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Efficiency Improvement Opportunities for Light-Duty Natural-Gas-Fueled Vehicles

J. F. Thomas
R. H. Staunton

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Engineering Technology Division

EFFICIENCY IMPROVEMENT OPPORTUNITIES FOR LIGHT-DUTY NATURAL GAS-FUELED VEHICLES

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ACRONYMS

CFFP	Clean Fuel Fleet Program
CI	compression ignition
CNG	compressed natural gas
CR	compression ratio
DI	direct injection
ECU	electronic control unit
EGR	exhaust gas recirculation
EPA	Environmental Protection Agency
FTP	federal test procedures
GGE	gasoline gallon equivalent
HC	hydrocarbon
IC	internal combustion
IDI	indirect injection
ILEV	inherently low-emission vehicle
MON	motor octane number
MPG	miles per gallon
MPGE	miles per gallon equivalent
NA	naturally aspirated
NG	natural gas
NGV	natural gas vehicle
NMHC	nonmethane HC
OAAT	Office of Advanced Automotive Technology
OEM	original equipment manufacturer
OTT	Office of Transportation Technology
PCV	positive crankcase valve
PFI	port fuel injection
PING	pilot fuel injection natural gas
R&D	research and development
RON	research octane number
SCG	Southern California Gas
SI	spark ignition
SMPI	sequential multiport electronic fuel injection
SULEV	super ultra low-emission vehicle
TB	throttle body
TDC	top dead center
TWC	three-way catalyst
ULEV	ultra low-emission vehicle
VW	Volkswagen

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EXECUTIVE SUMMARY

PURPOSE

The purpose of this report is to evaluate and make recommendations concerning technologies that promise to improve the efficiency of compressed natural gas (CNG) light-duty vehicles. Technical targets for CNG automotive technology given in the March 1998 Office of Advanced Automotive Technologies research and development plan were used as guidance for this effort. The technical target that necessitates this current study is to validate technologies that enable CNG light vehicles to have at least 10% greater fuel economy (on a miles per gallon equivalent basis) than equivalent gasoline vehicles by 2006. Other targets important to natural gas (NG) automotive technology and this study are to: (1) increase CNG vehicle range to 380 miles, (2) reduce the incremental vehicle cost (CNG vs gasoline) to $1500, and (3) meet the California ultra low-emission vehicle (ULEV) and Federal Tier 2 emission standards expected to be in effect in 2004.

APPROACH

The approach taken in this study can be broken into several steps. First, the state-of-the-art technology for light-duty CNG and gasoline vehicles was reviewed. A second step was to look at what general technology advances could meet the CNG efficiency goal and be validated by 2006. This involved examining the advantages and disadvantages of CNG and characterizing the range of compression ignition (CI) and spark ignition (SI) lean-burn engine technologies currently in use (for heavy-duty applications) or the subject of R&D. An effort was then made to narrow the list of engine technologies to those most applicable to CNG light vehicles. The last step was to determine what enabling technologies could or should be pursued to improve chances for successful implementation, and what development work is likely needed to prove the technologies.

MAJOR EFFICIENCY DRIVERS

Efficiency improvement technology will by necessity focus entirely on CNG engine advances. Vehicle technologies that improve efficiency but are not related to the engine are almost always "fuel generic," and because they are not specific to CNG, they were not considered. An exception is the effort to lighten the weight of CNG on-board storage tanks, but there is little opportunity for any further gain. It is apparent that advanced engine technology is the key to significantly boosting the efficiency of CNG light-vehicles.

Examining why a diesel engine can be far more efficient when compared to a spark ignition (SI) gasoline engine helps to illustrate the major efficiency drivers for internal combustion engines. The diesel engine generally operates with a much higher compression ratio (CR), utilizes lean-fueling, and is controlled to operate at part-load by reduced fueling. In contrast, today's gasoline engine operates with a stoichiometric air and fuel mixture, has a lower CR, and uses throttling to operate at part-load. Throttling causes significant gas pumping losses. High CR, lean-fueling, and lack of throttling are the major efficiency advantages of a diesel engine, and they would play an important role in developing engine technology to improve efficiency.

CURRENT ENGINE TECHNOLOGY

Current CNG and gasoline engine technology for light-duty vehicles is limited in efficiency because of emission requirements. The engine control systems are configured to keep the engine operating near a stoichiometric air-fuel set point to maximize the three-way catalyst (TWC) effectiveness. This technology works extremely well for NG fueling from an emissions point of view, and current regulations, the future ULEV, and Tier 2 standards can be easily met.

For heavy-duty vehicle applications, lean-burn SI CNG engines are currently in use. This is possible because the heavy-duty emission regulations are less stringent when compared to light-duty regulations and can be met with current technology. Heavy-duty lean-burn CNG engines are also capable of meeting the regulations for heavy-duty engines intended to be in place by 2004, although further reduction of regulated emissions is the subject of ongoing R&D.

LEAN-BURN AND DESIRED EFFICIENCY GAINS

A relatively large boost in light-duty vehicle efficiency could be realized if a "leap" could be made to lean combustion technology. NG has an apparent advantage over gasoline because NG engines are expected to have a significantly better chance of meeting emission standards for lean-burn engine operation. To make this leap, the ULEV and Tier 2 standards would have to be met (for the FTP-75 test cycle), but this is entirely unproven. An essential step in boosting CNG light-duty vehicle efficiency significantly is proving that meeting these emission standards is possible.

For stoichiometric operation, an SI CNG engine could be more efficient than a comparable gasoline engine mainly because a higher practical CR can be realized for NG. Other factors for NG when compared to gasoline include a penalty for the added weight of CNG on-board storage and the ability to avoid fuel enrichment for cold-start and other conditions. An additional penalty due to volumetric efficiency considerations will be a significant factor unless in-cylinder fuel injection or engine turbocharging is employed. The overall fuel economy advantage for NG could optimistically be as much as 7% for engines utilizing direct fuel injection or turbocharging, but cannot be expected to reach the goal of being 10% more efficient than gasoline. For CNG vehicles to reach the efficiency goal, the CNG engine technology must make the leap to lean-burn. For vehicles using CNG lean-burn engines, the fuel economy advantage compared with a gasoline engine with stoichiometric fueling is estimated to be 16–23% for SI engines and 24–37% for CI engines, far more than the 10% goal.

TECHNOLOGIES LESS APPLICABLE TO LIGHT-DUTY VEHICLES

To narrow the choices, applicable vehicles engine technologies were analyzed to find those that run counter to the OAAT goals and are least suitable for light-duty applications. The stoichiometric NG engine is recommended to be eliminated because it cannot reach the efficiency goal. It was estimated that NG CI engine technology would cost an additional $2000 to power a six-passenger car when compared to a gasoline engine and cost at least $1500 more than NG SI engine technology. The large cost for CI engine technology runs counter to the OAAT cost goal, and it is recommended that this technology be dropped from consideration. Use of high-pressure late-cycle NG injection to achieve air/fuel charge stratification could be attractive from an efficiency standpoint and possibly an emission standpoint. However, direct injection fueling technology that requires the CNG tank pressure to stay at a relatively high pressure (such as 500–600 psi) to operate, will significantly lessen vehicle range. It is recommended that only those stratified charge schemes that can utilize a low-pressure gas supply (150 psi or below) be considered further.

RECOMMENDED MAJOR R&D TOPICS

The R&D topics that are most likely to appropriately address the OAAT goals are described below. Included are development topics and enabling technologies for lean-burn SI engines. Note that lean-burn NG engine technology must be enabled to meet applicable emission standards to have any impact, regardless of efficiency gains and other performance factors.

1. A database of lean-burn, NG SI engine emissions needs to be established for light-duty application. Included should be emissions data for a broad range of meaningful engine conditions and FTP-75 cycle testing. Understanding the potential capabilities of lean-burn NG engines relative to the California Air Resources Board ULEV and Federal Tier 2 emission standards is important and could guide further R&D. A variety of engine design issues could be explored including valve placement and timing, turbulence and mixing, CR, fuel injection timing, spark timing, and exhaust gas recirculation (EGR) control.

