Advanced Natural Gas Vehicle Development

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The Applied Physics Laboratory, working in conjunction with private industry, has developed a compact-sized natural gas-powered automobile. This prototype, the Advanced Natural Gas Vehicle, operates with a high-compression, four-valve-per-cylinder engine tailored to natural gas, incorporates chassis and rear-suspension modifications to increase space for fuel storage, and uses composite-material tanks arranged into fuel storage assemblies as well as specially designed tires. The integrated design of the fuel storage system and chassis enables the prototype to carry sufficient compressed natural gas fuel for a 300-mi driving range, while maintaining adequate trunk storage space. Ultralow exhaust emissions have been demonstrated.

INTRODUCTION

The nearly 500 million vehicles in use worldwide today account for about 50% of yearly global oil consumption. If the trend in vehicle proliferation continues, 1 billion cars, trucks, and buses will be operating by the year 2030. This rapid growth poses many problems in terms of demand for oil, dependency of importing countries on the Middle East, large international trade deficits, and regional/global threats to the environment, both from exhaust emissions and oil spills.

A viable alternative to oil for vehicle transportation is natural gas, which has a long-established record around the world as a clean-burning truck/bus fuel. A 1989 survey[1] found more than 700,000 natural gas vehicles (NGVs) operating in nearly 40 countries worldwide, including Italy, the former Soviet Union, Argentina, New Zealand, and Canada.

Today over 30,000 light- to medium-duty NGVs (trucks, delivery vans, buses) in the United States operate out of centralized refueling stations. A small number of full-sized passenger sedans (generally used as taxis) also have been converted to operate on natural gas. Fuel tanks in these NGVs occupy much of the trunk space in order to provide a driving range of 125 to 175 mi. This illustrates one principal drawback of compressed natural gas (CNG)—its low energy density. Compared with gasoline, natural gas compressed to 3000 psig has about 25% of the energy content on a volume basis and about 33% of the energy content on a storage weight basis (considering the weight of both the natural gas and the pressure tank).

An untapped, potential market for the use of natural gas is the vehicle class that includes the compact-sized automobile (≈2500 lb) used extensively in local/federal government fleets, in corporate vehicle pools, and by the general public. These vehicles represent a large portion of the automobiles on the road today.

In addition to offering a new NGV marketplace, modern compact-sized, front-wheel-drive sedans are well-suited to run on natural gas. These vehicles are highly energy-efficient, providing overall fuel mileage of ≈30 mpg, which can translate into increased driving range. In addition, the front-wheel-drive layout and efficient packaging offer the potential to store sufficient CNG for ranges comparable to gasoline-fueled automobiles without substantially reducing trunk storage capacity.

The overall objective of the Laboratory's Advanced Natural Gas Vehicle (ANGV) project is to demonstrate a means for fully integrating CNG into a compact-sized automobile. The project has five goals (Fig. 1): (1) to achieve a city/highway operating range of at least 300 mi, (2) to meet the California Air Resources Board's Ultra Low Emission Vehicle emissions standard, (3) to maintain or surpass the baseline performance of the modified vehicle, (4) to minimize the likelihood of significant CNG leakage in the event of a severe collision, and (5) to maintain at least 75% of the trunk space.

As shown in Fig. 1, many of the lines overlap, highlighting a synergism that can be achieved through a systematic design focused on the use of CNG. For example, the means for achieving the ≥300-mi driving range (e.g., small-displacement engine optimized for efficient combustion of natural gas) also helps meet the low exhaust emissions goal.

Figure 1. The Laboratory has identified five goals for the Advanced Natural Gas Vehicle project as well as means for achieving those goals. (CARB ULEV = California Air Resources Board Ultra Low Emission Vehicle, NGV = natural gas vehicle, CNG = compressed natural gas.)

The Laboratory's ANGV prototype incorporates the following changes into the baseline (original equipment manfacturer) vehicle (Fig. 2): (1) replacing the baseline engine with a small-displacement, high-compression engine tailored to natural gas fuel, (2) modifying the rear suspension and underchassis to create additional space for CNG storage, (3) employing high-strength, lightweight all-composite tanks arranged in a storage system designed with a high margin of collision safety, and (4) applying run-flat (built-in deflation support) tire technology. The following discussion provides additional information on these design changes and presents preliminary prototype vehicle performance results.

