a rated speed of 2200 rpm, and approximately 800 lb-ft of torque at the torque peak speed of 1350 rpm. The engine is equipped with an oxidation catalyst mounted in the muffler canister. The engine is coupled to an Allison MD-3060 5-speed automatic transmission.

2.0 Fuel System Development

The fuel storage system consists of four 15-in.-diameter, 84-in.-long cylinders manufactured by CNG Cylinder Company. These tanks have a total capacity of 6872 scf at 3000 psi. The four tanks are mounted completely between the frame rails of the chassis, as shown in the chassis schematic in Figure 5.

The system fill nozzle is located behind the front axle on the right (door) side of the bus. The fill location is covered with an access door. A system pressure gauge and manual shutoff valve are located adjacent to the fill nozzle. The CNG fuel system complies to NFPA 52 and FMVSS 303, Fuel System Integrity for Compressed Natural Gas Vehicles. The CNG storage cylinders comply to National Highway Transportation Safety Agency (NHTSA) FMVSS 304 and NGV2-2 specifications.

For several reasons, fiberglass-wrapped aluminum cylinders were substituted for the proposed all-composite cylinders in the fuel storage system. The fiberglass-aluminum tanks can be designed to offer more storage volume, and Blue Bird was more comfortable with using a fuel tank with a proven design on the bus. Blue Bird is also more likely to incorporate the fiberglass-aluminum tanks in a production version of the bus.

3.0 Engine Development

3.1 Engine Modifications

The engine used for this project was the original Deere 8.1L gas engine developed by SwRI for Deere. This development was the basis for the production John Deere PowerTech 8.1L engine. Figure 6 is a photograph of the engine in its original configuration early in the project.

Several improved engine components were provided by Deere, including new pistons, piston rings, and liners. A new cylinder head was also provided by Deere, which included new valves and valve guide seals. New bainitic steel liners were used in all cylinders, and all the pistons were replaced. The new pistons were machined with a SwRI-designed combustion chamber shape at a compression ratio of approximately 11.3:1.

The engine control hardware was also modified to convert the engine to operate with the Rapid Prototyping Engine Control System (RPECS), a PC-based full authority engine management system. The production Mesa Environmental Gas Engine Management (GEM) system was removed from the engine, but most of the sensor and actuator package was retained. New engine speed and camshaft sensors were mounted on the engine for use with the RPECS controller. A fuel injector block that houses 12 injectors instead of the production-style 8 injectors was also fabricated. A 12-injector block was used to simplify the fuel control algorithms because of injector timing concerns. The power electronic driver circuitry for interfacing the controller with the engine control actuators was also fabricated and installed.

A new exhaust manifold was fabricated and installed. A closed crankcase ventilation system, which is required for 1998 engines, was also fabricated and installed. An electrically actuated recirculation valve was added to the turbocharger compressor section; this valve was used to suppress compressor surge during rapid throttle closings. A new Sherex OPW natural gas fuel pressure regulator was also installed on the engine. This regulator is standard equipment on Deere production engines and offers better performance than the previous Mesa regulator.

A boost pressure sensor was installed before the throttle. This boost pressure sensor was used for model-based air-fuel ratio control and wastegate control. The production preturbine pressure sensor was removed from the engine. It was decided that the preturbine pressure sensor would not be used for the RPECS control system because it would not be needed for wastegate or fuel control, and concerns about the durability of exhaust-mounted preturbine sensors existed. Two knock sensors also were installed on the engine for use in the knock detection work. A relative humidity sensor was installed in the intake air tube for the engine, along with an additional air temperature sensor to be used in calculating specific humidity. The Honeywell fuel mass flow/fuel composition sensor was installed on the engine.

Figure 7 is a photograph of the engine following the conversion process. The RPECS system is shown next to the engine for clarity; in actual operation the computer was located outside the test cell.

3.2 Turbocharger/Exhaust System Optimization

In an effort to extend the lean misfire limit of the engine, potential flow restrictions in the exhaust system were investigated. The engine exhaust system was found to exert excessive back pressure on the engine. Residual exhaust gas fraction levels are very dependent on the exhaust back pressure present in the engine and high residual fractions have a deleterious effect on the lean misfire limit, since it dilutes the fuel-air mixture in the combustion chamber. Analysis of the pressure distribution in the exhaust manifold showed

Figure 6. Original 8.1L engine configuration

Figure 7. Modified 8.1L engine configuration with RPECS unit

that the current production turbocharger and exhaust manifold had excessive restriction. To address this problem, a new turbocharger match was found, and a new low restriction exhaust manifold was designed and fabricated.

