ANL/ESD-37

Assessment of PNGV Fuels Infrastructure

Phase 2 Report: Additional Capital Needs and Fuel-Cycle Energy and Emissions Impacts

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Phase 2 Report: Additional Capital Needs and Fuel-Cycle Energy and Emissions Impacts

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Foreword

This report documents the methodologies and results of Argonne National Laboratory's assessment of additional capital needs and fuel-cycle energy and emissions impacts associated with using various fuels in vehicles that are three times as fuel-efficient as today's typical light-duty vehicles. These "3X vehicles" are being developed in the Partnership for a New Generation of Vehicles (PNGV) program. In 1994, the National Research Council's Peer Review Committee on the PNGV program called for an assessment of the potential impacts of 3X vehicles on the fuel infrastructure. In response, the U.S. Department of Energy (DOE) tasked Argonne National Laboratory (ANL) to investigate these impacts. In August 1995, the results of a preliminary analysis were presented to the Peer Review Committee. In January 1997, the results of the first phase of Argonne's analysis were published. The second phase of Argonne's analysis, which covers additional fuels and issues identified during the phase 1 effort, is documented in this report.

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Abstract

Argonne National Laboratory assessed the incremental capital needs and fuel-cycle energy and emissions impacts of using each of 11 different fuels in light-duty vehicles with tripled fuel economy (referred to as 3X vehicles). These 3X vehicles are being developed by the Partnership for a New Generation of Vehicles (PNGV). Findings indicate that investments in new fuel-production and -distribution facilities could be relatively modest for alternatives that are relatively similar to conventional fuels (e.g., reformulated gasoline or diesel, or relatively high percentage blends of those fuels). By contrast, alternative fuels with little established infrastructure tend to require far more capital investment. These higher cost alternatives do, however, provide greater energy and environmental benefits.

Summary

This report presents the methodologies and results of Argonne National Laboratory's assessment of the incremental capital needs and fuel-cycle energy and emissions impacts of using each of eleven different fuels in vehicles with tripled fuel economy (3X vehicles). These 3X light-duty vehicles are being developed by the government-industry Partnership for a New Generation of Vehicles (PNGV). Eleven fuels were included in the assessment: reformulated gasoline (RFG), reformulated diesel (RFD), methanol, ethanol, dimethyl ether (DME), liquefied petroleum gas (LPG), compressed natural gas (CNG), liquefied natural gas (LNG), biodiesel, Fischer-Tropsch diesel, and hydrogen. RFG, methanol, ethanol, LPG, CNG, and LNG were assumed to be burned in spark-ignition, direct-injection engines. RFD, Fischer-Tropsch diesel, biodiesel, and dimethyl ether were assumed to be burned in compression-ignition, direct-injection (CIDI) engines. Hydrogen, RFG, and methanol were assumed to be used in fuel-cell vehicles.

Impacts to the infrastructure that produces and distributes each of these fuels were analyzed under high and low scenarios of potential 3X vehicle market penetration. The scenarios established supply requirements (i.e., the volume of each fuel needed to meet the demands of all 3X vehicles likely to be on the road in each year of the analysis), which were used to specify the number and type of new facilities needed in each year. The cost analysis then translated facility requirements into capital costs. Results indicate that substantial capital investment will be needed to build new fuel production plants and to establish distribution infrastructure for methanol, ethanol, dimethyl ether, hydrogen, and CNG. With the exception of CNG and, to a certain extent, LNG, capital needs for production facilities far exceed those for distribution infrastructure for all fuels studied. Among the eleven fuels, hydrogen has the largest capital needs, with DME and, under certain assumptions, CNG distant runners up.

The fuel efficiency gain by 3X vehicles translated directly into reductions in total energy demand, fossil energy demand, and greenhouse gas (primarily CO_2) emissions. The combination of fuel substitution and fuel efficiency resulted in substantial petroleum displacement and large reductions in urban emissions of volatile organic compounds and sulfur oxide for all propulsion system/fuel alternatives considered. Although urban emissions of particulate matter smaller than 10 μm rose for CIDI engines operating on RFD, biodiesel, and Fischer-Tropsch diesel, such increases did not occur for CIDI engines operating on dimethyl ether. Fuel-cell vehicles produced large reductions in urban emissions of nitrogen oxide and carbon monoxide; compression-ignition engines operating on RFD, dimethyl ether, Fischer-Tropsch diesel, or biodiesel were also estimated to produce substantial reductions in urban emissions of carbon monoxide.