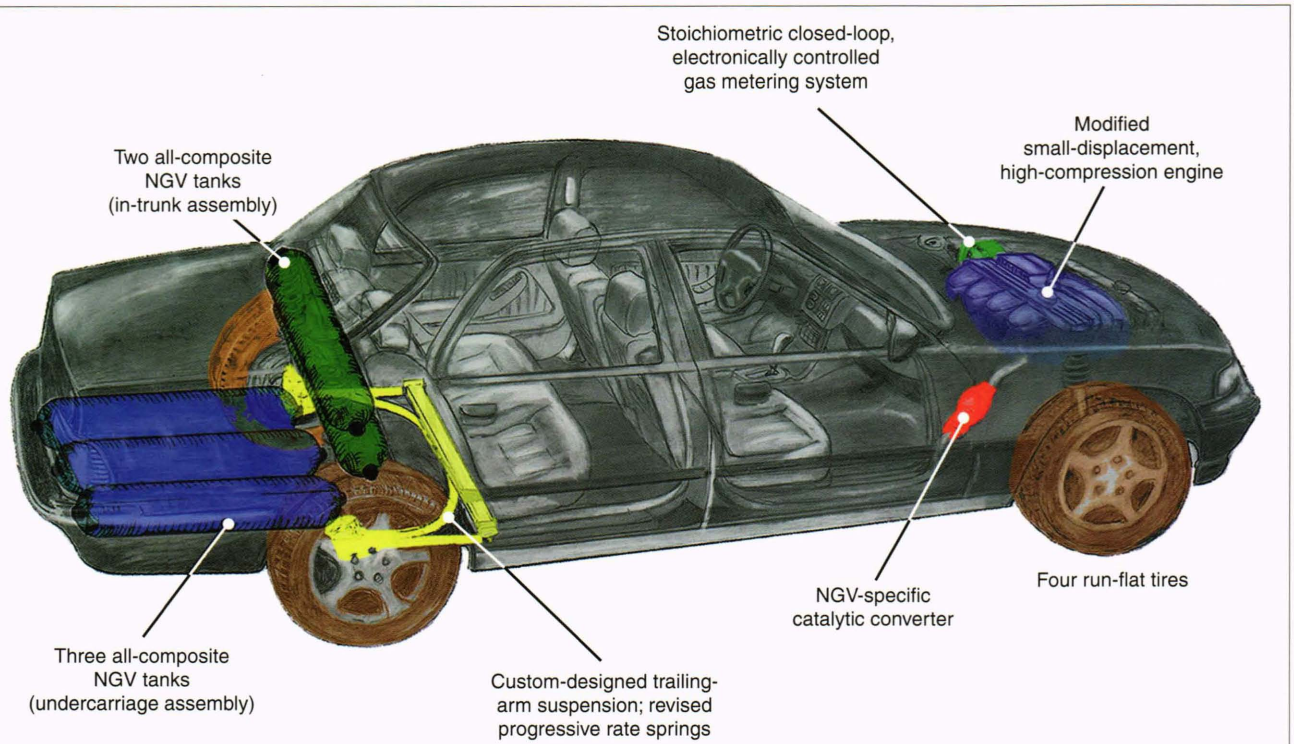

Figure 2. Modifications made to the baseline vehicle for the Advanced Natural Gas Vehicle project.

ENGINE DEVELOPMENT

To achieve the range, performance, and emissions goals, the engine must make full use of the energy potential available in natural gas. In straightforward add-on conversions from gasoline to natural gas, there is generally a 10% to 12% loss in engine power due to the smaller charge of fuel for the stoichiometric combustion of natural gas. Increasing the compression ratio is the key to regaining higher specific output while simultaneously improving engine efficiency. Natural gas is well-suited to high compression ratio operation because of its inherently high octane rating of about 130.

Working in conjunction with Chesapeake Automotive Enterprises of Reisterstown, Maryland, APL assembled a small-displacement (1.6-L), high-compression (12.7:1) engine that forms the basis of the power plant for the ANGV. The engine is based on the free-breathing, four-valve-per-cylinder design with dual-path induction, which features a central spark plug and dome-shaped combustion chamber. Basic research on natural gas engines[2] has shown that the shape of the combustion chamber and the location of the spark plug are critical for efficient combustion.