Several alternative turbocharger turbine housings were obtained from Garrett (the Deere turbocharger supplier), and tested. The original turbocharger could produce boost levels beyond those required, indicating that a larger turbine housing could be used. A larger turbine housing was expected to reduce the amount of exhaust back pressure as well as reduce the amount of wastegating required, leading to higher efficiency and leaner operation. Figure 8 shows the effect of the new turbine housing tested. This plot shows pumping mean effective pressure (PMEP) as a function of engine speed. PMEP is a measure of the work required to move air into and out of the engine; a negative value indicates the engine must do work to do the gas exchange, which is undesirable. Note that the 1.04 A/R (area to radius ratio) turbine housing has less negative PMEP at high speeds than the standard 0.93 A/R turbine housing, and higher positive PMEP at low speeds.

To further optimize the exhaust system, a prototype exhaust manifold was constructed. This manifold is shown in Figure 9. Figure 10 shows the reduction in restriction offered by the new exhaust system. This plot shows the cylinder head pressure differential, which is the intake manifold pressure minus the exhaust manifold pressure. Note that the new exhaust manifold reduces the restriction enough to create a positive pressure differential across the cylinder head. Also, it should be noted that there is a large reduction in restriction resulting from the change in turbine A/R from 0.93 to 1.04.

Figure 8. Pumping work versus engine speed for two turbine housing configurations

Figure 9. Prototype low restriction exhaust manifold

Figure 10. Pressure differential across cylinder head versus speed for turbine housing and exhaust system changes

4.0 Engine Controls Development

Development of advanced engine controls was a primary focus of this project. Figure 11 is a conceptual drawing of the various control system advancements investigated under the engine controls development task. The following sections describe in detail the results of these investigations.

4.1 Air-Fuel Ratio Control Investigation

Alternative air-fuel ratio control algorithms were developed and tested during this task. Both speed-density and mass air flow-based strategies were tested. Tests were designed to determine the performance of each method of control, using the deviation of the actual equivalence ratio to the commanded equivalence ratio as the measure of comparison. It is desirable to minimize these deviations in order to approach an optimum control algorithm.

An investigation of various alternative air-fuel ratio control strategies was conducted. Several combinations of sensors and algorithms were developed and tested. These combinations include:

- (1) Standard speed-density using manifold air pressure (MAP) sensor
- (2) Enhanced speed-density with manifold filling using MAP sensor
- (3) Direct mass air flow measurement using manifold air flow (MAF) sensor
- (4) Enhanced speed-density using a MAP observer
- (5) Throttle flow model with MAP sensor feedback
- (6) Throttle flow model with MAF sensor feedback

Each of these strategies was tested over the speed and load range of the engine. Figure 12 is an example of the transient data generated during this testing. The plot shows the ability of each algorithm to control the metered air-fuel ratio, as measured by the universal exhaust gas oxygen (UEGO) sensor. Note that the enhanced speed-density with MAP observer algorithm (denoted "Observer Control" in the figure) provides the best control over air-fuel ratio, particularly compared to a standard speed-density system. Also, compared to the standard speed-density algorithm, the mass air flow system shows an improvement in air-fuel ratio control during throttle opening, but does not satisfactorily control during throttle closure. The enhanced speed-density algorithm, which includes intake manifold filling and emptying effects, provides quite favorable air-fuel ratio control at all conditions. As shown in Figure 12, the use of a model-based algorithm provided additional benefits over the enhanced speed-density system.

4.2 Fuel Metering Investigation

A significant amount of work involving the use of continuous flow, proportional solenoid valves for fuel metering was conducted. Two proportional valves were tested: a Synchro-Start valve, used in the DAI Controls ProLean control system, and a prototype proportional valve made by the G. W. Lisk Co. The valves were tested under steady-state and transient conditions to determine if they could provide the fuel metering accuracy and response required. Software modifications were also made to optimize the fuel metering control loop for these types of metering valves. Figure 13 shows a comparison between the various metering methods. The plot shows the

Advanced Features For NREL Bus Engine

Figure 11. Schematic of advanced control system features

Figure 12. Equivalence ratio control comparison with various control algorithms - 1200 rpm, 0.1 sec tip-in, tip-out, min-max load

Figure 13. Equivalence ratio control comparison -- various fuel metering devices

ability of each metering device to track the desired fueling rate during a rapid throttle transient. Note that all of the metering devices can provide good equivalence ratio control during the throttle opening transient, but the proportional valves have some problems tracking equivalence ratio adequately during throttle closures. Pulsewidth-modulated injectors were found to provide the best all-around metering performance.

