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Natural Gas Vehicles: Status, Barriers, and Opportunities

Energy Systems Division

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NOTATION

AFDC	Alternative Fuels and Advanced Vehicles Data Center
AFV	alternative fuel vehicle
APTA	American Public Transit Association
CARB	California Air Resources Board
CEC	California Energy Commission
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CWI	Cummins Westport, Inc.
DEF	diesel exhaust fluid
DOE	U.S. Department of Energy
EER	energy economy ratio
EERE	Office of Energy Efficiency and Renewable Energy
EGR	exhaust gas recirculation
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
FY	fiscal year
GGE	gasoline gallon equivalent
GHG	greenhouse gas
GM	General Motors
GREET	Greenhouse gases, Regulated Emissions, and Energy Use in Transportation
GTL	gas-to-liquid
GVW	gross vehicle weight
GWPC	Ground Water Protection Council
HCNG	hydrogen/CNG blend
HDV	heavy-duty vehicle
LDV	light-duty vehicle
LNG	liquefied natural gas
MY	model year
N_2O	nitrous oxide
NGV	natural gas vehicle
NGVTF	Natural Gas Vehicle Technology Forum

NMHC	nonmethane hydrocarbon
NMOG	nonmethane organic gas
NO_x	nitrogen oxides
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PM	particulate matter
R&D	research and development
SCR	selective catalytic reduction
SULEV	super-ultra-low-emission vehicle
WMATA	Washington Metropolitan Area Transit Authority

Units of Measure

bbl	barrel
bhp	brake horsepower
Btu	British thermal unit(s)
g	gram(s)
h	hour
L	liter(s)
mi	mile(s)
mpgde	mile(s) per gallon diesel equivalent
mpgge	mile(s) per gallon gasoline equivalent

NATURAL GAS VEHICLES: STATUS, BARRIERS, AND OPPORTUNITIES

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ABSTRACT

In the United States, recent shale gas discoveries have generated renewed interest in using natural gas as a vehicular fuel, primarily in fleet applications, while outside the United States, natural gas vehicle use has expanded significantly in the past decade. In this report for the U.S. Department of Energy's Clean Cities Program — a public-private partnership that advances the energy, economic, and environmental security of the U.S. by supporting local decisions that reduce petroleum use in the transportation sector — we have examined the state of natural gas vehicle technology, current market status, energy and environmental benefits, implications regarding advancements in European natural gas vehicle technologies, research and development efforts, and current market barriers and opportunities for greater market penetration.

The authors contend that commercial intracity trucks are a prime area for advancement of this fuel. Therefore, we examined an aggressive future market penetration of natural gas heavy-duty vehicles that could be seen as a long-term goal. Under this scenario using Energy Information Administration projections and GREET life-cycle modeling of U.S. on-road heavy-duty use, natural gas vehicles would reduce petroleum consumption by approximately 1.2 million barrels of oil per day, while another 400,000 barrels of oil per day reduction could be achieved with significant use of natural gas off-road vehicles. This scenario would reduce daily oil consumption in the United States by about 8%.

1 STATE OF THE TECHNOLOGY

While natural gas is often the energy source for residential, commercial, and industrial processes, vehicles can operate on this fuel, either through the use of engines designed specifically for natural gas or by modifying an engine designed to run on gasoline or diesel. Natural gas vehicles (NGVs) can be dedicated to natural gas as a fuel source, or they can be bi-fuel, running on either natural gas or gasoline or natural gas or diesel. Because most natural gas engines are spark-ignited, the usual bi-fuel pairing is natural gas and gasoline.

Natural gas engine technologies can differ in the method used to ignite the fuel in the engine cylinders, the air-fuel ratio, the compression ratio, and the resulting performance and emissions capabilities. Natural gas has a high octane rating, which allows an increase in power in spark-ignition engines. However, natural gas occupies a larger volume in the engine cylinder than liquid fuels, reducing the number of oxygen molecules (share of air in the cylinder), which reduces power. The net effect on natural gas power versus gasoline is relatively neutral.

Because natural gas is a gaseous fuel at atmospheric pressure and occupies a considerably larger storage volume per unit of energy than refined petroleum liquids, it is stored aboard the vehicle as either a compressed gas or a liquid. The storage requirements are still much greater than those for refined petroleum products, which increases vehicle weight and tends to reduce fuel economy.

To become compressed natural gas (CNG), natural gas is pressurized in a storage tank (also called a cylinder) at up to 3,600 pounds per square inch. In the U.S. Honda Civic GX, the tank is mounted in the trunk and replaces the existing fuel tank. In more recently developed European CNG light-duty front-wheel-drive passenger vehicles, the tanks are mounted under the back seat and luggage compartment, thereby providing more storage space than in the Civic GX design. In U.S. trucks, the tank is mounted on the frame, and in U.S. buses, it is mounted on the roof. Although tanks can be made entirely from metal, they are typically composed of lighter-weight metal liners reinforced by a wrap of composite fiber material. Because of the lower energy density of natural gas as compared to gasoline or diesel, vehicle range is generally reduced.

To become liquefied natural gas (LNG), natural gas is cooled to –260ºF and filtered to remove impurities. LNG is stored in double-walled, vacuum-insulated tanks and is primarily used in heavy-duty trucks, providing increased range over CNG.

NGVs and their respective fueling systems must meet stringent industry and government standards for compression, storage, and fueling. They are designed to perform safely during both normal operations and crashes. Nozzles and vehicle receptacles are designed to keep fuel from escaping during refueling by locking together to form a sealed system. In case of a vehicle fire or impact, a pressure-relief device in the tank allows for controlled venting of the gas so pressure is not built up in the tank. Storage tanks must be regularly inspected for deterioration or damage. Both the Department of Transportation’s Federal Motor Vehicle Safety Standards and the American National Standards Institute/Canadian Standards Association’s Natural Gas Vehicle Standards call for visual inspections at least every 36 months or 36,000 miles, whichever comes first. After several decades of NGV operations, there has been only one fatality in the United States; it was caused by a breach in an NGV’s fuel system that resulted from noncompliance with safety standards (NGVAmerica 2009a).

2 CURRENT MARKET STATUS

2.1 VEHICLES AND ENGINES

According to the *Annual Energy Review 2008* and other data published by the U.S. Department of Energy (DOE)/Energy Information Administration (EIA), about 0.1% of natural gas is currently used as a vehicular fuel, in comparison with volumes delivered to other customers (EIA 2009a). The EIA estimated that there were 117,000 NGVs in use in 2007 and 0.2% of all fuel consumed by highway vehicles was natural gas (EIA 2009b; EIA 2010a). The Clean Vehicle Education Foundation reports that the inventory of NGVs has typically been overestimated and was more likely to be about 105,000 in 2008, after having peaked at about 110,000–115,000 in 2003 (Yborra 2008). The International Association of Natural Gas Vehicles estimates that more than 11.2 million NGVs currently ply the roads globally, with an annual average 28% growth rate since 2000 (IANGV 2010).

In general, the NGV strategy in the United States has been to pursue high-fuel-use urban fleets capable of central refueling (normally overnight). This market includes fleets of buses, trash haulers, taxis, and shuttle, delivery, port, and airport vehicles. According to the American Public Transit Association's *2009 Public Transportation Fact Book,* nearly 19% of the nation's full-sized transit bus fleet, or about 12,000 vehicles, operates on natural gas (APTA 2009). Furthermore, 2.7% of U.S. paratransit fleets operate on natural gas. Paratransit service is an alternative mode of flexible passenger transportation that does not follow fixed routes or schedules. The Clean Vehicle Education Foundation estimates there are approximately 3,000 natural gas refuse haulers, 2,800 natural gas school buses, and 16,000–18,000 medium-duty NGVs (such as airport shuttles and delivery vans). The remaining inventory includes about 65,000–75,000 light-duty NGVs (Yborra 2008).

Since 2007, only one domestic original equipment manufacturer (OEM) — American Honda — has been serving the CNG light-duty vehicle (LDV) market, and only recently have other OEMs re-entered the market to offer products. However, technological innovation has led to the current availability of optimized natural gas engines for commercial vehicles that meet strict 2010 emissions standards. These vehicles, which have gross vehicle weights (GVWs) of 8,500 lb and above, are tested with engine dynamometers and are subject to different regulations than vehicles below 8,500 lb GVW, which are tested with vehicle dynamometers.

The attributes of commercial vehicles can be defined in a number of ways (Bertram et al. 2009). Light-duty could refer to "class 2b" vehicles — mostly two-axle, four-tire pickup trucks equipped with either a gasoline or diesel engine. Medium-duty refers primarily to trucks with two or more axles and six or more tires on a single body (also called a single unit). For purposes of this document, it is useful to think of "heavy" commercial trucks as two types — single-unit and combination. Single-unit heavy-duty commercial trucks are conceptually similar to the two-axle, four- and six-tire light- and medium-duty trucks and generally serve urban areas. Combination trucks (the dominant type is often called an "18-wheeler") have a tractor and trailer and specialize in intercity movement of goods. Combination trucks effectively use only diesel engines. Nevertheless, according to Bertram et al., in 2002, about 38% of fuel used in commercial trucking was gasoline. In addition, their research showed that more than half of the 2002 light- and medium-duty commercial trucks were fueled with gasoline, although diesel's share was steadily increasing.

For medium- and heavy-duty NGVs, the primary natural gas engine manufacturers are Cummins Westport, Inc. (CWI), Westport Innovations, and Emission Solutions, Inc. Daimler Trucks North America recently teamed up with CWI to offer the Freightliner Business Class M2 112 medium-duty truck equipped with the Cummins ISL G natural gas engine, which meets the 2010 Environmental Protection Agency (EPA) and California Air Resources Board (CARB) emission standards without the use of diesel particulate filters or selective catalytic reduction (SCR). The truck will be offered in six CNG/LNG tractor and truck configurations, and the entire line will be available by the end of 2010. This would cover 90% of all North American truck applications, according to Roe East, CWI president (Consenseus 2009).

John Deere recently left the CNG engine market but still offers repair and maintenance services. Navistar and Clean Air Power, a joint developer of a dual-fuel combustion technology that enables heavy-duty engines to run on a combination of diesel and natural gas, have entered a concept development agreement to modify a Navistar MaxxForce 13 engine employing advanced exhaust gas recirculation (EGR) to meet the 2010 EPA emission standards (Piellisch 2010a). The market for this dual-fuel engine would be Class 8 applications, initially targeting the regional haul tractor market.

According to the *Guide to Available Natural Gas Vehicles and Engines* (Yborra 2009), the manufacturers listed in Table 1 currently produce natural gas engines. Four of the six are listed as 2010 compliant. However, production of the smaller of the engines — suitable for light-duty trucks where gasoline's share is highest — ended for the U.S. market (but the engine will still be available in the European, South American, and Asian markets). Doosan Infracore America Corporation is a new entrant to the U.S. natural gas engine market; it has built a manufacturing facility in Georgia and received both EPA and CARB certification for the 2007 standards (Doosan Infracore 2009). In addition, Doosan recently received certification for its 11-L heavy-duty natural gas engine, which uses SCR to meet EPA and CARB 2010 emission standards (Doosan Infracore 2010).

