NATURAL GAS
ENGINE AND VEHICLE
RESEARCH & DEVELOPMENT
FreedomCAR
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Demonstration of a Low-NO_x Heavy-Duty Natural Gas Engine

PROJECT IMPACT

This project demonstrated a heavy-duty natural gas engine emission reduction strategy resulting in oxides of nitrogen (NO_x) emissions of 0.54 g/bhp-h and particulate matter (PM) emissions of 0.004 g/bhp-h. Reducing NO_x and PM emissions is crucial for meeting increasingly strict regulations (Figure 1). By 2010, the U.S. Environmental Protection Agency (EPA) will require NO_x emissions of 0.2 g/bhp-h or less and PM emissions of 0.01 g/bhp-h or less. The technology demonstrated in this project may help natural gas engines meet the 2010 requirements. It is anticipated that this would lead to more extensive use of natural gas vehicles, resulting in reduced petroleum consumption.

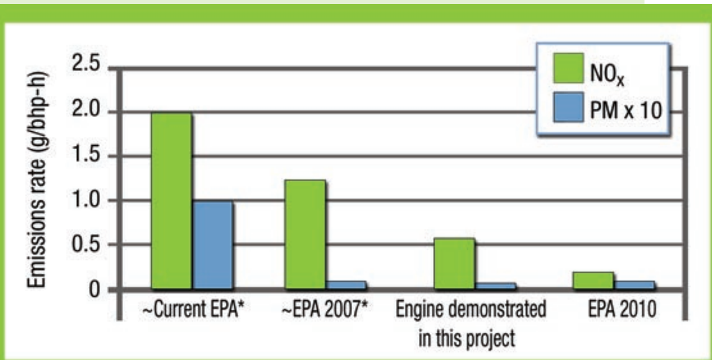

Figure 1. Progress Towards Meeting Increasingly Strict EPA Emission Standards

* This is an approximate 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 research through its FreedomCAR and Vehicle Technologies (FCVT) Program to help the United States reduce its dependence on imported petroleum. 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 the 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 liquefied natural gas vehicle applications. Specific targets included reduction of NO_x emissions in two phases: 1) below 0.5 g/bhp-h, and 2) below 0.2 g/bhp-h. Other targets included PM emissions below 0.01 g/bhp-h and maintained engine efficiency.

DUAL-FUEL ENGINES

The project was led by DOE's National Renewable Energy Laboratory (NREL) and Clean Air Power (formerly Clean Air Partners). Clean Air Power, in partnership with Caterpillar, Inc., has developed Dual-Fuel™ natural gas engine technology. The Dual-Fuel system converts standard Caterpillar diesel engines to run primarily on natural gas; a small amount of diesel fuel consumed along with the natural gas enables compression ignition. In this project, a Caterpillar C-12 Dual-Fuel engine (410 hp/1,250 ft-lb) was equipped with improved combustion and aftertreatment strategies.

EMISSION REDUCTION STRATEGIES

Two emission reduction strategies were proposed. Passive clean and cold exhaust gas recirculation (PACCOLD-EGR), which combines diesel particulate filter (DPF) and EGR technologies, was expected to reduce NO_x emissions to 0.5 g/bhp-h. Active clean and cold (ACCOLD) EGR, which combines the PACCOLD-EGR system with a lean-NO_x catalyst, was expected to reduce NO_x emissions further, to 0.2 g/bhp-h. Use of a catalyzed DPF was expected to reduce PM emissions to below 0.01 g/bhp-h. During the project, it was concluded that the proposed ACCOLD-EGR system could not meet the project objectives, and this strategy was abandoned.

PACCOLD-EGR

In an EGR system, part of the exhaust gas is reintroduced into the intake air and induced 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 oxygen, making less available for combustion, thus reducing the probability of interaction between nitrogen and oxygen even under lean conditions.

The PACCOLD-EGR system uses a full-time DPF in the exhaust, which greatly simplifies the EGR system because cooled EGR can be injected directly into the turbo compressor inlet. This is possible because the exhaust gas has been filtered and is

clean enough to enter the compressor and aftercooler without risk of contamination. The Clean Air Power PACCOLD-EGR system (Figure 2) consists of an Engelhard DPX™ catalyzed DPF, EGR cooler and Venturi assembly (both designed and fabricated by Clean Air Power), and EGR filter.