2. Advancements in lean-burn catalyst systems optimized for NG engines should be pursued. Such advancements would be an important enabling technology for meeting environmental regulations.
3. Advanced controls that address the special needs of lean-burn NG engines are going to be required to meet emission standards. Humidity in the intake air can significantly affect operation of lean-burn NG engines. A humidity sensor integrated into the control system appears necessary, along with excellent control over air and fuel flows, a highly sensitive wide-range oxygen sensor, and excellent EGR control.
4. Switching an engine between stoichiometric operation and lean-burn at the appropriate conditions is a potential method of meeting emission standards while retaining some advantages of a lean-burn engine. At conditions that generate substantial NO_X it may be desirable to use stoichiometric fueling to enable the TWC system to work effectively. At lighter loads when lower NO_X production is expected, the engine can switch to a lean-burn operating mode to limit throttling losses. Efforts to develop the necessary control system and test this concept are recommended.
5. Charge stratification is desirable to extend the effective lean-limit of engine operation, which can both improve efficiency and lower NO_X generation. Because requiring a source of high-pressure gas will diminish vehicle range, methods of achieving charge stratification using a lower pressure gas supply (<150 psi) are recommended. Axial stratification is achievable with gasoline using port fuel injection (PFI) techniques and special engine design features. Application of such techniques for gaseous fueling should be examined. Use of low-pressure gas (early injection) to achieve intake charge stratification for direct injection (DI) and indirect injection (IDI) systems may be possible and should be explored. The possibility of developing a unit-injection type system for NG, in which plunger action is used to significantly boost the gas pressure, should be examine. If viable, it would allow development of late-cycle injection charge stratification techniques.
6. In currently available lean-burn, heavy-duty, NG engines, high spark energies are needed for reliable ignition, which causes the ignition system to be a relatively high maintenance system. Ignition quality problems are issues for all fuels as engine operation approaches the practical lean-combustion limit and more robust ignition is seen as a method of extending the lean-limit. The major benefit of pushing engine operation farther into the lean regime (or to allow greater amounts of EGR) is suppression of NO_X, which improves the likelihood of lean-burn technology meeting emission standards. A secondary benefit is greater efficiency gains.

   Novel concepts in the area of spark ignition or optimization of more conventional systems that would improve ignition quality and lower maintenance requirements should be evaluated. Goals should include longer component life, more reliable ignition near lean-limit conditions, extension of the lean-limit, and more rapid flame kernel development (can improve heat release rate). Two specific suggestions include (1) a fuel pretreatment system that uses an arcing system to crack the fuel, producing some hydrogen; and (2) a special SI system that features a moving series of short-duration arcs that sweep over a relatively large area due to the presence of a magnetic field.

EFFICIENCY IMPROVEMENT OPPORTUNITIES FOR LIGHT-DUTY NATURAL-GAS-FUELED VEHICLES

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1. INTRODUCTION

The Office of Advanced Automotive Technologies (OAAT) is a part of the Office of Transportation Technologies (OTT) within the U. S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy. A major part of the DOE mission is to develop a secure and reliable energy system that allows economic growth while protecting the environment, from which follows DOE's goal of significantly reducing the nation's dependence on imported petroleum. The OTT is addressing dependence on petroleum by developing and promoting the commercialization of advanced transportation vehicles that use less petroleum and/or cleaner, domestically sourced, nonpetroleum fuels, as well as developing and promoting alternative fuels technologies. In turn, the OAAT is responsible for the research, development, and validation of energy-efficient light-duty vehicle technologies that could significantly reduce the nation's dependence on petroleum.

The OAAT has prepared an overall research and development (R&D) plan[1] (issued March 1998) that includes technical targets for the time frame extending through 2006. This plan covers a very broad range of applicable technologies, including several alternative fuels, one of which is compressed natural gas (CNG) technology. The attractiveness of utilizing natural gas (NG) as a light-vehicle transportation fuel to meet national goals is quite apparent. About 70% of all petroleum consumption in the United States is attributed to the transportation sector, with consumption for light vehicles being 42% of all U.S. petroleum use. Use of NG (a plentiful domestic resource) for light-vehicle fuel could have a significant impact on our dependence on imported fuel. Such displacement of gasoline with the use of NG would also reduce the emission of greenhouse gases and would likely improve air quality.

Three major barriers to CNG-fueled light vehicles are high initial cost (mostly because of the expensive fuel storage system), the lack of a refueling infrastructure, and limited vehicle range. The goals of OAAT CNG R&D are to enable CNG vehicles to become comparable to gasoline vehicles in cost, range, refueling convenience, safety, and increased consumer acceptance levels. Therefore, the R&D program must address these barriers. Improvements in CNG engine and vehicle efficiency would address (at least incrementally) the vehicle range barrier and would lower fuel consumption costs. Stated OAAT technical targets include the development and validation of technologies that (1) increase CNG vehicle range to 380 miles,* (2) improve fuel economy to 10% better than equivalent gasoline-fueled vehicles on a miles-per-gallon equivalent (MPGE) basis, (3) reduce the incremental vehicle cost (CNG vs gasoline) to $1500, and (4) meet the ultra low-emission vehicle (ULEV) and inherently low-emission vehicle (ILEV) standards.[1]

1.1 PURPOSE AND OBJECTIVES

The purpose of this report is to examine and evaluate the potential of technologies that hold promise to improve the efficiency of CNG light vehicles. Natural gas vehicle (NGV) efficiency depends mainly on engine-related technologies and, to a lesser extent, vehicle weight issues. For example, low rolling resistance tires are generic to automotive technology and therefore would not be considered, but technology for direct injection of gaseous fuels would certainly be appropriate. This study is also restricted to light highway vehicles, those road vehicles under 10,000-lb gross vehicle weight (GVW). However, engine technology being developed for medium- and heavy-duty vehicles (also known as class 3-8 trucks) may very well prove to be applicable to smaller vehicles, and such technology is reviewed here.

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*Table of conversion factors for SI units is provided after the references.

The efficiency goals of OAAT are to develop and validate technologies that enable CNG light vehicles to be more efficient than equivalent gasoline vehicles according to the following schedule: 5% more efficient by 2000, 8% more efficient by 2004, and 10% more efficient by 2006. In addition, all applicable emission and safety requirements must be met.[1] The objectives of this report are to (1) clarify the efficiency issues for CNG technology and compare them to gasoline technology, (2) identify and evaluate the various technologies that would allow the efficiency goals to be met, and (3) provide direction for a future R&D path to achieve the goal of maximizing the competitiveness of CNG automotive technology.

1.2 ADDRESSING THE COMPLEXITY OF EFFICIENCY ISSUES

Automotive internal combustion (IC) engines are complex devices that must operate under a broad range of conditions (speed, load, and temperature) and are designed and controlled to meet a number of competing goals, involving power and torque output emissions, fuel economy, maintenance, drivability, cost, etc. Furthermore, there are many engine designs and technical options to consider. The fuels themselves have a certain amount of variability in properties. This high level of complexity can cause difficulties when addressing the issues of fuel and vehicle efficiency. A reader following these discussions may require a certain amount of knowledge concerning IC engines and may need to refer to other portions of this report, to the citations, or to a reference on piston engine fundamentals.

The authors have attempted to keep issues as simple and clear as possible, focusing on the major efficiency drivers and engine design issues. This report consists largely of a direct comparison between CNG and gasoline engine technology, but it was found useful to also examine diesel engine technology. Although this study is about overall vehicle efficiency as opposed to only engine efficiency, the vehicle technology for gasoline and CNG is very similar. The only significant difference that affects efficiency is the vehicle weight. By necessity, this report must "venture out" to make some predictions concerning future engine and vehicle developments. These predictions depend heavily on comparisons to today's engine technology, including diesel engines, and in most cases explanations are provided of how efficiency estimates were derived.

This report will only deal with absolute vehicle efficiency in terms of miles per gallon (MPG) of gasoline and MPGE. Unless stated otherwise, MPG and MPGE values are those expected for the current Federal Test Procedure (FTP) cycle (sometimes referred to as the FTP-75 cycle). Often relative efficiency will be discussed; it refers to the efficiency of a vehicle/engine combination compared to a base case vehicle/engine. A 10% efficiency gain would imply that the FTP MPG or MPGE result would be 10% better than the base case in the comparison.

1.3 ORGANIZATION OF THE REPORT

The remainder of the report is structured to first familiarize the reader with the most important issues and background, then examine the potentially important CNG technologies and options, and finally to narrow the CNG technology options to those most applicable to light-duty vehicles in the 2006 time frame. The major efficiency issues for spark ignition (SI) and compression ignition (CI) engines are discussed in Chap. 2. In Chap. 3, important fuel properties for NG and gasoline are compared, and some consideration is given to diesel fuel and CI issues. Current NG transportation engine technology is discussed in Chap. 4, including light- and heavy-duty applications. The future of CNG engine and vehicle technology advances and efficiency and a comparison to current and future gasoline technology are explored in Chap. 5. Judgments concerning development paths are presented along with economic comparisons. Based on Chap. 5 results, the most promising engine technologies are recommended in Chap. 6.

2. OVERVIEW OF MAJOR ENGINE EFFICIENCY ISSUES

This section provides an overview of the most fundamental and important parameters that determine IC engine efficiency: compression ratio, stoichiometry, and throttling (power output control). An initial comparison between a diesel engine and a gasoline engine is presented to both introduce these topics and explain certain engine fundamentals that will be helpful in later discussions.