Several companies, including BAF Technologies (now a part of Clean Energy) and Baytech Corporation, offer dedicated CNG and bi-fuel retrofits of Ford (BAF) and General Motors (Baytech) gasoline engines primarily for shuttle and box truck cutaway chassis and Workhorse walk-in and step van chassis. Both companies have received EPA/CARB certification for certain model year 2010 vehicle chassis. In a recent development, Ford has begun to offer its fleet customers a 2010 model year gaseous fuel option for its full line of E-Series vans with a 5.4-L engine and will make this option available in the fall of 2010 in its F-450 and F-550 Super Duty chassis cab with a 6.8-L engine (NGVAmerica 2009b; Ford 2010). General Motors (GM) will also provide fleets with gaseous fuel options for model year 2011 for its Chevrolet Express and GMC Savana full-size vans using a 6.0-L engine (Cullen 2010). Both the Ford and GM vehicles are equipped with hardened valves and valve seats for improved wear

TABLE 1 Manufacturers of Natural Gas Engines

Manufacturer	Engine Type	Application	Certification
Cummins Westport, Inc.	5.9-L B Gas Plus (spark-ignited)	Medium-duty (e.g., school buses/shuttles); production ended 12/31/09	EPA 2007 compliant (0.01 g/bhp-h PM)
Cummins Westport, Inc.	8.9-L ISL G (spark-ignited)	Heavy-duty (e.g., refuse, transit/school buses, street sweepers, yard hostlers)	EPA/CARB 2010 compliant (0.2 g/bhp-h NO_x and 0.01 g/bhp-h PM)
Doosan Infracore America Corp.	11-L GK12-C (spark-ignited)	Heavy-duty (e.g., refuse trucks and transit buses)	EPA/CARB 2007 compliant (0.01 g/bhp-h PM)
Doosan Infracore America Corp.	11-L GK12-S (spark-ignited) w/SCR	Heavy-duty (e.g., refuse trucks and transit buses)	EPA/CARB 2010 compliant (0.01 g/bhp-h PM)
Emission Solutions, Inc.	7.6-L NG Phoenix (spark-ignited); remanufactures the Navistar International MaxxForce DT diesel platform to natural gas	Medium-duty (e.g., school buses/heavy-duty cutaway shuttles and work trucks)	EPA/CARB 2010 compliant (0.2 g/bhp-h NO_x and 0.01 g/bhp-h PM)
Westport Innovations	15-L GX (compression-ignited) dual-fuel high-pressure direct-injection (95% natural gas, 5% diesel)	Heavy-duty (e.g., work trucks and line-haul applications)	EPA/CARB 2010 compliant (0.2 g/bhp-h NO_x and 0.01 g/bhp-h PM)

resistance and durability (Ford 2010; Cullen 2010). In contrast, Navistar is planning to discontinue its V6 MaxxForce 5 V6 diesel engine in the United States because of difficulty in meeting 2010 standards (*Light and Medium Truck* 2009a,b).

In LDVs below 8,500 lb GVW, NGV availability peaked in 2002 at 18 models, as the American automakers were offering bi-fuel and dedicated options; however, availability dropped sharply thereafter, with only five models in 2005 and one OEM option available since 2007 (AFDC 2009). From 1996 to 2009, American Honda has offered the Civic GX to fleet operators in quantities of about a thousand per year in a limited number of states and is now also offering it to private customers, also in targeted markets. Honda's dealer network has grown to 136 in 33 states as it looks to target new fleet customers; the company estimates increased production of approximately 1,500–2,000 GXs for 2010 (Piellisch 2010b). This dedicated natural gas sedan has been rated by the American Council for an Energy Efficient Economy as the cleanest internal combustion engine vehicle available in the United States for several years. Honda began its 2010 model year production run for the GX in Indiana on May 13 (Hondanews.com 2009a). It initiated retail sales of the GX in California in 2006 (42 dealers sell retail now) and in New York in 2007 (nine retail dealers now), and just recently added sales in eight dealerships in Utah (Hondanews.com 2009b).

In place of the OEMs, small-volume manufacturers have begun to provide consumers with more options to purchase light-duty NGVs through aftermarket conversions of OEM cars, trucks, and vans. The companies offering EPA- (and in some cases CARB-) certified conversions include BAF, NGV Conversions, and Altech-Eco for Ford vehicles and Baytech, IMPCO, and NaturalDrive Partners for GM vehicles (Yborra 2009). Dedicated and/or bi-fuel models are available for such vehicles as the Ford Focus, Fusion, Transit Connect, Crown Victoria, Expedition, and F-150; Mercury Milan; Lincoln Town Car; and Chevrolet Impala.

With increased domestic demand for NGVs, the OEMs are returning to the U.S. market, either with in-house products or in joint efforts with small-volume manufacturers, as evidenced by recent announcements by Ford and GM and the fact that the major OEMs offer NGV products elsewhere in the world. Toyota exhibited a prototype CNG hybrid sedan at the 2008 Los Angeles Auto Show. At the 2009 Washington Auto Show, Mercedes-Benz displayed a CNG compact car, with the intent of someday introducing it to the U.S. market. Fiat's merger with Chrysler could also result in more NGV models in the future. Fiat is the largest manufacturer of CNG LDVs, including those with multiple fuel capabilities, such as the tetrafuel option, which allows the vehicle to be fueled on any level of ethanol, natural gas, or gasoline (Siuru 2009).

2.2 INFRASTRUCTURE

NGVs are fueled either with CNG, which is delivered through the pipeline system, or LNG, which is normally delivered by truck to the fueling station. The fuel can be made available at public stations, private fleet facilities, or even homes where natural gas pipeline distribution is available. As of 2001, approximately 63% of U.S. households used natural gas; however, this percentage varied by region, with the Midwest census region accounting for the highest percentage of households using natural gas at 79%, and the South having the lowest at 48% (EIA 2001). Public natural gas stations have dispensers that are similar in design to typical gasoline or diesel dispensers and have comparable filling times. Private facilities are used by dedicated fleet(s) and are either fast-fill or time-fill (i.e., tanks are filled over an extended period of time). For LNG, after the fuel is delivered to the fleet facility, it is stored in specially designed cryogenic tanks and pumped into vehicles in much the same way as other liquid fuels. According to the DOE Alternative Fuels and Advanced Vehicles Data Center (AFDC), there were 836 public and private CNG stations and 38 LNG stations in the United States as of June 2, 2010 (see Figure 1; AFDC 2010a).

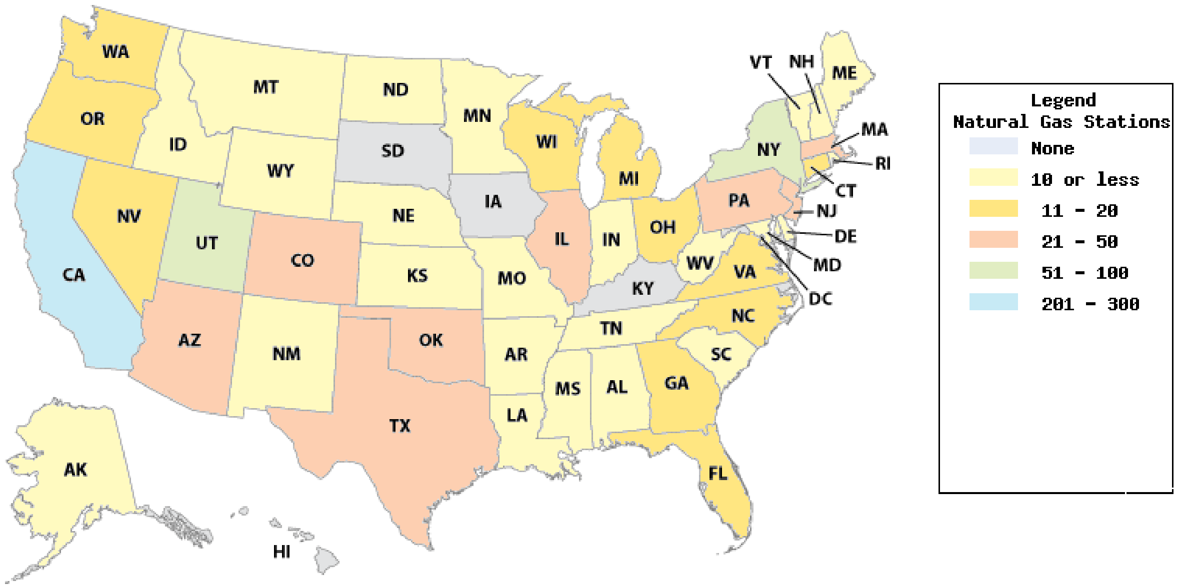

FIGURE 1 Natural Gas Stations by State (Source: AFDC 2010b)

In support of the Honda Civic GX, a home-fueling appliance known as Phill, manufactured by FuelMaker Corporation, was available in limited markets; approximately 400 units were sold. FuelMaker declared bankruptcy in April 2009, and Fuel Systems Solutions agreed to purchase its assets and continue the business activities of the former company (NGVAmerica 2009c). In June 2010, Fuel Systems Solutions subsidiary, BRC FuelMaker, began taking orders for Phill, with plans to expand production in early 2011 (Pirraglia 2010). The Phill appliance is connected to home gas and electricity supplies and mounted either in garages or on outside walls. The retail price is $3,000–4,000, with an installation fee of $1,000–$2,000 (German 2008). Federal income tax credits are available to offset these costs. In addition, many states and air quality districts offer incentives, and some utilities offer preferential gas rates to Phill customers. Depending on the amount of fuel already in a tank, 4–12 hours are required to complete the fill. A full tank gives the typical consumer more than enough fuel for the average vehicle's daily travel, which is approximately 32.7 miles (Davis et al. 2008).

The cost of the far more common method of refueling NGVs worldwide — a refueling station with fuel delivery equipment comparable to that found at typical gasoline stations — depends on the type of fueling equipment used: fast-fill or time-fill. When a high-pressure storage system is combined with a large compressor in a fast-fill station (the most comparable configuration to gasoline refueling), the cost is higher than in a time-fill system, which has no storage system and a smaller, less expensive compressor. According to Doug Horne of the Clean Vehicle Education Foundation, cost is directly related to station utilization; usually, the larger the station and the higher the utilization, the lower the cost per gasoline gallon equivalent (GGE) delivered (Horne 2009). Cost per GGE is most important to end users because that is what they see as a cost for operating their vehicles. Total infrastructure costs include the following:

Electric compression costs (estimated at 1 kWh/GGE): $0.09–0.15/GGE
Maintenance/repair/service fund: $0.15–0.35/GGE
Capital amortization of equipment: $0.35–0.65/GGE

Summing the values results in an estimated cost of $0.59/GGE at the low end and $1.15/GGE at the high end. These costs do not include the amortized incremental cost of CNG vehicles.

2.3 NATURAL GAS FUEL AND VEHICLE PRICING

On the basis of historical data from 2004 to 2007, the Energy Management Institute reports that natural gas was 48.6% less expensive than petroleum-based fuels on an energy-equivalent basis (EMI 2007). More recently, the percentage difference has declined somewhat. Table 2 shows a recent history of average monthly prices for the three fuels, as reported in the *Clean Cities Alternative Fuel Price Report* (AFDC 2010c). These prices include applicable federal and state motor fuel taxes. The federal tax per GGE for gasoline, diesel, and CNG are $0.184, $0.217 ($0.244 per diesel gallon), and $0.183, respectively, while state taxes vary for each fuel (IRS 2010).