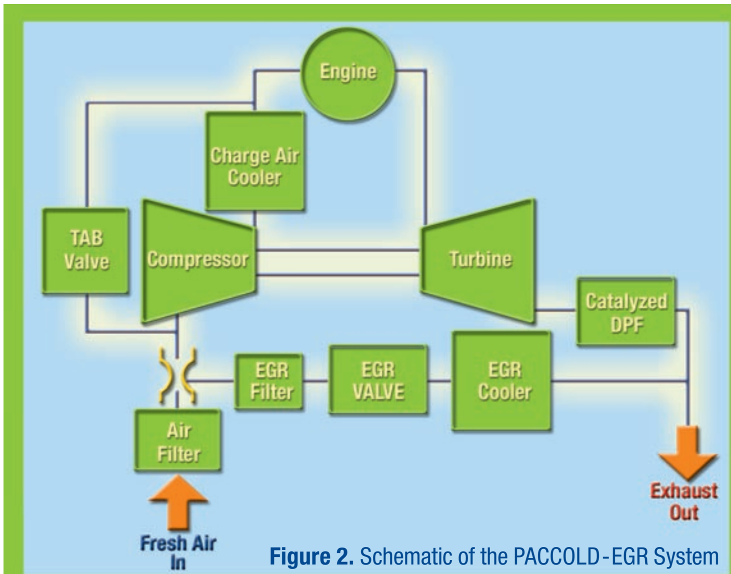

Figure 2. Schematic of the PACCOLD-EGR System

ENGINE TESTING

Engine tests were designed to evaluate the effect of PACCOLD-EGR in conjunction with existing control variables and strategies used on current C-12 Dual-Fuel engines. A baseline engine and one with the PACCOLD-EGR system were tested over the 13-mode European Stationary Cycle (ESC). Several factors were manipulated to optimize emissions and fuel economy: EGR rate, gas lambda (excess air ratio), pilot injection timing, EGR temperature, and air charge temperature.

RESULTS AND CONCLUSIONS

The following average emissions and fuel consumption were demonstrated with the PACCOLD-EGR system over the ESC:

Nonmethane hydrocarbons (NMHC)	1.44 g/bhp-h
Carbon monoxide (CO)	0.05 g/bhp-h
NO_x	0.54 g/bhp-h
PM	0.0037 g/bhp-h
Brake-specific energy consumption (BSEC)	7,610 Btu/bhp-h

Figure 3 compares emissions and energy consumption from engines with and without the PACCOLD-EGR system.

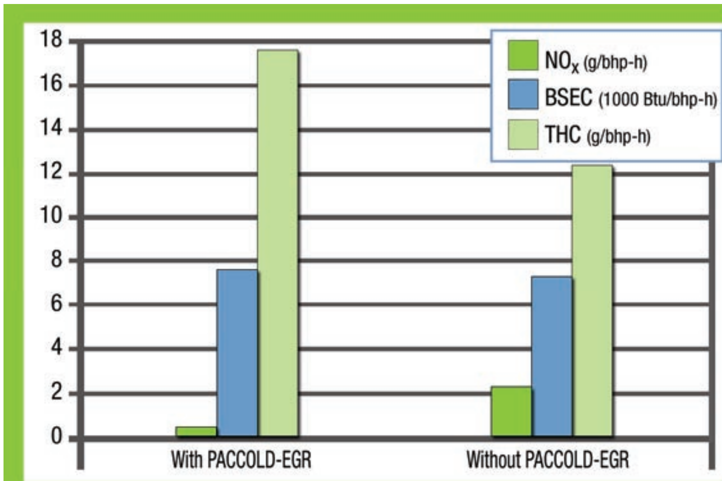

Figure 3. Emissions and Energy Consumption over the ESC for Caterpillar C-12 Dual-Fuel Engines with and without the PACCOLD-EGR System

The project resulted in the following conclusions:

- The C-12 Dual-Fuel engine equipped with the PACCOLD-EGR system demonstrated 0.54 g/bhp-h NO_x and 0.004 g/bhp-h PM.
- The PACCOLD-EGR system is based on fully validated aftertreatment components available today (the California Air Resources Board has verified the Clean Air Power catalyzed DPF for use with some Dual-Fuel engines).
- A reduction in NO_x of about 4% for 1% of EGR mass fraction is suggested as a working guideline.
- EGR mass fraction and pilot injection timing are the dominant parameters affecting NO_x emissions.
- Unfavorable tradeoff of hydrocarbons for NO_x is evident with retarded pilot injection timing.

Successful implementation of the PACCOLD-EGR technology will rely on the integration into a commercial package of catalyzed DPF and EGR components.

RELATED PUBLICATIONS AND WEB SITES

The report *Next Generation Natural Gas Vehicle Program Phase I: Clean Air Partners 0.5 g/hp-h NO_x Engine Concept* is available from the Alternative Fuels Data Center at *www.afdc.doe.gov.* Hard copies are available from the 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.ott.doe.gov/ngvtf.*

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