2.1 COMPARISON OF A DIESEL ENGINE TO A GASOLINE ENGINE

A brief comparison of the major differences between a current road-vehicle diesel engine and a gasoline engine is presented here to highlight the major efficiency issues that are relevant to boosting engine efficiency. The diesel engine is generally capable of being far more efficient than comparable gasoline engines as illustrated by Table 1, which compares the gasoline and diesel engine versions of the 1998 Volkswagen (VW) Jetta. The fuel economy values given are in MPG of gasoline for the gasoline vehicle and in MPG of diesel fuel for the diesel-fueled vehicle. Because diesel fuel contains about 12% more energy per gallon than gasoline, the diesel car is estimated to achieve about 47% better fuel economy than the gasoline version for the FTP-75 cycle.[2] Also note that this efficiency gain for the diesel Jetta comes at an increased vehicle price on the order of $1100–$1200 (Volkswagen of America, Inc., suggested retail price).[3]

Table 1. Fuel efficiency comparison of gasoline and diesel versions of the 1998 VW Jetta with five-speed standard transmission

	Adjusted fuel economy estimate (MPG)		
	City	Highway	Combined
1.9-L turbodiesel engine	40	49	43
2.0-L gasoline engine	24	31	26

Source: EPA, *1998 Fuel Economy Guide.*[2]

The two engines in this comparison do not behave identically, although both versions of the Jetta have adequate performance, and a comparison has some validity. The gasoline engine can produce greater peak power, while the diesel engine can generate higher peak torque. Better environmental performance is seen for the gasoline engine.

The most important reason for this comparison is to examine why the diesel engine can be so much more efficient than the gasoline engine. The major reasons for this stem from the very different ways that the engines operate and are controlled. The main efficiency drivers involve engine compression ratio (CR), stoichiometry, and throttling or power and torque control. These topics are addressed in the following sections.

2.2 CR AND ENGINE KNOCK

The CR of an engine is simply the ratio of the maximum cylinder volume to the minimum cylinder volume as the piston moves through its range. SI engines behave similarly (in a thermodynamic sense) to what is known as the ideal Otto cycle. The efficiency of the Otto cycle (for ideal gas) may be represented by the equation $\eta_c = 1 - (1/r_c)^{(\gamma-1)}$, where r_c equals the CR, and γ is the specific heat ratio for the gas.[4] Because γ is a number greater than 1 (a value near 1.3 is representative for engine conditions), as the CR increases, the fuel (or energy) conversion efficiency of the engine also increases. With limitations, this equation can be used both for trends and to approximate expected efficiency changes for changes in CR.

For large changes in CR, basic engine designs would actually be changed to reoptimize for high efficiency and other considerations. Efficiency gained by increasing CR with only minimal design alterations would be partly offset by higher frictional losses and degraded combustion efficiency.[4] Furthermore, as the CR increases, engine components must be strengthened to withstand the higher pressures and temperatures that will be generated. Limitations in CR may be due to consideration of engine weight (generally increases with CR), cost, life, maintenance, material limitations, and combustion problems (such as knock). Nevertheless, CR increases represent an important technical option for obtaining improvements in NG vehicle efficiency.

The CR of gasoline engines is limited mainly by engine knock, which becomes pronounced at increased CR. Fuel is normally sprayed into the intake air stream where it partially vaporizes and partially remains in droplet form. The fuel and air mixture is pulled into the cylinder by the piston motion. Gasoline engines initiate combustion by using an SI system. A desirable combustion event occurs when the small flame kernel formed by the spark event expands in a relatively "smooth" process, oxidizing virtually all the available fuel over a short but definite period of time. In-cylinder, high-speed photography shows an expanding flame front that progresses through the combustion zone and depletes the unburned fuel and air mixture. Engine knock occurs when a significant amount of the combustion process progresses very rapidly and causes an extremely fast and premature pressure rise. Instead of combustion progressing by an expanding flame front, the combustion occurs in an essentially instantaneous fashion throughout a volume of unburned fuel and air.

Severe knocking conditions can cause engine damage and poor performance. Knocking phenomena correlate with the unburned fuel and air mixture being at relatively high temperature and pressure, and so knocking is a direct function of CR. Light-vehicle gasoline engine CRs are typically limited to the range of 8:1 to 10:1 due to knock limits.

Diesel engines operate on the principle of CI and utilize significantly higher CRs than SI engines. In the diesel compression stroke, air alone is compressed and then, as the piston comes very close to or reaches top dead center (TDC), fuel is injected directly into the cylinder. Because of the properties of diesel fuel and the relatively high pressure and temperature of the air, the fuel ignites at the air-fuel interface almost immediately. The fuel is injected over a short but controlled length of time to control the pressure rise during the power stroke. Because the fuel injection process controls the rate and timing of combustion, diesel engines are not limited by the knocking phenomena found in SI gasoline engines. Transportation diesel engines often have CRs in the range of 15:1 to 22:1.

The normally high CRs of CI engines are an important reason that diesel engines are generally more efficient than SI gasoline engines. Although thermodynamic behavior of diesel engines probably deviates somewhat more from the ideal Otto cycle model discussed previously, the form of the dependence of efficiency on CR still holds (an ideal diesel cycle formulation is more complex than that for the Otto cycle). For the Table 1 comparison of VW models, the gasoline engine has a CR of 10:1 compared with 19.5:1 for the turbocharged diesel. There are additional reasons for the large efficiency advantage of the diesel engine.

2.3 STOICHIOMETRY

In the United States, virtually all automotive gasoline (and NG) engines are controlled to operate very near a stoichiometric air-fuel ratio under nearly all conditions to allow the three-way catalyst (TWC) system to operate well. The TWC system is meant to oxidize exhaust stream CO and unburned hydrocarbons and also to remove NO_X by reduction reactions. These competing reactions can only be carried out effectively and simultaneously for near-stoichiometric conditions. The catalyst efficiency in reducing NO_X drops sharply under lean-fuel conditions. At this time, engine control to maintain stoichiometric operation is quite effective for meeting emission regulations, although it is hoped that lean-burn gasoline combustion systems will be developed that can meet these same emission regulations.

In contrast to the gasoline engine, diesel engines are controlled to operate on lean fuel at all times. At least 40% excess air is used under the least lean-fuel operation, mainly to prevent excessive soot formation. A diesel engine alters the amount of fuel injected into the cylinder to control the power and torque output of the engine. Air intake into the engine is relatively unrestricted at part-load operation in contrast to the gasoline engine, which employs intake air throttling to restrict engine power output. As described in the next section, intake throttling reduces engine efficiency, and this is another major reason why SI engines are less efficient than diesel engines.

Another efficiency advantage for lean-fueled engines is realized because the combustion-gas specific heat ratio increases with lean fueling, which causes a favorable enough thermodynamic effect (see Sect. 2.2) to give a significant efficiency increase. Diesel engines can operate at very lean conditions for light loads because even very small amounts of fuel can be injected into the cylinder (or prechamber) and burned nearly to completion. The combustion is controlled by the injection process and occurs as a diffusion flame; therefore, is not subject to a lean limit.

Although virtually all current automotive gasoline engines operate at stoichiometric conditions, it is hoped that lean-burn gasoline or alternative-fueled SI engines will be developed that can meet regulations and be competitive. It is known that for SI gasoline and NG engines, the lean fueling lowers the flame speed; especially for high engine speeds, it causes the combustion to occur over a very broad range of crank angle (piston position). This effect lowers engine efficiency somewhat, but the overall effect is increased efficiency with increasingly lean conditions.[5] A limit is reached for SI engines due to combustion instabilities and misfire, which occurs well before the ideal lean flammability limit.

2.4 THROTTLING OR POWER CONTROL

In the SI gasoline engine, the speed and power are regulated by throttling (restricting) the air flow through the intake ducting system of the engine. At full power (wide-open throttle) the air flow is relatively unrestricted, and the cylinders fill with air and fuel at close to atmospheric conditions. At part-load, the restricted air flow causes the intake stream to be at pressures significantly below atmospheric pressure. Engine power output is controlled by this rarefaction of the stoichiometric air-fuel mixture, which limits the mass of intake charge to the cylinders. This creates undesirable pumping losses; however, the goal of maintaining a constant, stoichiometric air-fuel ratio (required for the TWC system) while controlling engine output is achieved. The pumping work that must be carried out by the engine at part-load significantly lowers engine efficiency.

In the CI engine, there is little or no throttling of the intake air flow; instead, power and torque are regulated mainly by the amount of fuel injected into the cylinders. Controlling power by limiting the fuel is effective in diesels because the diesel fuel (injected into the cylinder as a liquid) will burn under diffusion conditions without regard to the overall (cylinder averaged) stoichiometric conditions. Thus, when only a small amount of diesel fuel is injected into the compressed air contained in the cylinder, as in the case of an idling engine, ignition and combustion progress in a stable and effective manner.

2.5 COMPARISON SUMMARY

It is clear from this brief comparison of the diesel vs gasoline engines that the SI gasoline engine could have significantly improved efficiency if it were possible to (1) increase the CR, (2) reduce the use of intake air-stream throttling as the means for controlling power and torque at partial loads, and (3) employ a lean fueling scheme. Lean fueling is seen as a very attractive way to at least partially reduce the need for throttling in SI engines. This comparison generally holds true for alternatively fueled CI and SI engines.