TABLE 2 Monthly Average Price of Gasoline, Diesel, and Natural Gas ($ per GGE)

Month and Year	Gasoline	Diesel	Natural Gas
April 2010	2.84	2.71	1.90
January 2010	2.65	2.57	1.85
October 2009	2.64	2.50	1.86
July 2009	2.44	2.27	1.73
April 2009	2.02	2.26	1.64
January 2009	1.86	2.19	1.63
October 2008	3.04	3.27	2.01
July 2008	3.91	4.22	2.34
April 2008	3.43	3.71	2.04
January 2008	2.99	3.05	1.93
October 2007	2.76	2.79	1.77
July 2007	3.04	2.65	2.10
March 2007	2.30	2.35	1.94
June 2006	2.84	2.67	1.90
February 2006	2.23	2.48	1.99

Source: *Clean Cities Alternative Fuel Price Report* (AFDC 2010c).

Large natural gas fleets can secure long-term contracts with fuel suppliers, potentially escaping volatile price spikes in natural gas acquisition. Compared with prices of natural gas for home heating (both wholesale and retail), prices of natural gas as a motor fuel for commercial fleets have been more stable because of the greater ability of fleets to lock in unit gas prices for a relatively long period. Table 3 shows recent CNG price differentials between public and private CNG stations.

TABLE 3 Monthly Average Price of CNG at Public and Private Stations ($ per GGE)

Month and Year	Public	Private
April 2010	2.05	1.44
January 2010	2.03	1.38
October 2009	2.00	1.47
July 2009	1.85	1.38
April 2009	1.71	1.43
January 2009	1.78	1.39
October 2008	2.22	1.65
July 2008	2.61	1.58
April 2008	2.31	1.33
January 2008	2.21	1.18
October 2007	2.08	0.99
July 2007	2.15	1.87
March 2007	1.95	1.14
October 2006	1.78	1.58
June 2006	2.01	1.21
February 2006	2.02	1.72
September 2005	2.16	1.43

Sources: Laughlin (2009); AFDC (2010c).

For light-duty CNG sedans, the Honda Civic GX costs about $7,000 more than its gasoline counterpart, but federal tax credits and state and local incentives may help offset the extra cost (Cook 2009).

In previous years, medium- and heavy-duty NGVs have cost $20,000–50,000 more than comparable diesel vehicles. However, the differential is narrowing as the price of equivalent diesel vehicles rises in response to tough emission standards. The 2007 emission regulations required diesel vehicles to be equipped with oxidation catalysts and particulate filters in order to meet the 0.01 g/bhp-h particulate matter (PM) standard, which added to the cost of the vehicles because of the precious metal coating, roughly proportional to engine size, needed for both technologies (Longman 2010). In addition, Volvo has recently announced that it "would level a 'non-negotiable surcharge' of more than $9,000 to cover the costs of its U.S. 2010 emissions technology" (*Light and Medium Truck* 2009a,b). Navistar said it would add $6,000 to the cost of MaxxForce 7, 9, 10, and DT medium-duty engines and $8,000 to the 11, 13, and 15 heavy-duty engines (*Light and Medium Truck* 2009a,b). To meet the 0.2 g/bhp-h nitrogen oxides (NO_x) 2010 standard, some manufacturers are employing SCR technology using a urea-based solution, called "diesel exhaust fluid" (DEF), which will add to the cost of operation, as well as to the purchase price of the vehicle. At an estimated price of $2.70 per gallon of DEF and a usage of 2–3% of diesel fuel consumption, the added annual maintenance cost to a medium-duty vehicle operating 50,000 miles with a fuel economy of 10 miles-per-gallon-diesel-equivalent (mpgde) would be $270–470. Using the same assumptions for DEF price and consumption, a heavy-duty vehicle operating 120,000 miles per year with a fuel economy of 6 mpgde would incur an additional annual maintenance cost of $1,080–1,620.

While cost is one disadvantage of an SCR system, there are other trade-offs between it and EGR when comparing the technologies available to meet the 2010 heavy-duty engine emission standards: SCR only works when used with DEF, so devices to monitor compliance are needed; the system adds weight to the vehicle; and DEF storage will likely need to be heated because it freezes at 12°F (Leavitt 2008). SCR has advantages, as well: it allows the engine to operate at optimal combustion temperatures, which provides better fuel efficiency and power density. In contrast, EGR lowers the combustion temperature by adding cooled exhaust gas to the intake stream, which lowers NO_x but also fuel efficiency and power density. The advantages of EGR are that the technology does not require additional hardware, fluids, or driver intervention (or the costs associated with them).

The earlier anticipatory TIAX conclusion that natural gas would become competitive with clean diesel was based on a life-cycle cost analysis of owning, operating, and maintaining diesel and natural gas heavy-duty engines in compliance with 2010 EPA emission standards (TIAX 2005). It is an important prediction, because in 2004, heavy-duty diesel engines had a significant cost advantage over natural gas engines. TIAX estimated that after 2010, natural gas refuse haulers, transit buses, and short-haul trucks would have a cost advantage if oil prices were more than $31 a barrel.

2.4 NATURAL GAS SUPPLY

2.4.1 Fossil Natural Gas

Most of the natural gas consumed in the United States is fossil fuel produced domestically by drilling. About 16% is imported, either in gaseous form via Canadian pipelines, or as LNG, primarily from Trinidad and Tobago (EIA 2009c). Significant additional supplies continue to come from the Lower 48 States, mainly from unconventional resources, such as shale. Shale formations in the Lower 48 States are widely distributed and hold vast amounts of natural gas. One shale field in Texas produced 5% of the Lower 48 States' natural gas supply in 2007 (EIA 2009d).

Advanced drilling technologies (e.g., horizontal drilling and hydrofracturing) are helping to spur increases in supply because they allow for the economic production of natural gas from complex geologic formations. From 1998 to 2007, the number of proven dry natural gas reserves in the United States rose every year for a total increase of 45% (74 trillion cubic feet); in contrast, U.S. proven oil reserves increased by only 1.3%. Over the same 9-yr period, natural gas consumption increased by less than 4% (EIA 2009e).

The Potential Gas Committee, a nonprofit organization that receives guidance from the Colorado School of Mines, reported in its latest biennial assessment that the United States has a total natural gas resource base of 1,836 trillion cubic feet, which is the highest assessment in its 44-yr history. The Committee states that most of the increases result from the reevaluation of shale gas in the Appalachian Basin, Mid-Continent, Gulf Coast, and Rocky Mountains (PGC 2009).

Tapping unconventional resources will continue to play a significant role in natural gas supply; accordingly, the issue of natural gas availability in the United States is not a near-term concern. Rather, the concern is how to put natural gas resources to their best use in order to improve energy security and the environment.

2.4.2 Renewable Natural Gas

Renewable natural gas, or biomethane, is the result of anaerobic digestion of organic matter, such as municipal solid waste or animal waste. Once the biomethane is purified and either compressed or liquefied, it can be used to fuel standard NGVs, such as refuse trucks, buses, or municipal vehicles. In the United States, conversion of landfill gas to natural gas fuel is slightly past the demonstration stage; the process has been demonstrated in California and New Jersey and is now being implemented on a commercial scale in Columbus, OH; Dallas, TX; Orange County, Sonoma County, and Livermore, CA; Oklahoma City, OK; and Dekalb County, GA. Biomethane is an important component in meeting the European Parliament's target of 10% biofuel use in transport by 2020 (European Commission 2009). To date in the United States, only small quantities of methane have been derived from surface biomass.

2.5 TRANSITION TO HYDROGEN

Because natural gas is rich in hydrogen atoms and low in carbon, it is an excellent feedstock for producing hydrogen gas. Hydrogen is most commonly produced from natural gas by using high-temperature steam (i.e., steam methane reforming), and it can also be produced by burning methane in air (i.e., partial oxidation). Both methods result in "synthesis gas," which is reacted with water to produce more hydrogen.

Natural gas is sometimes touted by industry as a pathway to the hydrogen future because some aspects of hydrogen and natural gas distribution are similar — such as fuel storage, fueling, station siting, and training of technicians and drivers. It is generally believed that the knowledge gained from using natural gas for transportation will make the transition to a hydrogen economy easier.

As another stepping-stone to a hydrogen future, natural gas can be blended with hydrogen to make transportation fuel — either 20% by volume hydrogen (Hythane™) or 30% by volume hydrogen (HCNG) — and dispensed onto a vehicle in blended form. Thus far, this technology has been limited to demonstration programs involving either transit or private fleets. The key advantage of hydrogen-enriched natural gas is its potential to satisfy tougher emission standards without requiring the installation of expensive exhaust after-treatment devices.

Hythane™ has been shown to maintain fuel efficiency and reduce emissions of NO_x in a conventional natural gas engine without imposing major conversion costs (Del Toro et al. 2005). In comparison, the use of HCNG has demonstrated that it can meet strict NO_x standards, preserve fuel efficiency, and avoid expensive three-way catalysts; however, it requires expensive engine modifications (Kramer and Francfort 2003). Therefore, if the use of hydrogen-enriched natural gas becomes more common, the 20% blend could be used in existing natural gas engines, and the 30% blend could be used in new engines manufactured to operate specifically on that fuel.

Few modifications are needed to add a hydrogen-enriched natural gas option to an existing CNG station. One market barrier is that the two different fuel formulations could require fleet operators to commit to the long-term use of refueling equipment, suppliers, and vehicles. The major barrier to the use of hydrogen-enriched natural gas, however, remains the high unit costs of the initial infrastructure as a result of the diseconomy of small scale. Further, no standard design yet exists, so no two infrastructure projects are alike.

2.6 AVAILABLE FEDERAL INCENTIVES

Various federal laws provide incentives for natural gas fuel, vehicles, and infrastructure (see Table 4). State tax credits for fuel, vehicles, infrastructure, and business development exist in 25 states and further aid in the development of the market.

TABLE 4 Federal Laws with Incentives for Natural Gas Fuel, Vehicles, and Infrastructure

Incentive Type	Federal Law	Provision
Fuel	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users, P.L. 109-59 (8/10/05) (SAFETEA LU)	An excise tax credit is available for alternative fuel sold to operate a motor vehicle. The credit is $0.50 per GGE of CNG and $0.50 per liquid gallon of liquefied petroleum gas, LNG, and liquefied hydrogen. The entity eligible for the credit is the one that reports and pays the federal excise tax on the fuel. The tax credit is also available to nonprofit tax-exempt entities that fuel on-site. The excise tax credit, paid from the General Revenue Fund, is partially offset by an increase in the motor fuel excise tax rate for CNG/LNG, which is now on parity with that for other motor fuels. Section 204 of the Emergency Economic Stabilization Act/Energy Improvement and Extension Act of 2008 (P.L. 110-343, passed 10/3/08) amended the expiration date for the alternative fuel excise tax credit from 9/30/09 to 12/31/09. As of 8/1/10, an additional extension has not been granted to the excise tax credit provision, except in the case of liquefied hydrogen.
Vehicle	Energy Policy Act of 2005, P.L. 109-58 (8/8/05)	A “qualified alternative fuel motor vehicle” tax credit is available for the purchase of a new, dedicated, or repowered AFV. It is for 50% of the incremental cost of the vehicle, plus an additional 30% if the vehicle meets certain tighter emission standards. These credits range from $2,500 to $32,000, depending on the size of the vehicle. The credit is effective on purchases made after 12/31/05 and expires 12/31/10. The vehicle must be acquired for use or lease by the taxpayer claiming the credit. (a) The credit is only available to the original purchaser of a qualifying vehicle. If a qualifying vehicle is leased to a consumer, the leasing

TABLE 4 (Cont.)