A closed-loop electronically controlled fuel metering system was tailored to the engine with support from the manufacturer. Ignition spark advance, intake manifold control, and management of exhaust gas recirculation were optimized for performance on a chassis dynamometer. Engine exhaust treatment uses a palladium/rhodium methane-specific catalytic converter.

The engine is mated to a four-speed automatic transaxle with driver-controlled overdrive. The powertrain provides both excellent performance and high fuel economy. The ANGV proto-type has demonstrated city/highway fuel mileage of 27/38 mpg, respectively, in gallons of gasoline equivalent (124 standard cubic feet of natural gas equals 1 gal of gasoline).

REAR SUSPENSION/ CHASSIS MODIFICATIONS

To carry sufficient CNG onboard for the 300-mi range, we increased the under-carriage chassis space available for fuel storage by (1) replacing the baseline lateral-link rear-suspension system with a custom-designed trailing- arm suspension system and (2) replacing the spare-tire wheel well with a flat floor panel. The trailing-arm rear-suspension system eliminates lateral track bars/links to increase open space between the rear wheels. The vehicle chassis rear frame provides a rigid structure for mounting the new suspension system. The APL-redesigned rear suspension was developed to maximize compatibility with the baseline vehicle's spring/strut units and hub/brake assemblies. To offset the added weight of the natural gas storage cylinders, we used slightly longer rear springs to maintain ride height. Finite-element stress analysis of the suspension ensured a safe and lightweight design. Figure 3 is a computer-aided design image of the essential components of the trailing-arm rear-suspension system, showing its physical relationship to the underbody fuel storage tanks. Figure 4 shows a test fit of the manufactured trailing-arm rear-suspension and underbody fuel storage systems on a chassis mock-up located at APL.

Elimination of the spare tire increased chassis space for fuel storage. To compensate for the absence of a spare tire, the ANGV uses run-flat tires. These tires contain a built-in deflation support that enables the vehicle to be driven safely at highway speeds with no tire air pressure for up to 250 mi. A low-pressure warning system alerts the driver that a tire is operating in the run-flat mode. Goodyear Tire and Rubber Company of Akron, Ohio, specifically manufactured these extended mobility run-flat tires for the ANGV prototype.

COMPRESSED NATURAL GAS FUEL STORAGE SYSTEM

The ANGV fuel storage system comprises two assemblies: the underbody tank assembly and the trunk

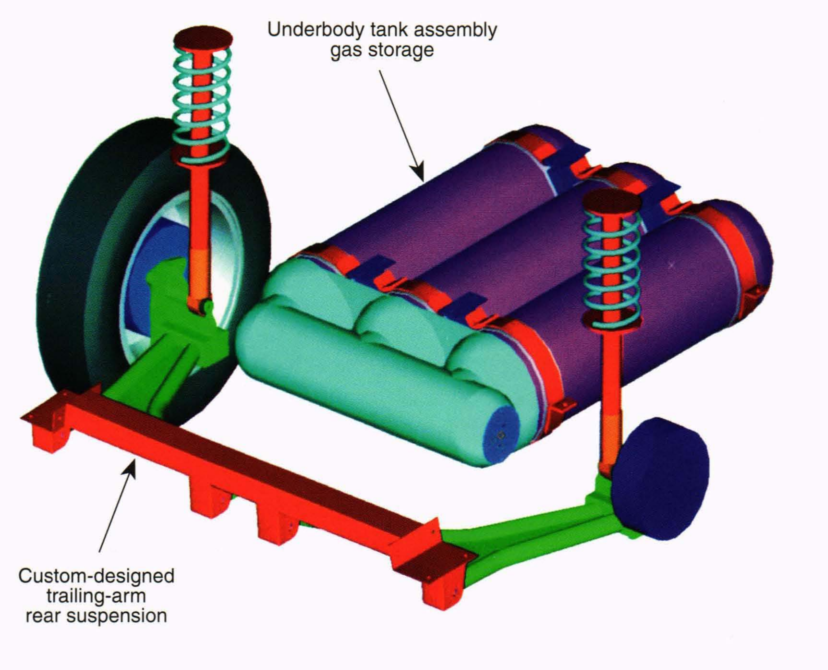

Figure 3. Computer-aided design image of the trailing-arm rear-suspension and underbody storage assemblies.

