NATURAL GAS

ENGINE AND VEHICLE RESEARCH & DEVELOPMENT

FreedomCAR

Development of the High-Pressure Direct-Injection ISX G Natural Gas Engine

PROJECT IMPACT

This project developed the heavy-duty ISX G natural gas engine with advanced emission reduction strategies, which demonstrated oxides of nitrogen (NO_X) emissions of 0.6 g/bhp-hr and diesel-like thermal efficiency. By 2010, the U.S. Environmental Protection Agency (EPA) will require heavy-duty engine NO_X emissions of 0.2 g/bhp-hr or less (Figure 1). The technology developed in this project may help heavy-duty natural gas engines meet the 2010 requirements while being cost competitive with diesel engines. It is anticipated that this would lead to more extensive use of natural gas vehicles, resulting in reduced petroleum consumption.

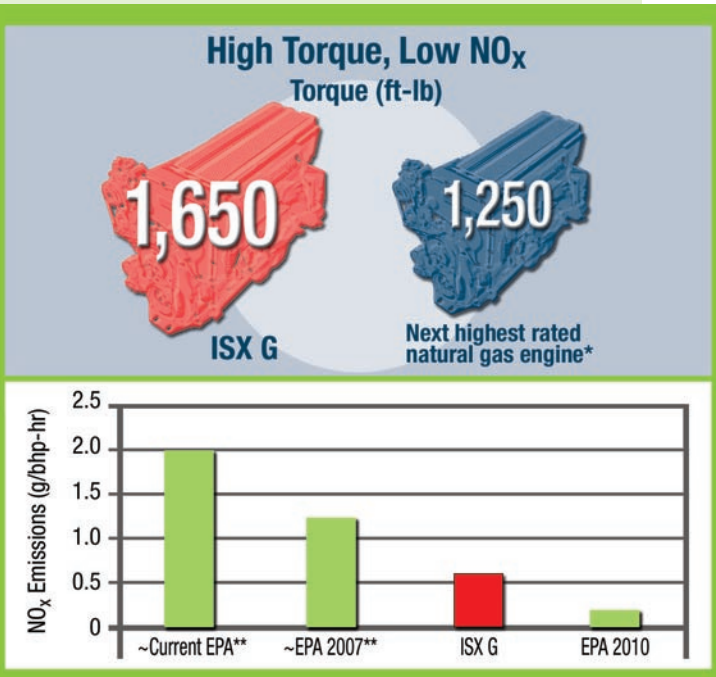

Figure 1. Demonstrated Torque and NO_X Emissions of the ISX G Engine Developed in this Project

* This statement is based on natural gas engines listed in the 2004 U.S. Department of Energy *Heavy Vehicle and Engine Resource Guide*. To obtain this document, visit the Alternative Fuels Data Center at *www.eere.energy.gov/cleancities/afdc*.

** This is an interpretation of the EPA NO_X standard. For more information on heavy-duty engine emission standards, visit *www.epa.gov*.

PROJECT GOALS

Natural gas is a domestically available resource. The U.S. Department of Energy supports natural gas vehicle R&D through its FreedomCAR and Vehicle Technologies (FCVT) Program to help the United States reduce its dependence on imported petroleum and to pave the way to a future transportation network based on hydrogen. Natural gas vehicles can also reduce emissions of regulated pollutants compared with diesel vehicles.

This project was part of the Next Generation Natural Gas Vehicle activity, which is supported by the FCVT Program, the South Coast Air Quality Management District, and the California Energy Commission. One goal of this activity is to develop advanced, commercially viable, medium- and heavy-duty natural gas engines and vehicles that will meet EPA 2007/2010 heavy-duty emission levels before 2007.

The goal of this project was to demonstrate prototype engine and vehicle technologies capable of reduced exhaust emissions and competitive operating costs for heavy-duty natural gas vehicle applications. Specific targets included the following:

- 1,650 ft-lb peak torque
- 450 hp rated power
- 40% peak thermal efficiency
- 0.5 g/bhp-hr NO_X emissions
- 0.1 g/bhp-hr particulate matter (PM) emissions.

THE HIGH-PRESSURE DIRECT-INJECTION SYSTEM

The project was led by DOE's National Renewable Energy Laboratory (NREL), Cummins, Inc., and Westport Innovations, Inc. The 15L ISX G engine is a Cummins ISX diesel engine modified to use the Westport-Cycle™ high-pressure direct-injection (HPDI™) fuel system. In this system, natural gas is delivered to the engine at high pressure along with a small amount of diesel fuel that ignites the natural gas in a compression-ignition (diesel) cycle. This enables the engine to retain the efficiency advantage of compression-ignition while consuming natural gas as its primary fuel. In this project, an ISX G engine was fitted with emission reduction equipment, calibrated, and tested over steady-state and transient cycles.