Section 1
Introduction

In September 1993, the U.S. government and the U.S. Council for Automotive Research (USCAR), representing Chrysler, Ford, and General Motors, formed the Partnership for a New Generation of Vehicles (PNGV). This joint research and development effort aims to (1) significantly improve national competitiveness in automotive manufacturing; (2) implement commercially viable innovations from ongoing research on conventional vehicles; and (3) develop vehicles that can achieve up to three times the fuel economy of today's vehicles, which would be about 80 miles per gallon (mpg) for six-passenger automobiles. These three-times-efficient (often called 3X) vehicles (goal three) must also meet the safety and emissions requirements expected to be in place when they are introduced, as well as provide the same performance, size, utility, and cost of ownership/operation as the conventional vehicles that they replace.

To develop 3X vehicles, the PNGV program has been focusing on the development and use of advanced automotive technologies and lightweight materials. These technologies could be incorporated into spark-ignition, direct-injection (SIDI) engines, compression-ignition, direct-injection (CIDI) engines, or fuel cells. To meet emissions goals or to provide the optimum fuel for these new propulsion systems, fuels other than gasoline or diesel fuel could be necessary.[1] If development of 3X vehicles is successful, there may be changes in automotive manufacturing, materials production, and fuel production and distribution. Those changes will produce additional perturbations in energy consumption and emissions.

Recently, the PNGV program completed a process to select technology options for further investigation. Four key areas were chosen for intensified R&D efforts: hybrid-electric-vehicle (HEV) drive, direct-injection (DI) engines, fuel cells, and lightweight materials.[2] Research on HEV drive is focusing on energy storage and increasing the efficiency of both power sources. High-power nickel-metal hydride, lithium-ion, and lithium-polymer batteries are particularly promising energy storage technologies that could be used in conjunction with HEV designs. Research on direct-injection engines is also related to HEV applications because efficient compression-ignition direct-injection

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[1] In addition to new fuels and/or propulsion systems, a 40% reduction in vehicle weight may be needed. Research on lightweight materials is focusing on increased use of aluminum, magnesium, titanium, and composites.

[2] HEV drivetrain designs incorporate two power sources: one generates energy from fuel stored on board, the other is an electric motor that gets energy from the first source and/or from an advanced energy storage device. HEVs can be designed to operate efficiently on both sources, as well as to capture energy now lost in braking to further improve energy efficiency.

(CIDI) engines are promising candidates for near-term HEV application.[3] Regardless of configuration, engine emissions are perhaps the greatest obstacle to the widespread use of CIDI engines. R&D efforts are now under way to lower CIDI engine emissions. Over the longer term, fuel cells could be used in HEVs to offer near-zero vehicle emissions. Fuel cells can generate electricity from such fuels as hydrogen, compressed natural gas, gasoline, methanol, or ethanol stored on-board the vehicle.

1.1 NRC Peer Review of the PNGV Research Program

The National Research Council (NRC), a part of the National Academy of Sciences, has created a standing committee to provide peer review of the PNGV research program. That Committee has evaluated the progress of the PNGV program each year since 1994. In its first annual report, the NRC Peer Review Committee noted a "very high probability that the PNGV concept vehicle will use technologies that will result in technological discontinuities with many of today's automotive technologies." (NRC 1994) The Committee foresaw the potential for discontinuities in vehicle manufacturing and in the road transportation system as a result of new materials, power trains, or fuels that, in turn, could affect capital requirements, employment, environmental consequences, and the safety and cost of vehicle operations. The Committee cited two examples that could result in such discontinuities: use of hydrogen in place of gasoline as a vehicle fuel and use of advanced, lightweight, nonmetallic materials in place of conventional iron and steel in vehicles. Consequently, the Committee stressed the need for in-depth assessment of changes that could occur in "infrastructure, capital requirements, shifts in employment, total environmental consequences, alternative safety strategies, and total cost of operation associated with each technology being explored in the PNGV program" (NRC 1994).