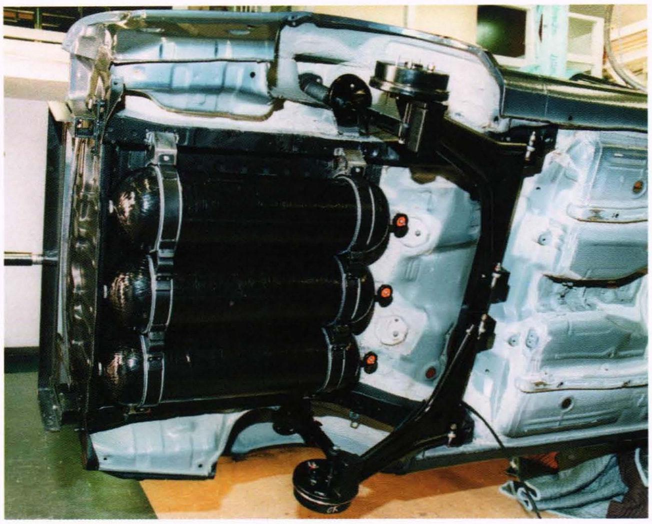

Figure 4. Form/fit check of the trailing-arm rear-suspension and underbody storage assemblies on the chassis mock-up.

tank assembly. Each assembly uses steel brackets to group tanks (three for the underbody and two for the trunk tank assembly) together into a unit, stainless steel lines for interconnecting the tanks, and manual isolation valves and an electrical solenoid valve for isolating each assembly from the fuel delivery system.

The APL-designed storage system adheres to specifications set by the National Fire Protection Agency. The system uses five all-composite tanks developed by Brunswick Composites[3] of Lincoln, Nebraska. The tanks are rated for 3600-psig operating pressure.

The all-composite, high-strength, lightweight tank features a liner manufactured from high-density polyethylene; metallic bosses are molded directly into the line, which is completely encased in a hybrid of carbon and fiberglass materials embedded in epoxy resin. The tanks have been qualified to a stringent government/industry standard that includes severe impact, bonfire, gunfire, abrasion, and repeated pressure cycling.

The storage tanks are highly unlikely to be the cause of a leak in the event of a severe collision. The more likely source is the valves/lines associated with the storage and delivery systems. For that reason, we developed a multiple-layered approach for the ANGV storage system that includes allowance for storage system movement in a severe collision, physical protection of valves/lines, and isolation from the fuel delivery system under certain conditions.

VEHICLE PERFORMANCE AND TESTING

After completing vehicle assembly, we road-tested the ANGV prototype to establish the following operating characteristics:

- ANGV fuel capacity is 9.3 gal of gasoline equivalent, with an overall fuel economy of 32 mpg for a range of 300 mi in combined city/highway driving.
- The trunk capacity of the ANGV is about 75% that of the baseline automobile, with most of the loss occurring in the space between the rear strut towers and under the package shelf. The curb weight of the ANGV is 240 lb more than that of the baseline automobile, with a slightly more rear-biased weight distribution of 57%/43% (front/rear).
- Handling, performance, and ride quality are similar to those found in most contemporary, front-wheel-drive compact sedans. The acceleration performance of 0 to 60 mph equals that of the baseline automobile equipped with the same size engine and automatic transmission.

In addition, we used a series of FTP (Federal Test Procedure) tests to calibrate engine timing, exhaust gas recirculation control, and the fuel mixer system for emissions and performance. The latest FTP test results were compared with the 1994 federal standard (Fig. 5) and the stringent California emissions standard. These FTP results were obtained with the catalytic converter aged after about 4000 mi of driving.