Incentive Type	Federal Law	Provision
		company may claim the credit. (b) For qualifying vehicles used by a tax-exempt entity, the person who sold the qualifying vehicle to the person or entity is eligible to claim the credit, but only if the seller clearly discloses in a document to the tax-exempt entity the amount of credit. The seller may pass along any savings of the tax credit but is not required to do so. The Internal Revenue Service does not set limits on the amount of credits claimed by any one entity.
Infrastructure	Energy Policy Act of 2005, P.L. 109-58 (8/8/05)	An income tax credit is available for 30% of the cost of natural gas refueling equipment, up to $30,000 in the case of large stations and $1,000 for home refueling appliances. The credit is effective on purchases placed in service after 12/31/05 and expires 12/31/10 (due to passage of the Emergency Economic Stabilization Act, P.L. 110-343). The American Recovery & Reinvestment Act of 2009 (P.L. 111-5, passed 2/17/09) amended the value of this credit for the purchase of equipment used to store and dispense qualified alternative fuels placed in service during 2009 and 2010. The credit for these years is $50,000 or 50% of the cost, whichever is smaller, for business property and $2,000 or 50% of the cost, whichever is smaller, for home refueling.

Sources: AFDC (2010d); NGVAmerica (2009d).

2.7 EXAMPLES OF STATE INCENTIVES FOR NATURAL GAS VEHICLES

While many states offer incentive programs for NGVs, Colorado and Utah are highlighted for the purpose of this report.

2.7.1 Colorado

Colorado provides alternative fuel infrastructure and vehicle tax credits. An income tax credit is offered for the cost of construction, reconstruction, or acquisition of an alternative fuel station. For the tax period 2009–2011, this credit is 20%. If the station is publicly accessible, the percentage is multiplied by 1.25. If at least 70% of the alternative fuel is produced from renewable sources for a period of 10 years, an additional credit of 1.25 is multiplied. Additionally, the vehicle tax credit is available on the purchase of or conversion to an alternative fuel vehicle (AFV) through 2015. The tax credits range from 10% to 85% of the incremental cost or conversion costs of vehicles classified as a “Low-Emission Vehicle” or better. This credit may be multiplied by 1.25 for certain vehicles if the purchase or conversion permanently replaces a motor vehicle that is at least 12 years old or older, up to 100% of the incremental or conversion cost. The law allows the taxpayer to carry forward for five years any excess should the credit exceed the person’s tax liability for the year in which the vehicle was purchased or converted. Generous rebates are available to tax-exempt organizations wishing to purchase or convert to an AFV (AFDC 2010d; Noblet 2009).

2.7.2 Utah

Along with some other states, Utah offers a clean fuel vehicle tax credit providing for 35% of the incremental cost (up to $2,500) of a clean fuel vehicle manufactured by an OEM or an income tax credit for 50% of the cost (up to $2,500) of a conversion made from January 1, 2009, to December 13, 2013. The state has also offered similar tax credits in previous periods. Salt Lake City has an AFV parking program, in which those vehicles do not have to pay metered public parking. The Salt Lake City Department of Airports also provides a credit against ground transportation fees to commercial ground transportation providers exclusively using clean fuels. The Public Service Commission has the authority to approve requests by gas utilities for a special NGV rate that is less than full cost and can allocate these additional costs to remaining rate payers. As in several other states, clean fuel vehicles in Utah are allowed to travel in high-occupancy vehicle lanes regardless of the number of passengers. Furthermore, in a recent House Concurrent Resolution, the state encouraged the EPA to adopt practices to facilitate vehicle conversions for small-volume manufacturers (AFDC 2010d).

3 EMISSION BENEFITS OF NATURAL GAS VEHICLES

Because of regional differences in fuel composition and engine configurations, potential "in-use" criteria air pollutant emission reductions from the deployment of NGVs can vary (certification test results are based on standard fuels, which are generally not the same as those used in the field). Compared with conventional gasoline LDVs, natural gas LDVs generally reduce smog-producing pollutants by 60–90% (DOE and EPA 2010). EPA has for many years rated the Honda Civic GX as the cleanest internal combustion engine vehicle in the world. The GX is the only non-hybrid to score 9 or higher (out of 10) on both EPA's Air Pollution Score and EPA's Greenhouse Gas Score (EPA 2010a). This vehicle is also certified to meet California's tough super-ultra-low-emission vehicle (SULEV) standard. For 2009 and many prior years, the American Council for an Energy Efficient Economy awarded the Civic GX its greenest ranking, beating clean diesel light-duty vehicles and the Toyota Prius (Stern 2009).

American-manufactured NGVs have not always had lower criteria pollutant emissions than comparable petroleum-fueled models of the same engine size. When running on gasoline, the Cavalier bi-fuel CNG/gasoline vehicle had slightly worse fuel economy than the comparable gasoline version, probably as a result of added storage system weight. On the basis of today's EPA ratings, past CNG vehicles were comparable to those of gasoline vehicles. According to the Fueleconomy.gov website, the 2010 Civic GX's criteria air pollutant score is 9.5 (of 10) in low-emissions states and 9 elsewhere, whereas the standard Civic has ratings of 6 and 7, respectively. The *degree* of superior performance of the GX against gasoline does not appear to be inherent in CNG. American manufacturers did not reproduce this degree of superiority in past models. The issue with some vehicles, especially those that are bi-fuel, could be that the manufacturer did not optimize the vehicle to run on natural gas; therefore, the emissions were not as low as they could have been.

Historically, engine dynamometer and vehicle dynamometer tests have shown that medium- and heavy-duty vehicles running on natural gas typically have lower emissions of PM, NO_x, nonmethane hydrocarbons (NMHCs), and evaporative products (hydrocarbons). However, recent EPA/CARB emission standards require heavy-duty engines to have extremely low emissions, especially for PM and NO_x. These regulations have even caused difficulty for natural gas engine manufacturers to meet them, while diesel engine manufacturers have needed to use expensive after-treatment options, such as particulate filters and SCR equipment (Hwang 2010). Therefore, the emission benefits of new heavy-duty NGVs versus new diesel vehicles are likely diminished (as witnessed by 2010 certification data), although vehicle testing would be needed to document in-use emission differences. Table 5 compares emission reductions of NGVs with those of diesel-fueled vehicles (these vehicles/engines were produced before the 2007 emission regulations). These data are based on a sampling of tests conducted by the National Renewable Energy Laboratory and the West Virginia University Heavy-Duty Vehicle Emission Testing Laboratory.

TABLE 5 Emission Reductions of Natural Gas Vehicles Compared with Similar Models of Diesel Vehicles (percent difference)

Emission	CNG Delivery Trucks (United Parcel Service)	LNG Buses (Dallas Area Rapid Transit)	LNG Semi Trucks (Raleys)	LNG Refuse Trucks (Waste Management)	LNG Dual-Fuel Refuse Trucks (LA Bureau of Sanitation)	CNG Buses with MY 01 CWI Engines, (WMATA)	CNG Buses with MY 04 John Deere Engines, (WMATA)
PM	-95	NSS	-96	-86	NSS	-60	-84
NO_x	-49	-17	-80	-32	-23	+6.1	-49
NMHC	-4	-96	-59 <diesel THC	-64 <diesel THC	NSS	EQN	EQN
CO	-75	-95	+263	+80	NSS	EQN	EQN

NSS = not statistically significant; THC = total hydrocarbons. EQN=Emissions Quantity Negligible. WMATA = Washington Metropolitan Transit Authority.

Sources: Chandler et al. (2006); Zuboy and Melendez (2008).

4 PETROLEUM AND GREENHOUSE GAS BENEFITS OF NATURAL GAS VEHICLES

Petroleum and greenhouse gas (GHG) benefits of NGVs are estimated by using Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. The model estimates the full-fuel-cycle energy use and emissions of LDVs operating on conventional and alternative transportation fuels and vehicle systems and can approximate results for larger (i.e., medium- and heavy-duty) vehicles. It can also examine different natural-gas-based fuels, such as CNG, LNG, methanol, and Fischer-Tropsch diesel, and can investigate the effects of different natural gas types and origins. GREET assumes as a default that CNG and LNG come from conventional North American sources. Results of an Argonne study on renewable natural gas show that the fossil energy use, petroleum energy use, and GHG emissions are near zero (Mintz et al. 2010). These results are comparable to recent findings by CARB (CARB 2009a,b).

On a miles-per-gasoline-gallon equivalent (mpgge) basis, GREET currently assumes that a dedicated light-duty CNG vehicle has an energy-equivalent fuel economy 5% lower than that of a conventional vehicle powered by a gasoline internal combustion engine with comparable performance. This is consistent with information on the Fueleconomy.gov website for past American-manufactured NGVs and the Honda Civic GX. However, better results have been attained in Europe with advanced technologies (see next section).

For heavy-duty vehicles (HDVs), as noted in Table 5, the National Renewable Energy Laboratory tested two types of Washington Metropolitan Area Transit Authority (WMATA) buses, on CNG and low-sulfur diesel, and found that the CNG-fueled buses had fuel economy similar to and in some cases better than diesel buses on a miles-per-gallon-diesel-equivalent basis, with the results varying slightly by model year and type of emission control (Melendez et al. 2005). These results are somewhat surprising because of the typically low thermal efficiency (when compared with compression-ignition diesel engine) for a spark-ignition engine operating at low speed and load (Barnitt and Chandler 2006). In another study comparing different WMATA CNG and diesel buses in operation, the average energy-equivalent fuel economy of the CNG buses was 18% lower than that of the diesel buses (Chandler et al. 2006). These results are consistent with other test results showing a 10–15% reduction in fuel economy for these vehicles (Unnasch and Pont 2007); however, fuel economy benefits need to be examined further, especially considering the implications of the 2010 emission standards on vehicle performance.

In 2010, on the basis of default GREET assumptions, a 23.4-mpgge light-duty gasoline internal combustion engine vehicle's full-fuel-cycle fossil-energy use would be 5,928 Btu/mi, its petroleum energy use would be 5,274 Btu/mi, and its GHG emissions would be 478 g/mi. The results for comparable vehicles using CNG and LNG from North American natural gas sources are shown in Table 6. Both natural gas pathways result in significant petroleum displacement (about 99%) and modest reductions (about 15%) in GHG emissions. While there are no light-duty LNG vehicles in the U.S. market at present, this approach shows the general trend in gasoline versus this natural gas fuel. Table 6 also shows that LNG vehicles are slightly more energy- and emissions-intensive than CNG vehicles, which is a result of the liquefaction process; this insight applies to HDVs as well.

TABLE 6 Energy Use and GHG Emissions of Natural Gas and Gasoline LDVs

Fuel	Fossil Energy Use (Btu/mi)	Petroleum Energy Use (Btu/mi)	GHG Emissions (g/mi)
Gasoline	5,928	5,274	478
CNG	5,886	31	405
LNG	6,137	66	407

Source: GREET (2009).

The GREET model's focus is light-duty vehicles, as its fuel economy and emissions data are based on LDVs. GREET can also estimate the energy use and GHG emissions of HDVs, such as transit buses, when the appropriate fuel economy is applied. The dynamometer results from the Melendez et al. (2005) study showed the CNG transit buses average about 3.08-mpgde and the diesel transit buses about 2.98-mpgde, while the in-use results from the Chandler et al. (2006) study showed that the CNG transit buses averaged about 2.34-mpdge and the diesel transit buses about 2.84-mpdge. The GREET results using these values are shown in Table 7. As expected, heavy-duty CNG vehicles showed a large reduction in petroleum use, as compared to diesel vehicles. However, the GHG reductions for natural gas HDVs really depend on fuel consumption, as compared to their diesel counterparts. The reduction in GHG emissions associated with natural gas HDVs can be minimal if there is a 10–20% drop in fuel economy (mpgde-basis) or moderate if the fuel economy can approach that of their diesel counterparts.