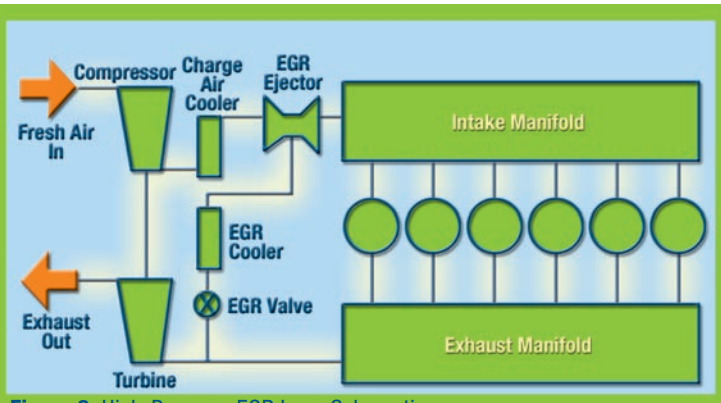

Figure 2. High-Pressure EGR Loop Schematic

Note: The final configuration included a turbine and compressor specifically designed for natural gas operation and two EGR coolers.

EMISSION REDUCTION STRATEGIES

The ISX G engine was equipped with a high-pressure exhaust gas recirculation (EGR) loop, which included a variable geometry turbocharger (VGT), EGR valve, and EGR cooler (Figure 2). In this EGR system, part of the exhaust gas is taken directly from the exhaust manifold and passed through an EGR cooler before being reintroduced into the intake air and back into the engine. The recirculated exhaust gases absorb some of the energy released during combustion of the fuel. This decreases peak combustion temperature, the most critical factor favoring high NO_X formation. The EGR fraction also displaces fresh oxygen, making less available for combustion and thus reducing the probability of interaction between nitrogen and oxygen atoms even under lean conditions.

The engine was further modified to include a smaller trim VGT compressor and second EGR cooler to enable the higher EGR rates needed to achieve the low-NO_X emission target. The second EGR cooler was installed in series with the original; this demonstration configuration is not yet practical for installation in a vehicle. A platinum/palladium oxidation catalyst was used to reduce nonmethane hydrocarbons, carbon monoxide, and PM emissions.

ENGINE CALIBRATION AND TESTING

The ISX G engine was initially calibrated and tested over the ESC 13-mode and AVL 8-mode steady-state tests, then fine-tuned for the transient Federal Test Procedure (FTP). The FTP is a 20-minute test that simulates city and highway driving and is used by the EPA to certify heavy-duty engines. The objective of the calibration and testing was to reduce NO_X emissions as much as possible without greatly increasing PM emissions and fuel consumption. Parameters such as pilot diesel and natural gas fuel quantities and timing, fuel pressures, and EGR fractions were varied to achieve optimization.

RESULTS AND CONCLUSIONS

Table 1 shows results obtained over the ESC and FTP. This project showed that the HPDI natural gas fueling system, a second EGR cooler, a smaller trim VGT compressor, and an oxidation catalyst enable significant emissions reductions on the ISX engine platform. Testing and modeling results also indicated that several untried hardware changes could improve performance and emissions. These are detailed in the full project report (see Related Publications and Web Sites below).

Table 1. ISX G Emission Test Results

	ESC 13-mode	FTP
Peak torque	N/A	1,650 ft-lb
Rated power	N/A	450 hp
Thermal efficiency (average)	36.1%	34.1%
Thermal efficiency (peak)	39.5%	N/A
NO_x (g/bhp-hr)	0.36	0.6
PM (g/bhp-hr)	0.04	0.03
THC (g/bhp-hr)	2.28	5.0
NMHC (g/bhp-hr)	0.20	Not measured
Methane (g/bhp-hr)	2.08	Not measured
Natural gas substitution*	94%	Not measured

NMHC—nonmethane hydrocarbons; NO_x—oxides of nitrogen; PM—particulate matter; THC—total hydrocarbons.
* Proportion of energy provided by natural gas, with remainder provided by diesel.

RELATED PUBLICATIONS AND WEB SITES

The report *Development of the High-Pressure Direct-Injected, Ultra Low-NO_X Natural Gas Engine*, which describes this ISX G project in detail, is available from the Alternative Fuels Data Center at *www.eere.energy.gov/cleancities/afdc*. Hard copies are available from the National Alternative Fuels Hotline at 1-800-423-1363 or *hotline@afdc.nrel.gov*. The Next Generation Natural Gas Vehicle activity is part of DOE's Natural Gas Vehicle Technology Forum. For more information, visit *www.nrel.gov/vehiclesandfuels/ngvtf*.

Send Questions or Comments to

NREL Gaseous Fuels Team

Mike Frailey
National Renewable Energy Laboratory
1617 Cole Blvd., MS 1633
Golden, CO 80401
Phone: 303-275-3607
Fax: 303-275-4415
E-mail: mike_frailey@nrel.gov

Produced by the

National Renewable Energy Laboratory (NREL)
NREL is a U.S. Department of Energy National Laboratory
Operated by Midwest Research Institute • Battelle

DOE/GO-102004-1940 ■ August 2004

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 20% postconsumer waste.

For more information contact:

EERE Information Center
1-877-EERE-INF (1-877-337-3463)
www.eere.energy.gov

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.