The intent of this comparison has been to clearly illustrate some very basic efficiency issues for SI and CI engines. Other efficiency issues are discussed later. Much of the balance of the report will concentrate on issues specific to NG-fueled (IC) engines.

3. COMPARISON OF FUEL PROPERTY CHARACTERISTICS OF NG AND GASOLINE

The differences in basic fuel properties between gasoline and NG are defining issues for the barriers to commercialization and the needed R&D for CNG vehicles. These fuel property differences are also pertinent to CNG engine and vehicle efficiency issues. In Table 2, the important differences between NG and gasoline (and in one case, diesel fuel) are summarized.

3.1 OVERVIEW OF FUEL PROPERTIES

The NG that is available in the United States generally has good combustion properties for SI engines, including those originally designed for gasoline-only or gasoline and NG use. Because NG has excellent antiknock properties (high octane index), dedicated NG (only designed for NG fuel), light-vehicle, SI engines could potentially be designed with CRs near 13:1. This gives NG a potential efficiency advantage over gasoline engines.

NG is seen as an environmentally friendly fuel. Because NG is composed largely of methane, NG engines emit less unburned hydrocarbons (HCs) that are regulated and known to degrade air quality. Methane is relatively inert in the atmosphere, and its emission from vehicle exhaust is currently not regulated. NG is also seen as more "tolerant" of high levels of exhaust gas recirculation (EGR) and lean conditions for SI engine applications. Strategies to reduce formation of NO_x emitted from an engine include the use of lean combustion and the use of significant EGR, and NG appears to have an advantage over gasoline in such applications.

The fact that NG is a gaseous fuel has drawbacks. Storage of CNG requires a relatively large pressure vessel system that adds cost and weight to a vehicle. Furthermore, fueling with NG can cause typical naturally aspirated (NA) SI engine technology to have a significantly lower power density due to lower volumetric efficiency (described in Sect. 3.3). Utilization of a higher displacement (and heavier) engine or adding turbocharging or other performance-enhancing technology is generally required to equal or exceed gasoline engine performance.

A comparison of selected properties of NG and gasoline is given in Table 2. The significance of these properties is discussed in the sections that follow.

Table 2. Properties of NG and gasoline

Property	Gasoline	NG
Octane number, 0.5[a] (RON + MON)[6,7,8]	85–94	120–140 (MON)[a]
Vaporization cooling	High	Not applicable
Volumetric efficiency effect [for NA engine with port fuel injection (PFI) or carburetor]	Standard	~10% Power loss compared to gasoline
Lean flammability limit equivalence ratio[8]	0.66	0.52
Lean misfire limits	Standard	More fuel lean
Cetane number	For diesel fuel 42–50	Undefined
Autoignition temperature at 1 atm (°C)	650	500
Ignition energy	Standard	Greater
Approximate energy density[9] [Btu/gal (MJ/L)]	114,000 (32.0)	36,000 (10.2) @ 3,600 psi

[a] Can be lower for NG that has been altered by air and propane injection in times of high demand.

3.2 ANTIKNOCK INDEX OR OCTANE RATING

Octane numbers were developed as a measure of the antiknock qualities of gasoline and other fuels used in SI engines. In general, higher octane numbers will allow the fuel to be operated under relatively high CR conditions. Standardized tests have been developed to determine octane ratings, the most common of which are the research octane number (RON) and the motor octane number (MON). It has been found that the RON correlates best with antiknock quality under low-speed relatively "mild" driving conditions, and MON correlates better with high-speed, high-severity conditions.[6] In the United States the octane rating (or antiknock index) is generally reported on gasoline pumps by the formula:

$$\text{antiknock index} = 1/2\,(\text{RON} + \text{MON}) .$$

Typical gasoline grades range in antiknock index from 87 to 93 compared with values of 120–137 for NG.[6–8] NG composition is quite variable, but MON is generally above 120.[7] An exception would be when the gas provider practices what is known as peak shaving: when pipeline NG demand exceeds supply, air and propane are injected into the NG supply to meet demand. The resulting composition is changed, and the octane number drops somewhat. The California Air Resources Board (CARB) has established composition limits that essentially guarantee a high antiknock index for NG used as a motor fuel, but no such national standards are in place.

The substantial advantage that NG has in antiknock quality in comparison with gasoline fuels is related to the higher autoignition temperature for NG (see Table 2). Because of such excellent antiknock properties, dedicated SI NG engines (designed only for NG fuel) could potentially be designed with CRs as high as 15:1, although 13:1 appears to be a likely practical limit for automotive applications.[6,10,11] This compares with maximum CRs of about 10:1 for current gasoline engines.

3.3 VOLUMETRIC EFFICIENCY

Volumetric efficiency is used to describe the effectiveness of an engine's intake induction process in a four-stroke engine. It is equal to the volume flow rate of air into the intake system divided by the rate of volume displacement in the combustion chamber. Although there are many factors that influence volumetric efficiency (e.g., temperature, CR, engine speed, and manifold design), whether the fuel is gaseous or liquid is an especially important factor. This discussion is limited to NA engines employing carburetors, throttle body, or PFI.

When a liquid fuel (such as gasoline or alcohol-based fuel) is injected into an engine intake manifold, the fuel mixes with the air, and the mixture is cooled by a portion of the liquid undergoing vaporization. Fuel and air are then inducted into the cylinder with the fuel both in vapor form and as small droplets of various sizes. Both the vaporization cooling and the fact that the droplets occupy negligible volume allow a larger mass of fuel and air to enter the cylinder (relative to gaseous fuel), contributing to increased power output from each combustion cycle. In contrast, NG enters the cylinder entirely as a gas, and the only volumetric benefit will be a small amount of gas expansion cooling. In comparison to liquid fuels, a lesser amount of fuel and air can be inducted into the cylinder during the stroke. As a result, a gasoline-fuel-designed engine converted to NG will be capable of significantly less peak power. Overall, the peak power capability of the engine is about 10% lower than the same engine fueled by gasoline.[6] For similar engine designs, this means that a somewhat larger (and heavier) engine displacement is needed (about 10% for an NA gasoline-designed engine), or supercharging or turbocharging must be employed to give the same power output compared to gasoline fueling.

Certain engine technologies are capable of negating some or all of this undesirable volumetric efficiency effect. These include utilizing NG injection inertial effects, variable valve timing, engine turbocharging, and direct injection (DI) of the fuel into the cylinder (after the intake valve is closed). Later discussions will address these technologies.

3.4 LEAN COMBUSTION LIMIT

NG holds some promise as a fuel that will perform well under lean-fuel conditions. As seen in Table 2, the lean flammability limit extends farther for NG than for gasoline. This extended lean limit is a major reason NG is viewed as having greater potential than petroleum-based fuels for meeting current and future emission regulations when utilized in lean-burn IC engines (a second major reason is favorable fuel chemistry).

Operating an engine at increasingly lean conditions provides certain advantages, the major one being increased engine efficiency. Today's SI gasoline engines and automotive SI NG engines are controlled to operate near a stoichiometric air-fuel ratio under most conditions to allow the TWC system to be highly effective (see Sect. 2.3). Control of torque and power output is achieved mainly by throttling, which is simply limiting air and fuel flow by partially blocking the engine intake path. Throttling increases the air "pumping" power consumed by the engine at part-load conditions and, in this way, lowers the engine efficiency. Throttling can potentially be replaced by using lean fueling to control engine power output (see Sect. 2.4).

There is a limit to how lean an NG fuel mixture can be (i.e., flammability limit) before the level of incomplete combustion or misfire begins to rise significantly. As the air-fuel mixture becomes increasingly lean, the combustion speed becomes lower and leads to instabilities in the engine. At some point increasingly lean conditions will cause the cycle-to-cycle mean effective pressure variation to become unacceptably high, misfiring will begin, and the hydrocarbon levels in the exhaust stream become excessive. Acceptable combustion apparently extends to leaner conditions for NG than for gasoline. Therefore, it appears to be less technically challenging to develop a lean-burn NG engine with satisfactory performance. In fact, a number of NG engines used in vehicles or tested in laboratories rely on lean-fueling to boost fuel efficiency.[6,11–19] Most lean combustion NG engine work has been associated with heavy-duty applications.

3.5 HEAT RELEASE RATE FOR LEAN CONDITIONS

The limit to lean fueling also depends on issues other than misfiring. From an idealized thermodynamic view, both SI and CI engine efficiency would be maximized if all the fuel's energy were released when the piston reached TDC. From a practical point of view, such instantaneous combustion is impossible and would be undesirable because such a sharp pressure rise would damage engines. It would be nearly optimal if the heat were released over a 15° to 20° (crank rotation) interval, but for actual fast-burn engines combustion occurs over at least 25° and may take place over 60° or more under certain conditions.[5] Lean fueling and high levels of EGR slow the combustion process, and engines must be designed to maximize flame propagation rate (through increased turbulence, higher CR, etc.), if high efficiency is desired.