A full-fuel-cycle assessment was conducted for California's Assembly Bill 1007 (Pavley) to develop a plan to increase the use of alternative transportation fuels in the state (Pont 2007). The assessment involved modifying Argonne's GREET model (version 1.7) by using assumptions specific to California. Two major changes were that they assume a lower fuel loss from the natural gas pipeline distribution and transmission (0.08% versus 0.45%), along with a higher energy efficiency for gas compression (98% versus 97.3%). The California version of GREET has about 30% lower upstream GHG emissions than the Argonne version, with the loss factor accounting for about 50% of that difference and the compression efficiency accounting for

TABLE 7 Energy Use and GHG Emissions of Selected Transit Buses

		GREET Results		
Fuel	Fuel Economy (mpgde)/ Testing Mode	Fossil Energy Use (Btu/mi)	Petroleum Energy Use (Btu/mi)	GHG Emissions (g/mi)
Diesel	2.84/in-use	48,131	43,753	3,936
CNG	2.34/in-use	55,918	292	3,791
Diesel	2.98/dynamometer	45,870	41,698	3,751
CNG	3.08/dynamometer	42,483	222	2,882

Sources: GREET (2009); Melendez et al. (2005); Chandler et al. (2006).

about 30%. This analysis looked at a range of model year 2012 CNG energy economy ratios (EERs), which is the ratio of the energy-equivalent fuel economy of an AFV compared with that of the conventional baseline vehicle. The CNG LDV EERs ranged from 0.98 to 1.08 (or 2% lower and 8% higher), with 1.0 being the CNG LDV baseline EER, resulting in a 20–30% reduction in GHG emissions (Unnasch and Pont 2007; Pont 2007). The CNG HDV EERs ranged from 0.9 to 1.0, with 0.94 being the CNG HDV baseline EER, resulting in an 11–23% reduction in GHG emissions (Unnasch and Pont 2007; Pont 2007).

The California GREET work was further refined into the Low Carbon Fuel Standard (LCFS) Program, where the EER was set at 1.0 for a CNG LDV and at 0.9 for a CNG HDV. The resulting GHG reductions from LCFS were set at an average of 29% compared with gasoline and 20% compared with diesel (CARB 2009c). It can be argued that the EERs for CNG vehicles in these analyses are aggressive when looking at past in-use data; however, the NGV industry has lobbied for a higher EER for HDVs on the basis of the improved efficiencies of CWI and Westport Innovations engines in recent years. The issue of natural gas vehicles EERs will continue to be contentious as GHG regulations try to assess the benefits of AFVs; therefore, further research is needed as new vehicles and engines hit the market.

5 IMPLICATIONS OF EVOLUTION OF CNG VEHICLE TECHNOLOGY IN EUROPE

A problem with citing past results (in this case for fuel economy) is that they may underestimate the potential of emerging and future technologies. Corporate average fuel economy standards in the United States have been tightened, imposing a need for more fuel-efficient engines over the next few years. Voluntary CO_2 reduction commitments by European manufacturers also will require significant improvements in technology. When currently available CNG-fueled European engines are compared with similar turbocharged direct-injection diesel engines, the two exhibit similar CO_2 tailpipe emissions but are considerably below those of conventional gasoline engines (Ademe 2009; Madegascar 2009; PR Newswire 2009; Auto Motor Sport 2010; Carfolio.com 2010; Carsplusplus 2010; GMEurope 2010; Whatgreencar.com 2010). However, the most advanced gasoline engine now available in Europe — the 1.4 TSI Twincharger — uses direct-injection, double-overhead camshafts, turbocharging, *and* supercharging. Introduced by Volkswagen in 2008 and named International Engine of the Year in 2009, this engine technology significantly reduces the fuel economy gap between the diesel engine and the gasoline engine. Since its introduction for gasoline engines, the technology has been successfully adapted to bi-fuel CNG engines and is available in Europe in the Volkswagen Passat (Table 8). More recently, Opel introduced a turbocharged (but not supercharged) bi-fuel engine in the Zafira, a seven-passenger van (GMEurope 2010). The most advanced European turbocharged CNG engines now have lower CO_2 emissions than competing diesel engines (Table 8).

The potential for turbocharging to offset the power loss caused by oxygen displacement when CNG is used in normally aspirated engines has been recognized since the 1990s. Tennant et al. (1994) found that turbocharging helped reduce air (oxygen) displacement in the cylinder, allowing the engine to take advantage of the high octane of natural gas and thereby achieve more efficient combustion. Turbocharging has long been common in diesel engines, but not in gasoline engines. It was recognized only a few years ago that emerging technology for spark-ignited engines was going to close the efficiency gap between spark-ignited gasoline engines and diesel engines (Smokers et al. 2006). What was not recognized at that time was the potential of the improved gasoline technology to match up well with the use of CNG in the same engines.

Table 8 illustrates the effects of engine technology on CO_2 tailpipe emissions reduction associated with CNG relative to gasoline and diesel engines. In all four examples, the diesel is turbocharged and direct injected, with double-overhead camshafts and four valves per cylinder. In the Fiats, the spark-ignited engines are the least advanced technologies, with only two valves per cylinder, a single-overhead camshaft, and no turbocharging. In the Volvos, the spark-ignited engines move up to double-overhead camshafts with four valves per cylinder, but no turbocharging. In the Opel/Vauxhall (GM) vehicles, turbocharging is added, while in the VWs, the spark-ignited engine goes beyond the level of the diesel, adding supercharging (twincharging). The CO_2 emissions benefits of CNG relative to diesel and gasoline rise steadily as the level of technology approaches that of the diesel, then surpasses it. The greater power per unit of displacement allows engine downsizing relative to the gasoline and diesel engines, which

TABLE 8 Fuel Use and CO_2 Tailpipe Emissions of Selected European LDVs: CNG vs. Gasoline and Diesel

Make	Model	Engine Size (L) and Name	Trans-mission	Engine HP	Fuel	Fuel Consumption (L/100 km)	CO_2 (g/km)	CNG (% CO_2 drop)
VW	Passat SW	1.4 TSI	M6	148	CNG	6.6	123	
VW	Passat SW	2.0 16S TDI	M6	170	Diesel	5.7	149	-17
VW	Passat SW	2.0 16S TDI	M6	140	Diesel	5.7	148	-17
VW	Passat SW	1.8 16S TSI	M6	160	Gasoline	7.8	186	-34
VW	Passat SW	1.4 16S TSI	M6	122	Gasoline	6.7	159	-23
Opel	Zafira	1.6 Turbo	M5	150	CNG	7.8	144	
Opel	Zafira	1.9 CDTI	M6	150	Diesel	6	159	-9
Vauxhall	Zafira	2.2 16V	A4	150	Gasoline	8.6	204	-29
Opel	Zafira	1.8 16V	M5	140	Gasoline	7.4	177	-19
Volvo	S60	2.4 Bi-fuel	M5	140	CNG	8.9	159	
Volvo	S60	2.4 Bi-fuel	M5	140	Gasoline	8.7	208	-24
Volvo	S60	2.4 Turbo	M5	124	Diesel	6.4	169	-6
Volvo	S60	2.4 Turbo	M6	161	Diesel	6.6	174	-9
Volvo	S60	2.4	M5	138	Gasoline	8.8	209	-24
Volvo	S60	2.4	M6	168	Gasoline	8.9	212	-25
Fiat	Grande Punto	1.4 Bi-fuel	M5	68	CNG	6.4	115	0
Fiat	Grande Punto	1.4 Bi-fuel	M5	77	Gasoline	6.3	149	-23
Fiat	Grande Punto	1.4	M5	76	Gasoline	5.9	139	-17
Fiat	Grande Punto	1.3 16V Turbo	M5	90	Diesel	4.5	119	-3

Sources: Ademe (2009); Auto Motor Sport (2010); Carfolio.com (2010); Carsplusplus (2010); GMEurope (2010); PR Newswire (2009); Whatgreencar.com (2010).

enhances fuel efficiency. Thus, these European examples imply that CNG is “inherently” superior to both diesel and gasoline engines in terms of tailpipe CO_2 emissions, once the level of technology is equalized.

The other key issues regarding European NG vehicles relate to platform configuration, cost, and regulated emissions. European CNG installations mount multiple tanks under vehicles equipped with front-wheel drive, retaining luggage space. They also are generally available in bi-fuel configurations, whereas there are no longer bi-fuel OEM CNG vehicles in the United States. In the U.S. Honda Civic GX, the single CNG tank is mounted within the trunk, sacrificing half of the luggage space. European tank placement configurations could be used in the United States if OEMs take this issue into consideration during vehicle design.

The use of both turbocharging and supercharging, along with the cost of natural gas cylinders, makes the VW CNG technology even more expensive than VW's competing diesel. The list price of the Euro 4-compliant (emissions standard) VW Passat Variant "TSI DSG Ecofuel" is about 3,000 euros (about $3,700 U.S.) more than a comparable Euro 6-compliant Passat Variant "Blue TDI" diesel (Auto Motor Sport 2010). (Note that in Europe emissions standards for diesel and gasoline are different from each other.) In contrast, Opel's recent announcement for the less-technologically complex turbocharged seven-seat Zafira CNG bi-fuel 150-hp model states that the CNG bi-fuel model is about 800 euros (approximately $1,000 U.S.) less than the competing diesel powertrain option. The vehicle is also about 8,000 euros (approximately $10,000 U.S.) less than the Passat CNG bi-fuel (GMEurope 2010).

Table 8 shows that for the least technologically advanced spark ignited engine, there is a loss of 10% in power when drivers choose to own and operate a 1.4-L bi-fuel Grande Punto powered by CNG, in comparison to a 1.4-L gasoline-fueled Grand Punto. The loss of power is significantly more pronounced in the U.S. Civic GX, at nearly 20% (Hondanews.com 2009a). The bi-fuel European CNG vehicles are rated at Euro 4 criteria pollutant tailpipe emissions standards, which are far weaker than the U.S. Tier II standards.[1] One technological question is whether the severe power loss of the Civic GX is a necessary sacrifice to make the vehicle one of the cleanest in the United States. A second is whether more technologically advanced CNG bi-fuel vehicles can meet any or all U.S. Tier II and California SULEV, as well as upcoming Euro 5 and 6 standards.

Still another area of uncertainty involves the regulation of methane emissions for purposes of greenhouse gas control. The International Association for Natural Gas Vehicles has recently argued that a proposed United Nations standard would make retrofit of NGVs throughout the world infeasible (Seisler 2009). World automobile manufacturers have not yet embraced CNG as a part of their manufacturing portfolio, although Europe is emerging as a possible exception. Seisler (2009) noted that 90–95% of CNG vehicles worldwide are retrofits. He also noted problems with the current Euro 5 and 6 standards for NGVs because they are based on total hydrocarbon emissions rather than NMHC or nonmethane organic gas (NMOG) emissions. In effect, if CNG is to become a fuel embraced by automakers, regulations worldwide will need careful examination. Regulatory separation of reactive gases contributing to ozone problems (NMOG or NMHC) from "nonreactive" methane would be beneficial (Seisler 2009). In the United States, NMHCs have been carefully measured since the 1990 Clean Air Act, while in California, NMOGs have been measured and regulated. However, for regulatory purposes, information is not collected on methane emissions, making them relatively uncertain at this time. In contrast, Europe measures total hydrocarbons (NMHC plus methane) and does not separate the two.