A metering valve produced by the Woodward Governor Co. was similarly tested to determine its performance. The response of this valve was found to be comparable to the other continuous flow valves tested. However, the steady-state metering accuracy of this valve was found to be superior to the other continuous flow valves tested. This is likely because of the valve's reduced hysteresis effects and the ability to operate this valve without the use of flow feedback from a hot wire flow sensor.

4.3 Humidity Compensation

An investigation of humidity effects on the lean misfire limit of the engine was completed. Lean misfire appears to be the major obstacle with this engine in reducing NO_x levels below 1.5 g/bhp-hr.

Humidity was found previously in the project to have a large effect on the performance of the engine. A well-known effect of humidity on performance is the displacement of air by water vapor, which leads to a slight power decrease. This effect, however, is quite minor in comparison to the effect that humidity has on the lean misfire limit. A water injection system, designed to vary the humidity level of the intake air, was developed and used to investigate the effects of humidity on the lean misfire limit. It was found that the equivalence ratio at which lean misfire occurs is increased considerably by specific humidity levels in excess of 1.2% (average humidity levels are approximately 1.0%). This behavior is shown in Figure 14. This effect is much more significant than the air displacement effect. An additional secondary effect is the change in exhaust gas composition resulting from humidity. As humidity increases, the exhaust gas oxygen concentration for a given equivalence ratio decreases. The control system senses this decrease in oxygen concentration, attributes it to overfueling, and compensates by reducing the fuel flow, thereby leaning the engine. This effect compounds the lean misfire problem because the engine operates leaner than expected, and the lean misfire limit is higher than anticipated. As a result of this, typical humidity levels can produce a situation in which the lean misfire margin calibrated in the fuel control system is reduced to zero, and misfire results.

To address this problem, two humidity sensors were tested. A sensor that incorporates both the sensor element and signal conditioning circuitry in one package was found to provide the best performance for intake manifold installations. This sensor, however, was expensive. Because ambient air humidity measurements are necessary, a lower cost, capacitive-type sensor and external signal conditioning would probably be a better sensor for a production engine.

4.4 Wastegate Control Investigation

An investigation of the efficiency gains to be made with a wastegate control that maintains a minimal pressure drop across the throttle during part load conditions was also conducted. A true "delta-P" wastegate control was obtained at all conditions by using a constant high pressure air source instead of boost air pressure for actuation of the wastegate. This new system provided the ability to open the wastegate at any engine condition, thereby allowing larger throttle openings and less throttling losses. Figure 15 shows the efficiency gains from using this system at low loads. The efficiency gains are shown in terms of percentage points, as opposed to a percent change in efficiency. For example, a 3% change in efficiency would represent a change from 30% to 33% brake thermal efficiencies (BTE). As such, the efficiency gains in Figure 15 are significant.

Figure 14. Increase in lean misfire limit because of intake air humidity increase

Figure 15. Efficiency improvements resulting from true "Delta-P" wastegate control

4.5 Surge Suppression Control Development

Elimination of turbocharger compressor surge is desirable from both a durability and controls viewpoint. Frequent occurrences of surge can lead to turbocharger compressor thrust bearing failures. Surge elimination also allows better air-fuel ratio control because of the reduction in pressure oscillations at the fuel mixer.

A method to eliminate turbocharger surge during rapid throttle closure was found. The production turbocharger compressor recirculation valve was used in conjunction with a three-way solenoid valve. The production valve was found to be too slow for eliminating surge because of the time delay in generating the manifold vacuum required for actuating the valve. The new setup utilizes a vacuum reservoir connected to the recirculation valve via the solenoid valve. At steady-state conditions, the valve is supplied boost air pressure, so that it will remain closed. During rapid throttle closures, the solenoid valve switches to the vacuum reservoir, so that the recirculation valve is exposed to vacuum immediately, and the valve actuates quickly enough to prevent surge. Figure 16 shows that mixer inlet pressure, i.e., boost pressure upstream of the throttle, oscillations have been removed using this mechanism.