Because combustion takes place over such an interval, it is also important to choose spark timing to maximize performance. The desired spark timing will vary considerably with engine conditions such as speed and load. The spark starts the combustion sometime before the piston reaches TDC so that the combustion is well under way when TDC is reached. Generally, spark timing is selected corresponding to maximum efficiency or power at any given engine condition, with consideration given to knock prevention and emission production. Spark timing is adjusted to eliminate knocking whenever necessary.

3.6 STORED FUEL ENERGY DENSITY

The low stored fuel energy density of NG is problematic in terms of fuel system cost and vehicle efficiency. Because NG is composed mainly of methane, which is a nonpolar molecule, it will only liquefy at essentially cryogenic conditions (e.g., 230 psi and –170°F). Ambient temperature storage for vehicle use must be in high-pressure fuel tanks. Currently, the most common storage pressure for CNG vehicles is 3000 psi, although a new 3600-psi standard is also in use. Even at 3600 psi, the nominal stored energy density of CNG is only about 32% that of gasoline. The CNG storage system takes up considerably more space and is heavier than the equivalent storage for gasoline, and vehicle range must be compromised to avoid very large fuel storage tanks. The increased vehicle weight reduces vehicle energy efficiency, but the biggest drawback is that the current practical CNG storage tanks can add several thousand dollars to the cost of a light-duty vehicle.

The CNG vehicle efficiency penalty due to a heavier NG storage system can be roughly quantified. The overall weight (fuel and tank) for gasoline storage is about 7.8 lb/gal, which compares to about 15 lb/gasoline gallon equivalent (GGE) for all composite type IV tanks (fully composite wrapped with a thermoplastic liner) containing CNG at 3000 psi. For a 15-GGE tank this means that a CNG vehicle will weigh at least 108 lb more than the gasoline equivalent. As a "rule of thumb," an increase in vehicle weight of 10% will cause a drop in fuel economy of about 6%. For a 3000-lb vehicle, an increase in weight of 108 lb translates into about a 2.2% drop in fuel economy. Other types of tanks, such as wrapped aluminum, wrapped steel, and all steel are estimated to weigh 24, 33, and 43 lb/GGE, respectively, which means that the efficiency penalty would be considerably greater (4.9%, 7.6%, and 10.6%, respectively) than for the all-composite-type tank in the example cited.[6]

3.7 AUTOIGNITION TEMPERATURE AND CETANE INDEX

Among the properties listed in Table 2 are cetane number and autoignition temperature. The cetane number for NG is considered undefined or a negative value, and NG has a fairly high autoignition temperature. The point is that NG will not behave like a diesel fuel, because NG is very resistant to CI. Work to date has shown that NG is very difficult to reliably ignite by CI, and although use of an extremely hot glow plug (e.g., 1200–1400 K)[20,21] is possible, this is not viewed as a practical solution. NG has been tested in CI engines using what is known as pilot injection of diesel fuel, although alternative high-cetane number fuels could be utilized as a combustion initiator. Combustion of the small amount of injected diesel fuel (or other fuel) acts as the ignition source for the NG.

4. CURRENT CNG TRANSPORTATION ENGINE TECHNOLOGY

The currently available CNG transportation engines are exclusively SI engines that can be placed into two major categories. For light-duty vehicles, the engines are SI, NA, and stoichiometric, using TWC systems. The engines tend to be modifications of engines designed for gasoline. The heavy-duty engines tend to be SI, turbocharged, homogeneous-charged, and lean-burn engines that do not employ EGR and may have an exhaust catalyst on the vehicle. Engine design is based on diesel engines but with lowered CR.

The results of several studies of light-duty fleet vehicles that included efficiency comparisons between CNG and gasoline versions of the same vehicle are presented in Sect. 4.1. Also included is a summary of an innovative conversion of a small turbocharged car in which achieving high-energy efficiency was the major goal. This latter study involves a research vehicle rather than a fleet vehicle, so any comparisons should be made with caution.

In Sect. 4.2, selected SI heavy-duty engine studies are discussed, both for fleet vehicles and R&D efforts. Selected innovative vehicle conversion investigations featuring NG CI are presented in Sect. 4.3.

Descriptions of technical changes will focus on the engine and exhaust system. Because the details of the fueling storage and pressure regulation/filter systems do not directly affect fuel efficiency, these modifications, although extensive and important, will not be described.

4.1 SELECTED RECENT CNG LIGHT-VEHICLE CONVERSIONS

Table 3 summarizes a selection of various vehicles that were converted to CNG and tested for efficiency during the 1990s. Generally, efficiencies are similar to gasoline versions of the same vehicle or are somewhat reduced. More detailed descriptions follow.

Table 3. Vehicles converted to CNG and tested

Vehicle	Displacement (L)	Gasoline CR	NG CR	Estimated NG efficiency vs gasoline (%)
Chevrolet van[22]	4.3, 5.7	8.6:1	8.6:1	–13
Dodge van[22]	5.2	9.08:1	9.08:1	–3.5
Ford van[22]	4.9	8.8:1	11:1	+4.5
Ford Crown Victoria[23]	4.6	9.0:1	10:1	0
Ford F-250, E-350[24]	5.4	9.0:1	9.0:1	–11
Honda Civic GX[10]	1.6	9.4:1	12.5:1	–6
Turbo Sprint, stoichiometric[11]	1.0	8.5:1	12.4:1	+7[a]
Turbo Sprint, lean burn[11]	1.0	8.5:1	12.4:1	+17[b]

[a] The turbocharged, stoichiometric, NG Chevrolet (Suzuki) Sprint is compared with the NA, stoichiometric, gasoline-powered Sprint. Much greater efficiency gain is seen if the comparison vehicle is the turbocharged, gasoline-powered Chevrolet Sprint.

[b] Turbocharged, lean-burn, NG operation compared with the NA, stoichiometric, gasoline-powered Chevrolet Sprint.

4.1.1 Clean Fleet Project

Chevrolet, Dodge, and Ford vans were operated by Federal Express (FedEx) in California in the early 1990s as part of a fleet testing program sponsored by the South Coast Alternative Fuels Demonstration Project (also known as the Clean Fleet Project).[22] The driver and route FedEx assignments were periodically rotated for the vans, and each van was used for three to five routes during the 2-year demonstration. Data collected during the project include fuel properties (heating value and density), mileage, route information, and fuel consumption. Pipeline-quality NG was supplied by Southern California Gas, who performed periodic dispenser calibration checks by weighing a test cylinder before and after fueling the vans.

The conversions to CNG were based on technology that was available in 1992 and differ by manufacturer as do engine type, size, etc., for each of the three models. Thus, the significant comparison is fuel usage within each group of manufacturer's models. The fuel consumption of the CNG and gasoline control group vans are compared using miles driven/GGE. A GGE is normally defined as an amount of fuel containing 115,000 Btu based on lower heating value (water is in the gas phase in the combustion products).

4.1.1.1 Chevrolet vans

The Chevrolet vans used converted 5.7-L gasoline engines for the CNG vehicles, in contrast to the control (gasoline-fueled) vans that were equipped with 4.3-L engines. Both engines have a CR of 8.6:1. The 5460-lb vans used a sequential multiport electronic fuel injection (SMPI) delivery system. The adjusted fuel economy based on a typical duty of 40 miles/d is 7.8 miles/GGE as compared to 9.0 for the control group for a statistically significant efficiency loss of 13.0%. The statistical error for fuel economy comparisons was reported to be less than ±5.8% at the 95% confidence interval. The use of significantly higher displacement engines for CNG use accounts for a portion of the efficiency difference in this comparison. Use of higher CR for CNG could improve fuel economy significantly.

4.1.1.2 Dodge vans

The 5120-lb Dodge vans used a throttle body (TB) fuel delivery system. The adjusted fuel economy based on a typical duty of 40 miles/d is 8.2 miles/GGE as compared to 8.5 for the control group for an efficiency loss of 3.5%. The efficiency loss is not statistically significant for a 95% confidence level criterion (the statistical errors are the same as for the Chevrolet data).

4.1.1.3 Ford vans

Ford's 5780-lb vans were modified to run on CNG using an SMPI system and increased CR. The gasoline-engine-equipped vans have a CR of 8.8:1 compared with 11:1 for the CNG vans. The adjusted fuel economy based on a typical duty of 40 miles/d is 9.3 miles/GGE as compared to 8.9 for the control group for a fuel economy gain of 4.5%. Although the apparent efficiency advantage for CNG is not statistically significant for a 95% confidence level criterion (the statistical errors are the same as for the Chevrolet data), it is consistent with the increased compression ratio.

4.1.2 Crown Victoria

The Crown Victoria is a 1995 production model, featuring a 4.6-L V-8 engine with a single overhead cam (SOHC) coupled to a four-speed automatic electronic overdrive transmission.[23] Special pistons are used in the engine to increase the engine CR from 9:1 (used in the gasoline version) to 10:1. Stellite-faced valves and valves seat inserts are used to prevent wear caused by the reduced lubricity of NG. Platinum-tipped, nickel-plated spark plugs are used to prevent corrosion that could be caused by water in the fuel and the increased production of water during combustion.