Seisler's (2009) estimates of methane emissions from European vehicles are consistent with those of the Argonne GREET model (~ 0.15 g/mi). Nam el al. (2004) performed chassis dynamometer methane emission tests on a CNG passenger car (0.039–0.047 g/mi) and truck

[1] The 2010 Prius is rated at the more strict Euro 5 level in Europe, at SULEV II in California, and at Bin 3 of Tier II in most of the rest of the United States. The 2010 Civic GX is rated at SULEV II in California and Bin 2 of Tier II in most of the rest of the United States.

(0.092–0.102 g/mi) and found that their emissions were four and seven times higher, respectively, than those of the non-CNG vehicles tested (model years 1995 through 1999). Gaines et al. (2007) and results in Table 8 suggest that current OEM CNG emissions rates could increase the CO_2-equivalent emissions from CNG by about 2–3%. It is not clear whether methane estimates are included in the European CO_2 totals in Table 8; in any case, the data in the table suggest that with advanced engine technologies, CNG can remain superior to diesel, even if methane emissions are not counted. Clearly detailed measurement of hydrocarbon species from advanced CNG vehicles would help to evaluate current technical feasibility; set emission control research priorities; and develop reasonable, balanced standards that are in the long-term public interest.

Still another question is whether and when the baseline advanced turbocharged direct-injection, four-valve-per-cylinder engine technology will make its way into U.S. vehicles. The 2011 model Chevrolet Cruze will have a 1.4-L turbocharged engine, to be built in Flint, MI (egmCarTech 2008), while Chrysler will build a plant to produce a 1.4-L four-valve-per-cylinder "multiair" engine for the Fiat 500 in Auburn Hills, MI (egmCarTech 2009). Chrysler will also begin producing a V6 engine by using Fiat technologies, such as "multiair," direct-injection, and turbocharging for initial use in the 2011 Jeep Grand Cherokee (Ponticel 2010a). The Fiat engine will have a "turbo version in the near future." Fiat has also announced a new twin-cylinder engine developed with multiair technology, which will be equipped with an automatic stop/start system; a bi-fuel (gasoline and natural gas) version of this engine will be built in the automaker's plant in Poland (Kendall 2010). Ford calls the direct-injection turbocharged spark-ignited engine its "EcoBoost" technology and plans to introduce it in a V6 F150 pickup truck. It was stated that this technology would allow "for a V6 to perform like a V8 of old, and an I4 as a V6 of old" (Ponticel 2010b).The automaker plans to market 500,000 cars a year powered by gasoline turbo direct injection (GTDI) engines by 2013 (Abulsamid 2008). Thus, the opportunity to implement advanced-technology, fuel-efficient, low CO_2 CNG engines manufactured in the United States will exist over the next five years.

6 HISTORICAL AND CURRENT ACTIVITIES AND STRATEGIES

The DOE Office of Energy Efficiency and Renewable Energy (EERE) Vehicle Technologies Program has supported the market for NGVs in three ways: (1) research and development (R&D); (2) technology transfer; and (3) deployment through the Clean Cities Program, a voluntary, grassroots effort that DOE began in 1993 to accelerate markets for alternative transportation fuels; the Advanced Vehicle Testing Program; and mandated fleet programs.

6.1 RESEARCH AND DEVELOPMENT

In 1999, DOE launched a range of R&D efforts on NGVs (primarily medium- and heavy-duty), from proof-of-concept (1) to near-term vehicle and engine development and (2) to commercialization and infrastructure development. In 2002, the Natural Gas Vehicle Technology Forum (NGVTF), a diverse group of industry stakeholders, was created to consolidate DOE's R&D efforts on NGVs and advise DOE on research needs.

DOE focused its research, including its work on four types of engine technologies — spark-ignition lean burn, spark-ignition stoichiometric, compression-ignition dual-fuel, and compression-ignition direct injection — on developing Class 3–6 CNG vehicles and Class 7 and 8 LNG vehicles that would meet 2007 emission standards. Work that began under this program, known as the Natural Gas Engine and Vehicle Research and Development Program, led to development of CWI's spark-ignition stoichiometric ISL G engine (which now meets the 2010 EPA highway heavy-duty emission standards), as well as other technologies used in commercial products.

Research has also been conducted on renewable natural gas, including development of cost-effective methods of methane gas recovery and cleanup from landfills and other biomass sources for conversion to LNG. Before landfill gas can be used for transportation fuel, the contaminants and most of the CO_2 must be removed. With the support of a DOE Small Business Innovation Research grant, Acrion Technologies developed its CO_2 Wash™ landfill gas purification technology and demonstrated the process at a landfill in New Jersey. The goal was to produce 10,000 gallons of LNG from landfill gas to fuel two Waste Management refuse trucks on commercial collection routes totaling 600 hours (EERE 2005).

Another area of research involves development of small-scale natural gas liquefiers for LNG production. A small-scale system gathers natural gas from a transmission pipeline at a point where the pressure is dropped for commercial distribution. As the gas pressure decreases, the gas expands and cools and is used as a coolant in the liquefaction process. A small-scale plant was built in Sacramento, CA, to liquefy 10–20% of natural gas entering the plant and produce 10,000 gallons of LNG each day. The plant technology was tested successfully and is now available to be licensed for commercial manufacturing.

DOE has also funded a safety evaluation of FuelMaker Corporation's Phill home refueling appliance. Thirty-three residential garages equipped with the Phill were evaluated to determine their design, construction, and air infiltration characteristics, and computer modeling was used to calculate garage gas concentrations from potential leaks. Risk scenario probabilities were identified and calculated; it was determined that the annual probability of a deflagration due to misuse failures is 1 in 7 million. The safety evaluation also led the manufacturer to incorporate suggestions from the study in the final design of the Phill (Waterlan et al. 2005).

By 2006, budget priorities had changed, and DOE ended its research programs on NGVs and infrastructure. However, this appears to be changing as Congress appropriated in FY10 $5.0 million for NGV R&D. Nevertheless, the industry forum was maintained by the California Energy Commission (CEC). In 2008, the forum partners met once again to discuss priorities for the NGV industry (AFDC 2008b). Their recommendations are discussed in the "Barriers in the Marketplace" section of this document. For a complete account of all NGV and infrastructure R&D, see *A Foundation for the Future: Natural Gas Vehicle and Infrastructure Research and Development Sponsored by the U.S. Department of Energy, 1999–2006* (Zuboy and Melendez 2008).

6.2 TECHNOLOGY TRANSFER

Clean Cities funded industry stakeholder meetings from 2000 through 2005, drawing 60 to 80 attendees, to help prioritize R&D. In addition to Clean Cities, the organizations attending were OEMs, vehicle and infrastructure packagers, national laboratories, government agencies, industry and trade associations, industry research groups, utilities and fuel distributors, fleets, equipment suppliers, and nonprofit firms. Discussions centered on industry coordination and information dissemination, technology updates, and NGV economics and policies.

In addition to previous support for the NGVTF, Clean Cities supports the Natural Gas Transit and School Bus Users Group, managed by the Clean Vehicle Education Foundation. Members share lessons learned and problem-solving techniques via webcasts. The group provides a forum for maintenance staffs of natural gas bus fleets to learn about the latest codes and standards, safety issues, and technologies. It also serves a valuable role by acting as a liaison between the fleet operators and natural gas vehicle and equipment manufacturers.

6.3 DEPLOYMENT

6.3.1 Clean Cities

Since 1993, DOE has funded a voluntary, grass-roots effort to accelerate markets for alternative transportation fuels, known as the Clean Cities Program. Primary support for NGVs and infrastructure has been provided through Clean Cities' competitive grant programs.

From 1999 to 2008, Clean Cities has awarded more than $19 million in competitive grants to pay for the incremental cost of light-, medium-, and heavy-duty NGVs; landfill gas projects; infrastructure for fleets and other consumers; and training and outreach for natural-gas-related projects. All grants have been heavily leveraged with funds from industry and other partners.

More recently, the American Recovery and Reinvestment Act of 2009 boosted funding for AFVs and infrastructure in 25 Clean Cities areas to historic levels. For natural gas vehicle projects, nearly 3,200 vehicles are estimated for purchase, with the construction of an extensive refueling network of approximately 135 natural gas stations. Project periods will consist of 4 years. A few notable projects include:

- *UPS Ontario-Las Vegas LNG Corridor Expansion project*, completing a LNG corridor across the southwestern United States and deploying 48 LNG trucks;

- *Utah's Clean Cities Transportation Sector Petroleum Reduction Technologies Program*, building 16 new CNG public stations and upgrading 24 existing CNG stations with an additional 678 CNG vehicles plying the roads; and

- *New Jersey's Clean Cities CNG Refuse Trucks, Shuttle Buses, and Infrastructure project,* bringing an additional 277 garbage trucks and shuttle buses to the state and the ability to fill-up at four new CNG facilities.

In 2007, 86 of the 87 Clean Cities Program coalitions reported that 41% of the total alternative fuel displacement was from NGVs, primarily medium- and heavy-duty trucks and buses (Johnson and Bergeron 2008). In 2008, this total replacement figure grew to 53% (Johnson and Bergeron 2009). Technical support through Clean Cities Tiger Teams has been able to solve specific infrastructure or fleet problems. Clean Cities has helped communicate best practices for the natural gas industry. Its CD-ROM, *Compressed Natural Gas: A Suite of Tutorials,* is an extensive repository of information on NGVs, codes and standards, and infrastructure. Evaluation of CNG fleets has also been funded; an example is a study of the SunLine Transit (Palm Springs, CA), an all-CNG bus fleet. More recently, NREL issued a report for Clean Cities, *Business Case for Compressed Natural Gas in Municipal Fleets,* that provides an evaluation of project profitability on the basis of a set of operating procedures of municipal vehicles, school buses, transit buses and refuse vehicles. All of these products can be found on the Alternative Fuels and Advanced Vehicles Data Center managed by the National Renewable Energy Laboratory. Funded by Clean Cities, the web-based data center includes an extensive natural gas portal, with important topics on NGVs and infrastructure.

6.3.2 Advanced Vehicle Testing Program

Beginning in the early 1990s, a series of LDV chassis dynamometer emission tests were conducted on NGVs and other AFVs under the DOE Advanced Vehicle Testing Program. Results were compared with those of otherwise identical gasoline vehicles in service. The program has expanded to include benchmarking and validation of the performance and capabilities of medium- and heavy-duty advanced vehicle technologies and fuels, including hydrogen-enriched natural gas.

6.3.3 Fleet Programs

Two other deployment programs, funded by DOE and created by the Energy Policy Act of 1992, have promoted NGV acquisitions. The State and Fuel Provider Fleet Program mandates the acquisition of a percentage of AFVs by certain states and fuel providers. From 1992 to 2009, more than 33,000 NGVs were acquired from a total alternative fuel fleet of nearly 159,000 (AFDC 2010e). The Federal Fleet Program requires certain federal agencies to acquire a percentage of AFVs each year. In the 2009 reporting period, more than 6,500 vehicles from a federal alternative fuel fleet of roughly 148,000 were natural gas (AFDC 2010f).

7 BARRIERS IN THE MARKETPLACE FROM RESEARCH TO DEPLOYMENT

7.1 PRODUCT AVAILABILITY

For the long term (but not necessarily delayed), engine and fuel tank vehicle integration should be a key focus of research, because it appears to be a major barrier to the deployment of more natural gas trucks and other vehicles. The potential viability of bi-fuel CNG and gasoline vehicles using advanced turbocharged engines for medium- and light-duty vehicles also merits significant research. Since 2007, only one OEM has offered a light-duty natural gas vehicle. SVMs, due to the volume of their production, have difficulty with the EPA certification process because it requires significant time, costs, and resources. Small-volume manufacturers and fleet users cite the process as complicating product availability in offering products in a timely fashion. However, in 2010, EPA has proposed to streamline the certification requirements of low-mileage vehicles and clarify the procedure to convert high-mileage vehicles (AFDC 2010d). This effort is expected to reduce costs and expand the availability of alternative fuel aftermarket conversion systems.