Responding to the Committee's concerns, Argonne National Laboratory (ANL), together with Oak Ridge National Laboratory (ORNL), conducted a preliminary assessment for the Office of Advanced Automotive Technologies (OAAT) in the U.S. Department of Energy (DOE) to quantify major impacts resulting from the commercialization of 3X vehicles. ANL analyzed fuel-related infrastructure issues, while ORNL was responsible for lightweight-materials-related infrastructure issues. ANL defined first-order effects for advanced automotive technologies, quantified potential demand for PNGV fuels other than gasoline or diesel oil, and explored the importance of the length of the transition period. Results of that preliminary assessment were presented to the NRC Committee and were later published in the proceedings of the 29th International Symposium on Automotive Technology and Automation (ISATA) (Wang and Johnson 1996).

In its second annual review report, the NRC Peer Review Committee emphasized the need for continuing the infrastructure analysis (NRC 1996). The Committee observed

[3] DI engines in stand-alone configuration are subject to the same emissions problems (i.e., high engine-out emissions of NO_x and toxics).

that "modifications to the current vehicle infrastructure associated with changes in safety criteria, automotive service industries, fuel use and vehicle-operator interactions have important implications for market acceptance of a PNGV-type vehicle." The Committee called for "a study to establish the energy balance, in-use environmental effects, and resource requirements, as well as the production and distribution costs, for any fuels other than gasoline or diesel fuel being considered for use in Goal 3 vehicles" and stated that "due attention must be given to the total environmental impacts, including in-use emissions and energy consumption in fuel production and distribution." The Committee stressed that a careful assessment of infrastructure issues associated with alternative technologies should be an essential part of the downselect process scheduled for 1997.

In 1996, with funding from DOE's OAAT, Argonne continued its efforts to analyze issues related to PNGV fuels infrastructure. In particular, ANL estimated capital requirements for the facilities to produce and distribute several candidate fuels to be used in 3X vehicles. Six fuels were included in this so-called Phase 1 analysis: reformulated gasoline (RFG), low-sulfur diesel, dimethyl ether (DME), methanol, ethanol, and hydrogen. Using the GREET (Greenhouse gas emissions, Regulated Emissions, and Energy use in Transportation) and IMPACTT (Integrated Market Penetration and Anticipated Costs of Transportation Technologies) models, both of which were developed at Argonne, ANL estimated the fuel-cycle energy and emissions impacts of introducing 3X vehicles powered with each of the six fuels. The Phase 1 results were presented to the PNGV Review Committee at its third annual review meeting. Details regarding methodologies, assumptions, and results of the Phase 1 effort were documented in a later report (Wang et al. 1997a).

In its third and fourth annual review reports (NRC 1997 and NRC 1998), the PNGV Peer Review Committee reiterated its concern about the environmental and economic impacts of PNGV vehicles and their potential effect on fuel infrastructure. In its third annual review, the Committee stated that "it is important that the power plant configurations and fuel types being considered are accurately represented and evaluated with suitable infrastructure models as an integral part of the downselect process of the PNGV technologies." The Committee further asked that the GREET model be used with specific engine and fuel configurations in various downselect scenarios. Finally, in its fourth annual report, the Committee emphasized the need for extensive investigation of the feasibility, economics, and environmental impacts associated with production and distribution of PNGV fuels.

In 1997, ANL continued to analyze PNGV fuels infrastructure issues. Responding to comments from the automotive and fuels industries (as well as from the Peer Review Committee), ANL included six additional fuels in its so-called Phase 2 effort: reformulated diesel (RFD), compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), biodiesel, and Fischer-Tropsch (F-T) diesel. ANL delved further into the specific impacts of fuel-cycle energy use and emissions, separating emissions of criteria pollutants into total emissions and urban emissions and estimating emissions of all three main greenhouse gases (CO_2, CH_4, and N_2O). In the area of capital requirements, ANL expanded its initial estimates of total capital needs for fuel production and distribution infrastructure to generate cost estimates for each year between 2007 and 2030 under two potential 3X vehicle market penetration scenarios and estimated each fuel's per-gallon increment associated with those costs. Table 1.1 compares the scope of ANL's Phase 1 and Phase 2 efforts. This report documents the methodologies, assumptions, and results of the Phase 2 effort.