The closed-loop emission control system includes multipoint fuel injection, EGR, a positive crankcase valve (PCV), and TWC. Stoichiometry and ignition timing are altered for the CNG vehicle to make the catalyst operate efficiently. For instance, rich operation and spark retard are used after engine start to decrease catalyst light-off times. The NG engine can be run slightly rich to lower NO_x, because although total HC emissions may be high, the nonmethane HC (NMHC) levels will remain low. The engine-out emissions for CO and NO_x are similar to the gasoline engine, but the NO_x levels at the tailpipe are much lower. This car model was the first to be certified by CARB as an ULEV and also certified by the Environmental Protection Agency (EPA) as an ILEV under a special subclass of the Federal Clean Fuel Fleet Program (CFFP).

Due partly to a decrease in volumetric efficiency, the torque and power of the CNG engine were found to decrease by ~12% when compared to the gasoline version. In terms of drivability, the NG vehicle had reduced range and a slight degradation of torque resulting in reduced acceleration times.

EPA city driving fuel efficiencies of the CNG and the gasoline versions are identical (i.e., 17.2 miles/GGE in both cases). The EPA highway performance is also essentially identical (i.e., 25.7 miles/GGE for NG vs 25.8 miles/GGE for gasoline).

4.1.3 Ford F-250 Truck and E-250/E-350 Vans

Ford introduced additional CNG vehicles in mid-1997: the 5.4-L F-250 full-size pickup truck and the 5.4-L E-250/E-350 full-size vans.[24] The development priority for these CNG vehicles was excellent environmental performance rather than high fuel efficiency. The engine used in the vehicles is a Triton V-8 featuring an overhead cam, aluminum head, cast iron block, port fuel injection, and coil-on-plug ignition. The engine modifications for CNG operation include the following:

- Eatonite flat-faced intake and exhaust valves;
- Winsert cast Stellite valve seat inserts for both intake and exhaust;
- high-energy ignition system with modified timing;
- platinum-tipped, nickel-plated spark plugs for high-ignition energies;
- patented fuel control strategy;
- elimination of EGR and secondary air injection; and
- a conditioning catalyst system for the engine exhaust stream.

These were the first original equipment manufacturer (OEM) vehicles to certify at the super ultra low-emission vehicle (SULEV) standard in California for medium-duty vehicles. Federal Tier II standards were also met. Durability runs to 120,000 miles demonstrated that the conditioning catalyst was able to maintain low levels of NO_x at the tailpipe even in the absence of EGR.

The estimated EPA-adjusted fuel economy (FTP-75 cycle) values reported in the 1997 Fuel Economy Guide[2] for the F-250 truck are 13 MPGE for CNG vs 15 MPG for gasoline. For the E-250 van the figures are 12 MPGE for CNG vs 14 MPG for gasoline. No values were given for the heavier E-350 vans. The EPA Fuel Economy Guide values are rounded to the nearest integer value for MPG or MPGE, so the rounding error in this comparison may be relatively large. Reported CNG vehicle economies in Ref. 24 were 13.3 MPGE for the F-250 truck and 12.2 MPGE for the E-350 van. The comparison value of –11% in Table 3 is based on 13.3 MPGE for the CNG F-250 compared to 15 MPG for the gasoline truck. Measurements revealed that the CNG vehicles operate with significantly higher exhaust back pressures compared to the gasoline vehicles, due to differences in the catalytic control systems. Back pressure is known to reduce efficiency.

4.1.4 Civic GX

Honda R&D has developed a redesigned 1.6-L Civic to operate on CNG with extremely low emissions.[10] The engine is a SOHC, 16-valve, in-line, 4-cylinder model. The mechanical alterations to the Civic include the following:

- increased CR (from 9.4 to 12.5);
- modified pistons, rings, valve seats, and head gasket;
- addition of an EGR system;
- use of two oxygen sensors to monitor conversion efficiency;
- use of different spark plugs;
- addition of a sequential multipoint manifold gaseous injection system;

- electronic control of the valve train system; and
- use of two catalytic converters in the exhaust system.

The electronic valve train system and PFI system is used to promote a strong swirl and turbulence in the combustion chamber. Some amount of axial charge-stratification is also claimed to be achieved. The combined effect is increased flame propagation to improve heat release rate. A CR of 12.5 was selected as being near optimum because efficiency gains above 12.5–13.5:1 were estimated to be cancelled by increased engine friction.[10]

Testing was performed on the CNG Civic to characterize the vehicle and to evaluate engine durability. Emission levels proved to be very low and amounted to only 10% or less of the ULEV levels for CO, nonmethane organic gas, and NO_x. The fuel economy of the CNG Civic compared to the gasoline version is reported as 30.5 miles/GGE vs 32.4 miles/GGE (a reduction of 6%) for city driving and 43.3 miles/GGE vs 46.4 miles/GGE (a reduction of 7%) for highway driving. The increased CR for the CNG vehicle should boost efficiency, but the addition of a second catalyst and controlling the engine for excellent environmental performance are known to reduce efficiency.

4.1.5 Turbo Sprint

A 1991 Chevrolet Turbo Sprint was converted to operate on CNG and used in an evaluation of both lean-burn and stoichiometric operation.[11] The five-speed manual Sprint coupe was powered by a Suzuki Motor Corp., 1.0-L, three-cylinder, turbocharged engine with an intercooler. The 1991 Chevrolet Sprint is essentially the same vehicle marketed as the Geo Metro, the Pontiac Firefly, and the Suzuki Swift.

This research effort was unique because it involved a small turbocharged car engine, it employed lean-burn combustion for part of the study, and efficiency improvement was a major goal. The fuel management system was calibrated to produce either carefully controlled stoichiometric fueling or lean-burn combustion, utilizing approximately 40% excess air over most of the operating range of the engine. The key mechanical and control system alterations to the Sprint include the following:

- a Suzuki developmental electronic control unit (ECU),
- a multiport NG injection system,
- raising the CR from 8.5:1 to 12.4:1 with flat-topped pistons and modified head,
- modified valve timing (via a modified camshaft pulley),
- modified ignition timing to achieve peak efficiency under a wide range of conditions (timing set for maximum brake torque), and
- highly accurate closed-loop control over stoichiometry.

The flat-topped pistons were designed for a very small crevice volume to minimize incomplete combustion. The same gas fuel injection system and controller were used for both stoichiometric and lean-burn operation. The fueling scheme also included changes to eliminate any enrichment during and after cold start, elimination of enrichment at cold temperatures, modified intake air temperature correction, no warm-up acceleration enrichment, no power enrichment, new idle air control strategies, new fuel cut strategies at high revolutions per minute (rpm), elimination of the knock sensor, and reduced asynchronous acceleration injection.

Stoichiometric operation showed potential to meet ULEV standards due to effective suppression of NO_x levels by the catalysts. The NO_x levels were 30 times greater in lean-burn operation due to the ineffectiveness of the catalysts under oxygen-rich exhaust conditions. The NO_x levels during lean burn would have to be reduced to meet current and future emission standards.

Gasoline testing of the particular Turbo Sprint test vehicle was not performed before conversion to NG and was not really feasible once the vehicle conversion was completed (CR was far too high for gasoline). Therefore, the FTP-75 (standard EPA FTP certification tests) fuel economy comparisons in Ref. 11 are based on independent testing of a gasoline-powered 1991 Chevrolet Turbo Sprint performed by Transport Canada and EPA Certification results. These data indicate that there is a dramatic (22%) improvement in fuel economy for the stoichiometric NG fueling tests and an even greater (33%) improvement for NG lean-burn operation. These results, although very positive, must be considered to be approximate because different cars, laboratories, equipment, etc., were used to evaluate fuel economies of the two different fuels in this model vehicle.

The excellent fuel economy results beg further analysis. In Table 4, selected standard EPA FTP-75 certification results have been added to the results from Ref. 11 for further comparison. Comparing the CNG results to the 1990 EPA results for the gasoline turbocharged vehicle indicates even greater efficiency improvements of 28 and 40% for stoichiometric operation and lean burn, respectively. If the turbocharged CNG vehicle is compared to NA versions of the Sprint, the efficiency advantage is considerably less, being about 7 and 17% for stoichiometric operation and lean burn, respectively. In any case, even the 7% improvement is quite good compared to most other reported CNG light-vehicle results.