As previously noted, the Natural Gas Vehicle Technology Forum, a diverse group of industry stakeholders, was created to consolidate the DOE R&D efforts on NGVs and advise DOE on research needs. While Clean Cities is not authorized to fund research and development programs, it may be able to assist to some degree in demonstration and technology transfer efforts. To achieve a robust penetration of NGVs, industry stakeholders at a NGVTF meeting in November 2008 agreed on the research, demonstration, and deployment needs listed in Table 9 (AFDC 2008).

7.2 EMISSIONS TESTING DATA

The lack of on-road testing and evaluation data for recent-model natural gas HDVs is problematic. According to Davies et al. (2005), data to properly quantify the benefits of natural gas over diesel fuel are not yet available. They do discuss what level of testing will be necessary to provide reliable estimates in the future. For now, their findings are that the GHG effects of natural gas versus diesel are similar. In the “cleanest” comparison — for the same vehicle type on the same driving cycle with a natural gas and diesel version of the same engine block family from the same manufacturer — natural gas was better than diesel, as is also shown in Table 7.

Other data and comparisons have not consistently favored natural gas, and Davies et al. concluded that no statistically reliable conclusion could be reached. None of the comparisons yielded evidence of a GHG penalty, so carefully moving forward with NGVs for energy security should be a safe strategy with respect to possible GHG concerns. Table 8 indicates that spark-ignited CNG engines promise consistently lower emissions than diesel engines. Thus, if criteria pollutant or methane emissions regulations impede the CNG pathway, we need to know why and whether the circumstances should be altered via properly tailored regulation, R&D for improved after-treatment, or both. With testing and incentives/penalties, natural gas can likely be implemented in transportation, improving energy security and reducing GHG emissions.

TABLE 9 Research, Development, Demonstration, and Deployment Actions Identified at NGVTF Meeting, November 2008

Description	Estimated Cost
Engine Development and Vehicle Integration Recommendations	
Integrate available natural gas engines into more models and applications by OEMs	>$1.0 million
Develop a broader range of natural gas HDV engine sizes and applications and improved efficiencies	>$2.0 million
Develop NGV versions of off-road applications	~$1.0 million
Develop a variety of hybrid natural gas HDVs	~$1.0 million
Develop engine technology optimized for hydrogen/CNG blend fuel	~$1.0 million
Develop NGV homogeneous charge compression-ignition engine technology	~$1.0 million
Fueling Infrastructure and Storage Recommendations	
Develop legacy fleet engine controls and or fueling infrastructure upgrades to accommodate fuel variability	~$1.0 million
Research an improved composite tank safety device and installation protocol to avoid tank rupture in localized fire	≤$500,000
Develop improved handling, reliability, and durability during LNG dispensing and on-board storage	≤$500,000
Develop low-cost, lightweight, and compact on-board storage of CNG at a lower pressure and higher density	>$1.0 million
Provide global positioning system navigation information for NGV fueling station locations	Now completed — Clean Cities
Develop the next generation of home refueling technology	~$1.0 million
Technical and Strategic Studies Recommendations	
Revitalize the Natural Gas Vehicle Technology Forum	<$500,000
Update the roadmap through a Roadmap Advisory Council	<$500,000

7.3 WATER ISSUES

Recent shale finds indicate the United States has adequate supplies of domestic natural gas; however, some states may limit shale gas production because of the water requirements of fracturing and fears of aquifer contamination.

Water consumption from natural gas recovery varies with geology and the technology used. Extracting natural gas by using horizontal wells, the common method for shale formations, requires up to five times more water and sand than conventional vertical-well extraction of on-shore sources (Sumi 2008). Initial drilling requires a large amount of water withdrawal and consumption. Once production begins, the well generates produced water along with the gas/oil mix, which can be reinjected or disposed of. Sumi (2008) noted that a well drilled in the Marcellus Shale in the Appalachian Basin may have to be hydraulically fractured, or "fracked," several times over the course of its life to keep the gas flowing and that each fracking operation may require more water than the previous one. A majority of the water returns to the surface, and this "flowback," or wastewater, needs to be treated or disposed of. For cost reasons, most flowback has historically been placed in disposal wells. However, if water resources dwindle, it will be necessary to treat and reuse more of this water.

The Ground Water Protection Council (GWPC), an association of state resource protection professionals, has been characterizing the shale gas resource and its production requirements, including water consumption (GWPC and ALL Consulting 2009). Their study concluded that "Water use for shale gas development will range from less than 0.1% to 0.8% of total water use by basin." On behalf of the GWPC, Scott Kell (2009) testified to the House Committee on Natural Resources that "As a result of our regulatory review and analysis, the GWPC concluded that state oil and gas regulations are adequately designed to directly protect water resources through the application of specific programmatic elements such as permitting, well construction, hydraulic fracturing, waste handling and well plugging requirements." Recommendations for regulatory improvements were included in the testimony.

Natural gas production from shale probably consumes considerably less water per unit of energy delivered than coal production, ethanol production, tar (oil) sands, or oil shale, among others. Although more independent research on the topic is under way, Chesapeake Energy (2009), quoting the GWPC characterization of shale and DOE characterizations of other fuels, has compiled a fact sheet that implies that once full-fuel-cycle water use evaluations of various sources of energy have been completed, shale gas will be among the lower users, even if it is more water consumptive than present natural gas production.

However, concerns over proper water treatment may slow some shale development. The GWPC acknowledges that circumstances vary, and water issues are best addressed in the context of local conditions.

7.4 DISINTEREST OF UTILITY PARTNERS

Other deployment barriers include utility partners in some areas of the country that no longer find value in marketing NGVs. The American Gas Association, a trade association that represents public utilities, has recently formed a transportation fuel advisory group to promote NGVs to its members. Once the objections from disinterested parties are understood, a strategy to engage key utility partners by high-level officials at DOE could renew interest in greater vehicle deployment.

7.5 LINGERING PERCEPTIONS

Another challenge is that the industry is still fighting perceptions from the early 1990s, when less-than-robust natural gas engines were deployed. Some fleet managers with adverse experiences remain in these positions or have been promoted and given higher decision-making authority, preventing new vehicle introductions. Bertram et al. (2009) concluded that the reliability of diesel engines in medium-duty trucks provided a better explanation for their expanded use than did fuel savings.

7.6 HIGH COST AND LACK OF INFRASTRUCTURE

In some cases, especially for large municipal fleets, the high cost of infrastructure is still a barrier, even though incentives are available for tax-exempt fleets that can assist with shortening the payback period. Often these fleets are not even aware of the tax benefits. With fewer than 1,000 natural gas stations nationwide, fleets that operate on longer routes cannot justify making the switch unless additional public- and private-sector partners come together to build or make available existing stations along key routes.

8 OPPORTUNITIES IN THE MARKETPLACE

8.1 INTRA-CITY TRUCKS, TRANSIT BUSES, AND OFF-ROAD VEHICLES

One optimistic source for future use of natural gas in heavy-duty transport is the California State Alternative Fuels Plan of December 2007. This source estimates a maximum amount of alternative fuels that could be in use in 2022 (CEC 2007). Of this total, about 17% is natural gas. The CEC plan sees natural gas as being primarily an intra-city "return-to-base" HDV fleet fuel, although the possibility of using CNG in LDVs in small quantities is also considered. The report includes scenarios to 2050, one of which includes a very significant penetration of natural gas (36%) in HDV transport.

When this 36% penetration estimate is applied to EIA projections for 2030 (EIA's farthest projections) and GREET modeling of U.S. on-road HDV use (including transit buses), a reduction of approximately 1.2 million barrels of oil per day is achieved, with a comparable increase in domestic natural gas use. While not the primary focus of Clean Cities, similarly, if 36% of the off-road vehicles used in construction and industry were replaced with NGVs, a further reduction of almost 400,000 barrels of oil per day could be achieved. In 2030, on-road and off-road HDVs will use an estimated combined total of 4.5 million barrels of oil daily, while total U.S petroleum consumption is estimated to be approximately 20 million barrels a day. This scenario would reduce total daily oil consumption by about 8%.

The U.S. transportation sector would consume 2.5 quads of natural gas largely in commercial trucking and 0.8 quads in off-road vehicles in this 2030 scenario. Currently, 8 quads of natural gas are consumed in the residential and commercial sectors, 8.1 quads in the industrial sector, and 6.8 quads in electric power generation (EIA 2009c). Current petroleum consumption in the transportation sector is 28 quads.

When examining the potential for NGVs to achieve a significant penetration of the HDV fleet, we see that the commercial trucks are quite diverse. Bertram et al. (2008, 2009) recently examined long-term U.S. trends in commercial truck fuel use, studying shifts from gasoline to diesel fuel. They divided commercial trucks into heavy-, medium-, and light-duty trucks, on the basis of a size and configuration accounting format used by the Federal Highway Administration (FHWA), and divided heavy commercial trucks into combination trucks and single-unit trucks. Recent data suggest a possible reversal in the long-term trend toward increased dieselization in single-unit trucks. Since 2007, the gasoline share of commercial single-unit truck sales increased by 20% or more, depending on size class (*Light and Medium Truck* 2008).

Diesel fuel prices jumped relative to gasoline prices in late 2007 and this situation continued even after crude oil prices collapsed in late 2008 (Table 2 and EIA 2010b). That increase occurred as ultra-low-sulfur diesel fuel was introduced, and U.S. and world demand for gasoline has dropped. Whether the new increase in diesel cost relative to gasoline cost is permanent remains to be seen. However, in the future, natural-gas-fueled medium- and light-duty trucks probably should be compared on a total-cost-of-ownership basis not only to diesel-fueled heavy-duty vehicles but also to gasoline-fueled trucks, particularly single-unit trucks used for urban delivery. Further, those considering GHGs are increasingly thinking long term, so the evaluation should cover possible events over several decades.

As the TIAX (2005) study found, efforts to make the diesel engine as clean as the gasoline engine appear to be significantly changing the relative economic merits of diesel (the new "clean" diesel) versus other fuels. The capability of U.S. commercial truck natural gas engines has been developed over two decades. The kinks are largely out of them, and, as observed earlier, most of the engines meet the 2010 tailpipe emission standards that many diesel engine manufacturers have struggled with.

Combination trucks (FHWA heavy) dominate intercity transport and have relied on diesel fuel for many decades. FHWA medium trucks predominantly serve intra-city transport and only in the last 30 years have come to rely almost exclusively on diesel fuel. FHWA light commercial trucks have increasingly adopted diesel fuel over the last 20 years. Among the three categories, Bertram et al. (2008) estimated that in 2002, FHWA heavy (combination trucks) used 15.4 billion gallons of fuel a year, FHWA medium (6 or more tire, straight trucks) used 6.8 billion, and FHWA light trucks (commercial two-axle, four-tire trucks) used 13.8 billion — for a total of 36.1 billion gallons per year. EIA estimated the total on-highway distillate fuel consumption for 2002 to be 34.3 billion gallons (EIA 2009f). The estimates of Bertram et al. included gasoline-fueled commercial trucks. According to their estimates, gasoline use was dominant in the FHWA light truck category (less than 10,000 lb GVW). For light, medium, and heavy commercial trucks, approximately 57% of their 2002 fuel use was estimated to be by single-unit (urban delivery) trucks, about two-thirds of which would be two-axle, four-tire trucks.