THE FUTURE

The Director of APL, Gary Smith, publicly introduced the ANGV prototype on 4 November 1994 to U.S. Department of Energy Deputy Secretary William White. Following the public introduction, the ANGV

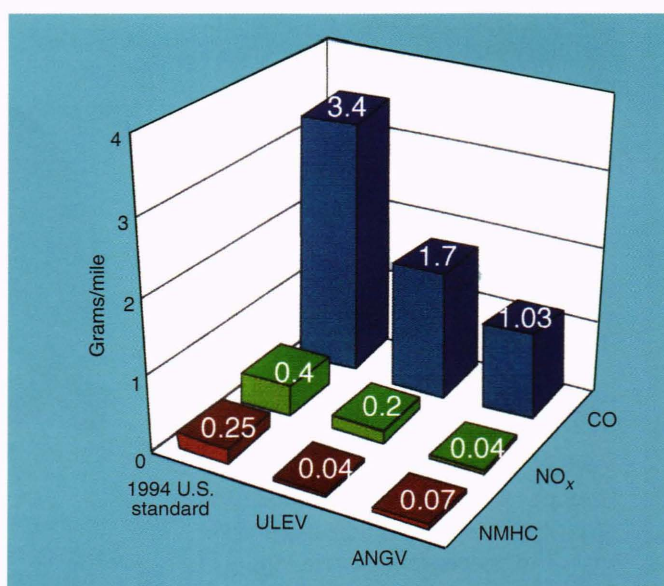

Figure 5. Advanced Natural Gas Vehicle (ANGV) Federal Test Procedure exhaust emissions compared with U.S. and California Ultra Low Emission Vehicle (ULEV) standards for carbon monoxide (CO), oxides of nitrogen (NO_x), and nonmethane hydrocarbon (NMHC).

prototype vehicle will undergo real-world evaluation in the APL vehicle fleet, which operates in the Baltimore–Washington region. The ANGV will be used as any other vehicle; data will be collected on driver acceptance, durability, exhaust emissions, and overall utility of the vehicle.

Work is under way to reduce the weight, complexity, and cost of the CNG storage system through a joint APL/Brunswick Composites effort to develop an integrated storage system. The introduction of precise, gaseous fuel injection is ongoing to further improve performance and fuel economy and reduce exhaust emissions.

The ultimate goal of the ANGV project is the design of a compact-sized, CNG-powered automobile that in every way—range, drivability, performance, and safety—is the same as its gasoline-powered equivalent, yet exhibits dramatically lower exhaust emissions.

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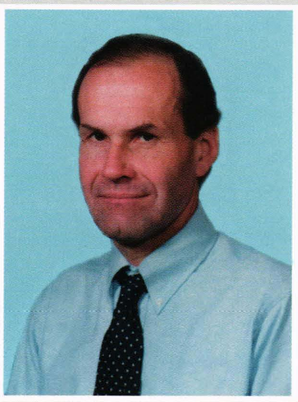
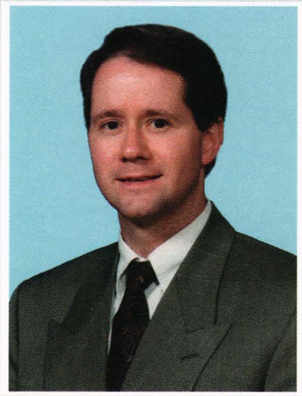
THE AUTHORS



JOHN J. WOZNIAK received a B.S. from Lowell Technological Institute in 1966 and an M.S. from the University of New Hampshire in 1971, both in mechanical engineering. He served in the Air Force from 1966 through 1970 working on fluidic systems for arming and fuzing. Mr. Wozniak joined APL in 1973 and during 1973–1979 worked as a project engineer assisting the Navy's Strategic Systems Project Office with the development of systems related to missile underwater launch. In 1979, he joined the Aeronautics Department and has worked on a wide variety of projects focusing on the design and analysis of prototype systems for military and civilian use. He has worked with the medical staff at the Johns Hopkins Hospital and holds several patents that have medical and biomaterial applications. In 1989, Mr. Wozniak initiated a broad-based study of alternative fuels for land transportation and later led a small team of engineers exploiting options for natural gas vehicle development. In 1992, he became program manager of the Laboratory's Advanced Natural Gas Vehicle project. Mr. Wozniak is a member of the Principal Professional Staff at APL and is Assistant Supervisor of the Fluid Dynamics Group.



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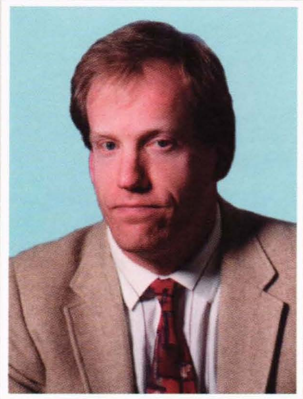

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