Actual driving performance was reported to be very good for the CNG stoichiometric case, perhaps with better performance than the gasoline Turbo Sprint. Power was degraded significantly for the lean-burn case.[25]

Table 4. Further economy comparisons for the Chevrolet Sprint or equivalent vehicle with 1.0-L displacement engine, three-cylinder, five-speed manual transmission

Fueling, test car, and test agency	Miles/GGE		
	City	Highway	Combined
CNG, stoichiometric, 1991 Turbo Sprint, Saskatchewan Research Council			50.1
CNG, lean-burn, 1991 Turbo Sprint, Saskatchewan Research Council			54.8
Gasoline, 1991 Turbo Sprint, Transport Canada			41.2
Gasoline, 1990 Turbo Sprint/Firefly, EPA certification results	37.0	42.0	39.0
Gasoline, 1990 Sprint (no turbocharger), EPA certification results	46.0	50.0	47.0
Gasoline, 1991 Sprint (no turbocharger), EPA certification results	45.0	50.0	47.0
Gasoline, 1992 Sprint (no turbocharger), EPA certification results	46.0	50.0	47.0

4.1.6 Observations

From examination of past CNG light-vehicle development and implementation, it appears that high efficiency has generally been a secondary goal. Apparently, few efforts like those for the Turbo Sprint[11] have been made to produce engines and vehicles with energy efficiency significantly better than gasoline light-duty vehicles. Certainly, market forces have not been in place for engine manufacturers to justify aggressive research, development, and design efforts toward producing high-efficiency automotive NG engines. Instead, much of the focus has been on developing very environmentally attractive vehicles with performance comparable to gasoline vehicles. Much more emphasis has been placed on developing high-efficiency NG engine technology for heavy-duty vehicles.

4.2 HEAVY-DUTY, SI NG ENGINE APPLICATIONS

A significant amount of R&D effort has been put forth to develop efficient, heavy-duty, SI NG engines. Emphasis has been placed on turbocharged engines with designs similar to diesel engines that operate lean, while producing very low emissions. The lean operation gives the engine both a thermodynamic advantage that improves energy efficiency and allows throttling to be reduced somewhat to boost efficiency further. CRs are typically near 10.5:1 to 11.5:1,[14,26,27] which is much lower than for diesel engines, and throttling is still required at part loads. These engines are 15 to 30% less fuel efficient than diesel engines[18,19,28] depending on the specific application, but can be 10 to 20% more fuel efficient than a current (stoichiometric) gasoline engine.

There are a number of efficiency-related development issues for these engines. It may be possible to make further gains by increasing CR (while avoiding knock) and by operating at increasingly lean conditions. This means the next generation of engine design and control systems will push to extend the practical lean limit (misfire limit) and knock limit while keeping emissions low. To achieve this, excellent closed-loop control over lean stoichiometry is necessary and has been the topic of recent development work.[18,19,28, 29] Furthermore, sensitivity of the lean limit to humidity is known, and humidity sensing very likely will be a requirement of an advanced control system.[19,28,29]

Because of the lean operation, catalytic reduction of NO_x is ineffective, and keeping NO_x low depends on careful combustion control to keep NO_x formation minimized. Use of EGR is currently uncommon in heavy-duty, SI NG engines, but further work in this area could be quite helpful in optimizing these engines.

Additional R&D that could extend the efficiency of SI NG engines includes skip-fire operation, IDI (prechamber) fueling, or DI-stratified charge fueling. The effective or average stoichiometry can become very lean using these techniques, without misfire occurring. The engine efficiency improvements are mainly caused by the reduction or elimination of throttling losses at lower loads. Skip-fire techniques simply allow fuel to be completely absent from certain power strokes; this is not a method unique to NG fueling.

4.3 CI NG VEHICLE ENGINE TECHNOLOGY

Future use of CI CNG engines may be attractive because of the potential for high thermal efficiency and low emissions. A major drawback is the very poor autoignition characteristics of NG, which make use of CI relatively difficult. Assuming that proper ignition can be achieved, it is possible to use the same basic diesel engine designs for NG that are used for diesel operation. It is important to consider that diesel engine powering is generally more expensive than gasoline and will generally add weight to the vehicle. This may significantly diminish the attractiveness of CI NG engine technology for light-vehicle application and goes counter to the OAAT technical target of reducing the incremental vehicle cost (CNG vs gasoline) to $1500. The trade-off between fuel efficiency and engine cost is the major reason that diesel engines are the powering system of choice in the heavy-vehicle sector and that gasoline engines dominate the light-vehicle sector.

A limitation for using NG for CI engines stems from the very poor autoignition properties of NG when compared to diesel fuel. To assist the compression ignition of NG, pilot diesel fuel (or other high-cetane-number fuel) injection or glow plug assistance must be used. However, even glow plug usage presents a difficult challenge because the glow plug surface temperature requirement is 1200 to 1400 K.[20,21] Lower temperatures than this result in (1) ignition being slow to develop and more variable, (2) reduced engine efficiency, (3) higher emissions, and (4) possible damage to mechanical parts. Because glow plugs operating in the range of 1200 to 1400 K can be expected to present a formidable reliability/durability problem, developing such a component within the OAAT program time frame may not be achievable.

The pilot fuel injection option appears desirable from a technical standpoint, but may be fairly complex and costly. Some drawbacks include the need for two separate fuel systems and the unknown effect on emissions of using various amounts of diesel fuel. A pilot fuel injection (or micropilot) engine using 95 to 99% NG and 1 to 5% diesel would likely require electronic port gas injectors or direct injectors, electronic control of the pilot injector, and electronic control of the air-fuel ratio.[28] A prechamber for the pilot may be included for some cases, and an EGR system with controls may be required.

To obtain efficiencies close to those of a diesel engine would require NG injection in DI or IDI mode. If homogeneous charge combustion (by PFI or early-cycle DI) is used, the lean combustion limit will still reduce part-load efficiency significantly because throttling will be necessary. The lean limit could be extended through charge stratification using an IDI NG (prechamber) fueling strategy. Use of late-cycle DI using high-pressure NG would most closely simulate typical DI diesel fueling strategy. The NG would burn more in a diffusion flame mode for very late cycle injection, and there would effectively be no lean-limit concern.

Cost and complexity are the main challenges of these approaches, and development time may even be problematic for supporting the OAAT program (i.e., most research to date pertaining to CI CNG engines with diesel pilots has focused on heavy-duty engines). Generally, CI NG engines seem much more suited to engines sized for heavy-duty truck engines and locomotives.[28,30,31]

5. SUITABILITY OF HIGH-EFFICIENCY CNG ENGINE TECHNOLOGIES FOR LIGHT-DUTY APPLICATIONS

This chapter presents the information and arguments to narrow the options for engine technology to those most suitable for light-duty NGVs and to support the goals in the OAAT R&D plan. A large range of IC engine technologies can be considered for NG fueling, including both CI and SI engines. Any type of CI engine will be similar to current diesel engines, and the potential for relatively high efficiencies appears achievable. For the NG SI approach, the engine technology will be similar in design to current gasoline engines, and more modest efficiency gains appear to be achievable. Both types of engines will be considered further.

5.1 POTENTIAL FUEL EFFICIENCY GAINS FOR NG ENGINES

It is important to understand the potential for improving NG fuel efficiency for the many options that are available. A summary of estimated energy efficiency ranges for selected engine designs relative to current stoichiometric gasoline engines is given in Table 5. The effects of certain engine design parameters and vehicle weight are also included. Table 5 essentially presents a hierarchy of NG engine designs based on fuel efficiency. Some of the general assumptions include excellent control over stoichiometry for all lean-burn engine technology and all SI engines designed for a single fuel with efficiency as a major design goal. Further explanation of the table entries follows.

1. The base case for this efficiency comparison is a current light-duty SI gasoline engine that operates at stoichiometric conditions, uses a TWC system, is NA, PFI, and has a CR near 9.0:1.
2. If a gasoline engine described in case 1 is configured for NG without changing the CR, the engine is expected to have lower peak power and is likely to have lower efficiency. The fleet experience described in Chap. 4 provides evidence for this.
3. A light-duty NGV will weigh more due to the storage tank. The assumed weight penalty is 5% more weight, which would be 150 lb added to a 3000-lb vehicle. The efficiency penalty is scaled from the assumption or "rule of thumb" that a 6% loss in MPG results from a 10% increase in vehicle weight with no other changes.
4. This estimate of efficiency improvement only considers a CR increase for an NG-fueled engine; no other effects are considered. The efficiency gain estimate has been calculated from the ideal Otto cycle efficiency expression using gamma = 1.3.
5. This entry is an estimate for the efficiency gain that could be realized for using excellent control over air and NG to avoid all rich fueling conditions, combined with use of reduced crevice volume pistons in a stoichiometric SI engine employing a TWC.[11]
6. The NGV examined employs an SI, stoichiometric, turbocharged, or DI engine that has the attributes described in cases 4 and 5. The relative efficiency gain is for a vehicle; therefore, the weight penalty in case 3 is included.[11]
7. The efficiency gain for SI, gasoline, lean-burn, early-cycle DI (homogeneous charge) is estimated from information from Ford Motor Company[32] and recently published work.[18,33,34] Gasoline DI cases include a small efficiency increase due to a higher CR allowed because the knock limit has moved favorably. At this time, gasoline DI engine tests show disappointing environmental performance.
8. The NG lean-burn technology efficiency gain values are derived by comparison to the gasoline technology in case 7. The NG engine is assumed to be capable of operating at conditions that are slightly more lean than gasoline lean-burn engines.
9. The efficiency values for the gasoline, lean-burn, SI, DI stratified charge, or IDI engine system are somewhat better than for homogeneous charge technology and are derived from Refs. 28 and 32–34.
10. The NG lean-burn technology efficiency gain values are derived by comparison to the gasoline technology in case 9. The NG engine is assumed capable of operating at conditions that are slightly more lean than gasoline lean-burn engines.