4.6 Gas Composition Sensing

A Honeywell fuel mass flow/fuel composition sensor was tested on the engine. During limited testing, the flow sensor did not appear to function correctly, and Honeywell was consulted to determine the cause of the problem. Electromagnetic interference was the likely cause. The sensor was able to distinguish between various gas blends, in terms of motor octane number, stoichiometric oxygen demand, and relative density. This technology is very promising, because it will help to compensate for the one major remaining operational variable of gas engines. Additional development would be necessary to make this sensor viable in an on-engine environment.

Figure 16. Effect of turbocharger surge suppression compensation

5.0 Engine Diagnostics Development

5.1 Knock Detection and Control

Knock sensing systems were also tested. The most successful commercially available knock sensor equipment tested was a Jenbacher integrated knock sensor/signal conditioner unit supplied by Deere. This unit could repeatably detect low levels of engine knock. The sensor was sensitive to location. However, a sensor located at the front right bottom corner of the cylinder head was found to provide a good signal and was convenient to access. A knock sensor system using piezoelectric knock sensors made by Siemens and Bosch and a signal conditioning circuit provided by Deere was also tested. Work was also done on the Gas Research Institute (GRI) magnetostrictive knock sensor project being conducted in parallel with this project. A knock sensor system using a magnetostrictive knock sensor and a SwRI-designed signal conditioning circuit was tested. This system was found to work well for detecting knock, and appears to be more sensitive for knock detection than the piezoelectric sensors. A knock control algorithm was developed and implemented on the RPECS platform. This algorithm modified both spark timing and boost pressure when knocking conditions were detected. Figure 17 shows a typical response for the knock control system under non-knocking and knocking conditions using the magnetostrictive knock sensor. This system was found to work well.

5.2 Misfire Detection

A misfire detection unit, manufactured by Lean Power, Inc., was tested. The unit detects misfire based on instantaneous crank angle velocity (ICAV) measurements. The unit was found to be sensitive to misfire and the detection threshold could be calibrated to accurately detect misfire at a single operating condition. However, as engine speed was changed significantly, the threshold level had to be recalibrated to perform well. This technique was promising, however, because the engine control system could be configured to send a speed- and load-dependent threshold signal to the unit.

In order to test the functionality of the Lean Power unit, the RPECS software was modified so that misfire could be induced in any cylinder for a programmable percentage of cycles. The test results shown in Figure 18 demonstrate that the Lean Power unit could reliably detect misfire under steady-state conditions, although the misfire threshold voltage level was adjusted as a function of speed and load. Additional work will be required to adapt the unit for use during vehicle operation.

An alternative form of misfire detection, based on ionization levels in the exhaust gas stream, was also investigated. The technique utilized an ionization sensor composed of a Langmuir probe along with an amplification circuit to determine the level of ionization in the exhaust gas. Complete misfire cycles have no ionization levels present, and slow or partial burn cycles have high ionization levels. This technique is promising and has been shown to be successful by other researchers. Misfire detection using exhaust ionization sensing was found to provide an excellent indicator of misfire at stoichiometric or rich equivalence ratios, but was less reliable at lean equivalence ratios.

5.3 Catalyst Monitoring

Catalyst monitoring using a dual UEGO scheme was found to be impractical. This method is based on measuring the difference in oxygen concentration before and after the catalyst. Analysis of exhaust oxygen measurements from both a good catalyst and an inactive catalyst is shown in Figure 19. These data show that the respective oxygen concentration differentials were so similar in magnitude that a UEGO sensor with normal signal conditioning and measurement accuracy would be unable to detect the change. Figure 20

Figure 17. Typical data from knock detection and control system

Figure 18. Typical data from misfire detection system

Figure 19. Exhaust gas oxygen measurements before and after catalyst -- 2200 rpm, 100% load

Figure 20. Change in UEGO voltage output across catalyst - 2200 rpm, 100% load

shows that a change in UEGO output of only approximately 12 mV is obtained between the working catalyst and no catalyst. The signal-to-noise ratio for a signal of this magnitude is quite low, rendering this method very difficult to use. Improved signal conditioning, which increases this voltage difference, may allow this method to become marginally effective, but alternative methods are currently being pursued. These alternative methods include using dual CO sensors and also a new catalytic-type sensor. Figure 21 shows the dramatic reduction of CO levels across a functioning catalyst. Use of CO sensors before and after the catalyst could be used to determine whether the catalyst is working or not. No data are available on the performance of the catalytic sensor at the time of this writing.