The latter class of truck is at the heavy end of gasoline-fueled vehicles long manufactured by Ford, GM, and Chrysler and more recently by Asian manufacturers, with Toyota being relatively successful. Although the only light-duty OEM CNG vehicle now available is a passenger car — the Honda Civic GX — as recently as 2004, CNG models were available from Ford and GM in pickup trucks, box trucks, and standard-sized shuttle vans; availability will increase, however, as both Ford and GM have announced they will again be offering CNG packages for these vehicles. Several small-volume manufacturers' NGV modifications of Ford and GM models are also currently available. On the basis of the availability of the CWI, Westport Innovations, and Emission Solutions natural gas engines for medium-duty and heavy-duty truck applications, the estimates above suggest that 36% of "EPA-heavy"-duty (8,500-lb GVW and up) on-highway fuel use replacement by CNG in urban areas is technologically feasible, although considerable engine technology (re)development and refinement across a wider range of truck offerings would be necessary, consistent with R&D needs noted in Table 9.

In some respects, this medium-light commercial truck market penetration scenario seems aggressive, considering historical achievements for CNG use in U.S. transportation. Nevertheless, we noted earlier that CNG use worldwide has been expanding dramatically, generally in nations with considerable domestic natural gas supplies and little domestic oil. Egypt and Argentina are two nations that have been oil-short and gas-rich for decades. This has not been the U.S. circumstance; however, recent trends in the ratio of domestic gas and oil reserves will make the United States much more like Egypt and Argentina in the future. Egypt and Argentina use natural gas not only in commercial vehicles but also in some personal LDVs. Argentina has one of the greatest market penetration of natural gas for transportation, having started in 1980 (IANGV 2010). Gas prices were held low as a matter of public policy (recently 70% cheaper than gasoline). Taxi fleets were converted first, and personal-use vehicles followed. Today, nearly 30 years later, about 15% of Argentine vehicles are fueled with natural gas and natural gas refueling stations are common (Bridges 2008). Such price controls would not be possible in the United States, but in terms of numbers of vehicles, the U.S. commercial vehicle scenario referred to above — though admittedly aggressive — would be well below 15% of vehicles nationwide.

CNG is not the only way to use natural gas to provide transportation services. LNG can be used where range is important. Fischer-Tropsch diesel (gas-to-liquid, or GTL) could also be used, but is not as desirable from a GHG perspective. Natural gas is an excellent fuel for power generation, which in turn can provide miles of service via electric drive for passenger cars and small sports utility vehicles, with even lower GHG emissions per mile than CNG (Gaines et al. 2007). Medium-light commercial truck use of CNG sits in a potential "sweet spot" where more range is needed per day than can be provided economically by batteries in electric vehicles and plug-in hybrids. However, less range is needed for medium-light commercial trucks than for large intercity combination trucks, for which LNG (requiring new infrastructure) or GTL (emitting more GHGs) would be needed to meet range requirements.

In summary, even with the expansion of domestic natural gas reserves, which the CEC (2007) study projects, it is unlikely that natural-gas-fueled LDVs could replace a large portion of gasoline-fueled LDVs. However, it is possible that natural gas might forestall a revival of gasoline use in medium-duty trucks. Natural gas could be a big niche fuel with market shares in the tens of percentage points, as projected in the CEC report. The most cost-effective approach would likely involve a regional focus on natural gas, where the market is near the resource base.

8.2 EMISSIONS AND DURABILITY TESTING

Although deployment, not vehicle testing, is the primary responsibility of Clean Cities, early, well-organized field testing of competing model year 2010 CNG, clean diesel, diesel hybrid, and gasoline powertrains should be encouraged by Clean Cities. Deployment efforts are inevitably related to the information available on emissions and fuel consumption of vehicles being selected. Given the major turnover of engine and emissions control systems in 2010, it is desirable that quality data be made available demonstrating when criteria pollutant and GHG neutrality or improvement via use of natural gas is assured (in comparison to gasoline, diesel or, particularly, diesel hybrids). It is highly unlikely that a new round of criteria pollutant emissions standards will be passed in the next decade.

Accordingly, there are likely significant benefits to the early tracking of new emissions control technologies that have been developed to meet 2010 standards, because the best of them will likely be in use for a decade or more. Avoidance of surprises is particularly desirable in light of possible competition between natural gas and diesel hybrid trucks. Existing engine dynamometer certification test procedures for commercial trucks cannot properly evaluate hybrids. There has already been a revision to testing for LDVs, partly in response to debates about the true fuel economy of hybrid LDVs and, to a lesser extent, diesels (EPA 2006).

Testing on vehicle dynamometers and possibly in-use emissions measurement for light and medium commercial trucks is possible and desirable for the target market suggested here (Davies et al. 2005). This is particularly true if and when hybridization of natural gas trucks is to be implemented, as has been suggested. Davies et al. do not even suggest use of engine dynamometer tests for accurate determination of in-use GHG and fuel use rates. Early evaluations of 2010-compliant CNG engine durability versus the new clean diesel systems in selected fleets should be considered. In contrast to emissions testing — which is not Clean Cities' responsibility — this is probably a suitable use of deployment funds. Solicitation of funding of periodic emissions tests from other DOE offices or federal agencies or local jurisdictional districts (i.e., large metro area air quality control regulatory bodies), in conjunction with such fleet field evaluations, could be considered.

Greenhouse gas regulations were finalized in 2010 by the EPA and Department of Transportation's National Highway Traffic Safety Administration for model years 2012 through 2016 passenger cars, light-duty trucks, and medium-duty passenger vehicles. The standards require vehicles to meet an estimated combined average emissions level of 250 g/mi CO_2 in model year 2016, which is equivalent to 35.5 mpgge if the automakers were to meet the standard only through fuel economy improvements (EPA 2010b). The EPA also set standards for tailpipe nitrous oxide (N_2O) and methane (CH_4) emissions at 0.01 and 0.03 g/mi, respectively. These N_2O and CH_4 emission levels were set to cap the emissions of current gasoline and diesel vehicles so that future levels did not exceed current ones with the idea that this would require little to no new technological effort or expense. However, automakers expressed concerns that these levels would pose challenges to some vehicle technologies (including NGVs) that can reduce overall GHG emissions. Therefore, the EPA agreed to allow automakers to meet the N_2O and CH_4 standards by using an optional CO_2-equivalent approach. This would allow manufacturers to convert the N_2O and CH_4 test results into CO_2-equivalent values using the global warming potentials of each and add this sum to the CO_2 emissions.

Good test data on emissions, durability, maintenance costs, and other factors in a variety of applications would clearly assist Clean Cities coordinators and fleet managers understand the benefits of NGVs and could help them support wise purchase decisions by transit, private, and municipal fleets.

8.3 EXTENSION OF TAX CREDITS AND EVALUATION OF OTHER INCENTIVES

Near-term incentives that should be considered include extending the vehicle and infrastructure tax credit and fuel excise tax credit beyond their current expiration dates to 2011 or beyond to help manufacturers continue to sell natural gas products and provide additional cost savings and greater convenience to fleets with additional fueling stations. There does appear to be a potential problem with the scheduled end of current incentives in December 2010 (the fuel excise tax expired in 2009). It is unlikely that sound evaluation of model year 2010 trucks can be completed in time for Congress to develop appropriate new incentives for the following decade..

A gap in incentives in 2011 could create significant problems for engine and truck manufacturers if customers wait for new policy measures to be implemented.

Other policies should be analyzed further, including developing an incentive for fleets to trade-in old high-emitting diesel vehicles and replace them with NGVs. This could be similar to the recent Cash for Clunkers program, which allowed consumers to upgrade their old vehicles to more fuel-efficient models. Promoting the replacement of older single-unit diesel trucks with new CNG vehicles could provide rapid reductions in criteria pollutant emissions, which would improve local air quality and accelerate market penetration. Without such incentives, a slump in the sales of clean, new commercial trucks could continue well past 2010 as owners hold on to older, much "dirtier" diesels for an extended period.

The importation of automakers' larger light-duty NGVs, manufactured abroad but still meeting U.S. emission and safety standards, would help stimulate the intended niche market. While in the short term the vehicle-manufacturing jobs would be overseas, the expansion of natural gas output would be domestic, dealers would have product to sell, and the stage would be set for LDV manufacturers to expand domestic production of NGVs.

8.4 CLEAN CITIES

The Clean Cities network of nearly 90 cities, covering 73% of the population, is poised to help DOE implement a major deployment effort in intra-city trucks and off-road vehicles and renewed emphasis on transit. While the Clean Cities Program has focused on these niche markets in years past (with the exception of off-road), the program could develop new tools including materials that address the following:

- Supply of natural gas;
- Results from new testing of emissions and durability;
- Product offerings meeting 2010 emission standards;
- Fuel economy and performance;
- Safety concerns for fleets, including cylinder issues (i.e., inspections, labeling, end-of-use life) (and for small businesses and consumers, should single-vehicle overnight refueling equipment like the Phill be marketed once again);
- Guidance on maintenance facilities; and
- Payback period for the total investment by a fleet, including the initial vehicle cost and operating cost (fuel, maintenance, product longevity, insurance rates, and resale value).

While Clean Cities is more focused on on-road vehicles, off-road vehicles can potentially help build throughput to assist in making infrastructure economical. Evaluating the costs and benefits of off-road alternative fuel options should be a priority. In addition, technician training seems to be lacking in some areas of the country; therefore, an analysis could show where best to provide training and recommend ways to spur involvement of current training centers. Clean Cities could benefit from understanding the workforce potential of a strong NGV industry — this could provide an additional impetus for state and local policy makers.

Utilities that were once engaged in promoting NGVs must revitalize their efforts to deploy NGVs in their own fleets and promote these vehicles to fleets and other consumers in their communities. Again, with federal leadership and support, including Clean Cities, utilities could play an important role. Furthermore, interest is developing among independent producers to build the transportation market for NGVs. Clean Cities could work in tandem with independent producers to find new fleet customers and strengthen efforts.

In addition to utilities and independent producers, Clean Cities should work with key national fleets, a list that has already been developed. While not every organization will select natural gas as the fuel of choice, it is a good opportunity to present options to targeted fleets with significant intracity and intraregional vehicle operations, large warehouses using off-road equipment, and possibly shipping companies moving cargo containers within ports. Complementary to this effort, Clean Cities could develop a corporate imaging program, including awards to fleets making significant purchases that could be promoted to national media outlets.

Because there is good long-term potential, policies are needed now to foster market development. Funds are available through 2010 (Table 4) to reduce buyer's incremental costs for NGVs and infrastructure. However, these near-term incentives do not last nearly as long under current legislation as incentives for plug-in hybrids, which last until 2014 (AFDC 2010d). To ensure the future success of the market, two near-term strategies are suggested: (1) "quality assurance" via on-road demonstration to determine durability, with some tracking of emissions rate reliability (deterioration) of the CNG trucks as compared with their clean diesel (and gasoline) competition, supported by (2) extension of some incentives beyond 2010. Furthermore, a renewed emphasis by Clean Cities and key stakeholders must also occur to help place available natural gas trucks in the best segments of the market niche we have designated.

Ultimately, if the challenges and opportunities cited above are addressed, a significant long-term attainable penetration of 36% in natural gas in commercial truck transport and off-road vehicles could result in petroleum reduction for the entire nation of 1.6 million barrels of oil per day.

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