Table 1.1 Scope of ANL's PNGV Fuels Infrastructure Analysis: Phases 1 and 2

	Phase 1 (1996)	Phase 2 (1997)
Fuels	RFG, LSD, MeOH, EtOH, DME, H_2	RFG, RFD, MeOH, EtOH, DME, H_2, CNG, LNG, LPG, biodiesel, F-T diesel
Capital requirements	Two snapshot estimates of total capital requirements	Estimates of annual capital requirements under two market penetration scenarios; $/gal cost estimates
Fuel-cycle energy and emissions estimation	Energy use: total energy, fossil energy, and petroleum	Same
	Criteria pollutants: total emissions	Criteria pollutants: total and urban emissions
	GHGs: CO_2	GHGs: CO_2, CH_4, and N_2O

1.2 Study Scope and Approach

This analysis, sponsored by DOE/OAAT, focused on two infrastructure issues: the cost to build/put into place the fuel production and distribution infrastructure needed for each of the fuels under consideration for 3X vehicles and the fuel-cycle energy and emissions impacts of using each of those candidate fuels. As a point of departure, this study assumed that technological obstacles will be overcome; that is, the PNGV's primary goal of tripling fuel economy will become an engineering reality for all fuel/engine combinations being considered. This is consistent with PNGV goal three. In all likelihood, however, the PNGV program will aid in the development and introduction of some intermediate technologies that, though failing to achieve the 3X goal, will provide significant improvements in vehicle fuel economy (e.g., 2 times fuel economy improvements). A practical issue in analyzing programs like the PNGV is whether to assume that intermediate technologies provide the opportunity for initial market introduction and the basis for incremental improvements to the technology, or whether market introduction must await full achievement of technological goals, which, by definition, limits the analysis to more advanced technologies. There are no easy answers to this issue, but if intermediate technologies are to be considered, the PNGV program will have to rethink its schedule for introducing PNGV technologies.

For this analysis, the two infrastructure issues dictated two largely discrete approaches. To estimate the capital requirements of establishing fuel production and distribution infrastructure, it was first necessary to estimate the annual fuel needs of all 3X vehicles expected to be on the road. To do so, two broadly dissimilar 3X vehicle market penetration scenarios were specified to cover a relatively broad range of potential market acceptance of new 3X vehicles. These scenarios were run through ANL's IMPACTT model to estimate the stock of 3X vehicles and their fuel demand for each year from 2007 through 2030. For each fuel, production technologies and distribution infrastructures were then characterized and appropriate unit costs were developed. Capital requirements for the determined fuel production and distribution infrastructure could then be estimated as a function of unit costs and production/throughput volumes.

To estimate energy and emissions impacts of 3X vehicles, the GREET model was run to generate rates of energy consumption and emissions (i.e., Btu/mi and g/mi) by engine and fuel type, and the IMPACTT model was run to generate estimates of (1) total energy and emissions for a base or reference scenario without 3X vehicles, (2) energy and emissions by conventional vehicles still on the road under the two market penetration scenarios, and (3) energy and emissions by 3X vehicles incorporating each fuel/engine combination under those scenarios. The energy and emissions impact of each fuel/engine combination was then the difference between the reference scenario value and the sum of a conventional vehicle component and a 3X vehicle component corresponding to that fuel/engine alternative.

Note that each candidate PNGV fuel/engine combination was assumed to compete solely with conventional vehicles in the light-duty-vehicle marketplace. This approach was adopted for three reasons. First, if a mix of PNGV fuels and vehicle technologies were to compete with one another, as well as with conventional vehicles, results would show the aggregate effects of the mix, not the effects of each technology. It is the latter that is of interest here. Second, this analysis is intended to identify the maximum infrastructure impacts of introducing a given fuel or technology. By definition, the individual components of a mix are less than the sum. Third, historical precedent suggests that one advanced technology will achieve market dominance after initially vigorous competition. It matters not why dominance occurs — whether because of the superiority of the winning technology itself, the cost to establish and maintain infrastructure for multiple technologies, or simply inefficiencies of scale — only that market penetration assumptions be consistent with its occurrence.

The analytic time frame of this study is between 2007 (three years after completion of the research and development for 3X vehicles) and 2030 (when a significant portion of the light-duty fleet could be expected to be composed of these highly efficient vehicles). The study therefore assumed that 3X vehicles will be introduced beginning in 2007 and that 3X vehicle sales will increase steadily to a defined maximum sales target.