Figure 21. Exhaust gas CO measurements before and after catalyst - 2200 rpm, 100% load

6.0 Engine Development Results

To gauge the success of the engine development process, a comparison was made of the lean misfire limit of the original engine configuration and that of the final engine configuration. The original engine configuration was defined as the engine at the beginning of Phase II of this project, and the preliminary lean limit mapping data, collected previously, were used in the comparison. Data were collected in an identical manner for the new engine configuration for use in the comparison.

The lean misfire limit of an engine is a function of engine speed, manifold pressure, and spark timing. For comparison purposes, an engine speed of 2200 rpm and a manifold pressure of 30 psia was chosen, because the original engine had the smallest lean limit margin at similar conditions. This speed was also a good choice because high-speed, high-load operation tends to contribute largely to the overall emissions measured by the Federal Test Procedure transient cycle, and the emphasis of the development process was to achieve lower oxides of nitrogen (NO_x) emissions. Figures 22 and 23 show a comparison between the original engine configuration and the final engine configuration, respectively. These data are presented as a contour map as functions of equivalence ratio and spark timing, with the ranges of equivalence ratio and spark timing chosen to deliver NO_x emissions well below 2.0 g/bhp-hr (see Figure 24). Note that each figure contains two plots: a contour map for the coefficient of variation of indicated mean effective pressure (COV_{imep}), and a contour map of unburned hydrocarbon (HC) emissions. Several definitions for the lean misfire limit exist, but for this project two specific definitions were used. One plot defines the lean limit as the point where the COV_{imep} exceeds 5%, which is the point where combustion variations are considered excessive. The other plot defines the lean limit in terms of emissions, by indicating the region at which the HC emissions become unacceptably high. A total HC emissions level greater than 2500 ppm, or approximately 1.0 g/bhp-hr of nonmethane hydrocarbons (NMHC), was considered to be the lean limit. Examination of the plots in each figure indicates that these two limits are actually quite similar; however, the COV_{imep} criterion is probably the most reliable indicator of misfire limit.

The plot shows that overall, the new engine configuration delivers both lower COV_{imep} values and HC emissions. A comparison at a typical point clearly shows the difference between the new and original engine configuration. For example, for an equivalence ratio of 0.62 and a spark timing of 24 degrees, the original engine operated at a COV_{imep} of approximately 7 % and produced more than 3000 ppm HC. The new engine, however, operates at a COV_{imep} of slightly less than 5 %, and HC emissions of approximately 2200 ppm. This constitutes relative reductions in COV_{imep} and HC emissions of roughly 30% each; this is a dramatic improvement in engine performance. These conditions also will provide NO_x emissions close to the 1.0 g/bhp-hr level, as shown in Figure 24.

Figure 22. COV_{imep} and HC contour maps for lean limit determinations for original engine configuration - 2200 rpm, 30 psia MAP

Figure 23. COV_{imep} and HC contour maps for lean limit determinations for modified engine configuration - 2200 rpm, 30 psia MAP

Figure 24. BSNO_x contour map for modified engine configuration - 2200 rpm, 30 psia MAP

7.0 Presentations

Project personnel traveled to Washington, D.C., for an NREL quarterly review meeting on January 30, 1995. A summary of the project goals and plans was presented, as well as results from the Phase I design work.

A presentation was made at the Windsor Workshop for Alternative Fuels in Toronto, Ontario, on June 13, 1995. This presentation was a brief overview of the project, including descriptions of the project goals, the subcontractor team, and the proposed schedule. The presentation also gave an update on the project results to date.

A project presentation was made at the Automotive Technology Contractors Coordination Meeting in Dearborn, Michigan, on October 25, 1995. The presentation described the overall project goals and organization. Some interesting results concerning the dependence of lean burn engine performance on several factors, which were obtained from the engine development activities, were also presented.

8.0 Conclusions

The work described in this report represents state-of-the-art developments in both the vehicle and engine areas. The prototype bus is the most advanced vehicle of its kind. The features incorporated into the design of the bus definitely improve the safety of the bus. In particular, the visibility of passengers and pedestrians to the driver has been significantly enhanced. Also, the visibility of the bus to traffic and pedestrians has also been improved.

The engine development effort was quite successful. Modifications made to the design of the engine increased performance significantly. The control system advancements investigated here include the most extensive work to date for improvements in lean burn engine control.

This work should provide an excellent foundation for the integration work to be accomplished in the next phase, leading to an integrated vehicle that is ultra safe for its passengers and emits ultra-low levels of pollutants.

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