Table 5. Expected relative efficiency changes due to selected engine technologies or engine and vehicle parameter changes (an FTP-75 duty cycle is assumed)

Selected engine design, engine parameter, or vehicle parameter	Energy efficiency change from baseline gasoline engine (%)
Base case gasoline engine and typical NG fleet vehicle engine	
1. Base case engine: SI, gasoline, NA, PFI, ~9.0:1 CR, TWC, in a light-duty vehicle	Base
2. NG engine very similar to case 1: SI, NA, PFI, ~9.0:1 CR, TWC, lower volumetric efficiency, lower peak power	–9 to –2
Selected design parameter	
3. Light-duty NGV weight penalty, adding 150 lb to a 3000-lb vehicle	–3
4. NG, CR increase from 9.0–10.0:1 to 12.0–13.0:1	+5 to 11
5. NG, control of air and fuel to avoid all rich conditions, use of reduced crevice volume piston, in a stoichiometric SI engine employing TWC	+2 to 4
Stoichiometric SI engines	
6. NG, stoichiometric, turbocharged or DI, SI, NGV with effects of cases 2, 3, and 4 included; compared with current fuel-efficient NA gasoline engine (base case)	+5 to 11
Lean-burn SI engines	
7. Gasoline, lean-burn, early-injection DI, homogeneous charge	+11 to 15
8. NG, lean-burn, turbocharged PFI or DI early-injection (essentially homogeneous charge), SI, with CR increase (case 4) and weight penalty (case 3)	+16 to 20
9. Gasoline, lean-burn, SI, DI stratified charge or IDI (prechamber)	+14 to 18
10. NG, DI stratified charge or IDI (prechamber), lean burn, with CR increase (case 3) and weight penalty (case 2)	+19 to 23
11. Skip firing added to case 8 or 10 to reduce/eliminate throttling	+23 to 34
CI engines	
12. NG, CI, turbocharged, homogeneous charge, micropilot ignition (~19:1 CR), some throttling needed; weight penalty of 250 lb for 3000-lb vehicle included	+24 to 29
13. NG, CI, turbocharged, DI stratified charge or IDI (prechamber), micropilot ignition (~19:1 CR); weight penalty of 250 lb for 3000-lb vehicle included; a small amount of throttling is assumed to be required	+28 to 37
14. Diesel fueled, turbocharged, IDI, and DI engines	+30 to 44

Note: CI—compression ignition, DI—direct injection, IDI—indirect injection, SI—spark ignition, PFI—port fuel injection, NA—naturally aspirated, CR—compression ratio, NGV—natural gas vehicle.

11. The estimated efficiency range is based on eliminating remaining throttling requirements and comparisons to cases 10 and 14. A CR of 13:1 is assumed for the NG engine and 19:1 for the diesel engine.[28] Skip firing may be considered a "generic" technology and may also apply to gasoline.
12. The efficiency is estimated by comparison to case 8, but with an added weight penalty for a heavier engine and the CR increased from 13:1 to 19:1.
13. The efficiency is estimated by comparison to case 10, but with an added weight penalty for a heavier engine and increased CR from 13:1 to 19:1.
14. Efficiency for an automotive diesel is estimated using the VW Jetta comparison as a maximum efficiency gain. For the VW comparison, the diesel Jetta had essentially the same weight as the gasoline version of the vehicle. This likely would not be typical, and a weight penalty was added to compensate for a heavier engine. References 28 and 35 were also considered.

5.2 CI vs SI TECHNOLOGY

Looking at the broad view of reasonable CNG engine technologies shows a basic choice in paths between CI and SI engines. With the CI approach, designs will be similar to current diesel engines and the highest efficiencies can be achieved, but the engine cost will also be relatively high. For the SI approach, engines similar in design and cost to current gasoline engines would be expected.

5.2.1 CI Engine Cost

As described earlier, CI has limited or perhaps very challenging choices in methods to reliably ignite NG because of the very poor CI qualities of this fuel. We conclude that pilot ignition using a liquid high-cetane-number fuel is a reasonable choice for the near term. It is estimated that a turbocharged diesel engine will increase the cost of a six-passenger light vehicle by more than $1500. A turbocharged CI NG engine would be more costly than a turbocharged diesel engine due to the duel-fuel requirement. An incremental engine system cost near $2000 is expected for such a pilot ignition CI engine system when compared to a gasoline engine. This cost is due to the need for a turbocharger system, higher stress and temperature components, a high-pressure liquid fuel injection system, an NG injection system, and other components. The CI engine is also likely to add at least some weight to a vehicle when compared to gasoline technology. Note that the costly CNG fuel system is a separate incremental cost for any CNG vehicle.

If a $1500 incremental vehicle cost were realized by 2006 for a CNG fuel system, then the likely overall incremental vehicle cost for including NG CI technology would be approximately $3500. Perhaps this initial cost can be recovered through fuel savings for vehicles that normally use relatively large amounts of fuel, but it may be out of the range for light-duty vehicles. This high added cost due to the CI engine runs counter to the stated OAAT technical target to reduce the incremental vehicle cost (CNG vs gasoline) to $1500, but it would aid in achieving the target for a 380-mile vehicle range.[1]

5.2.2 SI Engine Cost

From the standpoint of applicability, the cost of SI NG engines appears more appropriate for light-duty vehicles. Engine technologies featuring lean-burn NG with turbocharging or DI fueling would likely cost no more than $500 per engine compared to gasoline technology.

5.2.3 SI vs CI Economic Comparison

A simple economic comparison is made in an attempt to narrow the list of possible engine technologies on economic grounds. A comparison is presented between a lean-burn SI and a CI-powered light-duty NGV. Even with a simple comparison, a relatively large number of governing assumptions must be made. The lean-burn, SI NG engine employs either turbocharging with PFI fueling or DI early-injection (essentially homogeneous charge) fueling, listed as case 8 in Table 5. An efficiency level 18% higher than current gasoline technology is assumed, and the estimated incremental engine cost is $500. The CI engine used for comparison is turbocharged, DI-stratified charged or IDI (prechamber), micropilot ignition (CR ~ 19:1), and is listed as case 13 in Table 5. The CI engine efficiency is assumed to be 33% higher than current gasoline technology with an incremental engine cost of $2000.

A number of other assumptions are given in Table 6. Both the fuel costs and the miles traveled per year are standard values used by EPA for automotive certification calculations.

The CI pilot fuel injection natural gas (PING) engine is assumed to burn 95% NG and 5% diesel or another liquid fuel. The proportioned fuel cost is estimated at about $0.81/GGE. A 5% CNG tank size reduction is assumed for the CI engine due to 5% liquid fuel use.

For the comparison shown in Table 7, the CNG tank is sized for a 380-mile vehicle range at the assumed MPGE value shown. These MPGE values are based on a current six-passenger gasoline vehicle that achieves 20 MPG.

Table 7 shows that the benefit from a smaller (16% less capacity) CNG tank and 5 years of fuel savings does not come close to the added cost of using a CI engine compared to an SI lean-burn engine. Fuel savings are just below $50/year (15,000 miles traveled). There do not appear to be reasonable scenarios for which a CI PING-type engine would be economically suited for automotive application when compared to SI engine scenarios.

Table 6. Assumptions for economic benefit comparison

Assumption	Source/comment
Diesel fuel cost = $1.07/GGE	EPA 1998 certification data standard cost[2] Diesel price is $1.20/gallon but contains 12% more energy than gasoline
Natural gas cost = $0.80/GGE	EPA 1998 certification data standard cost[2]
Distance traveled = 15,000 vehicle miles/year	EPA 1998 certification data standard cost[2]
Vehicle range = 380 miles	OAAT goal[1]
CNG tank cost = $80/GGE	Current cost is about $125/GGE, reduced to 64%
Gasoline vehicle fuel efficiency = 20.0 MPG	
SI NG lean-burn engine efficiency improvement = 23.6 MPG at 18%	
CI NG engine efficiency improvement = 26.6 MPG at 33%	

Table 7. Cost comparison of engine types

			Cost 1	Cost 2	Cost 3		
Engine type	CNG (MPGE)	380-mile tank capacity (GGE)	380-mile tank cost ($)	Incremental engine cost ($)	5-year incremental fuel cost ($)	Sum of costs ($)	Incremental cost ($)
SI, DI, lean-burn NG	23.60	16.10	1288	500	2542	4330	Base
CIDI, PING	26.60	13.57	1086	2000	2294	5380	1050

5.3 USE OF HIGH-PRESSURE NG INJECTION

A technology that is potentially attractive for increasing NG efficiency is using late-cycle NG injection into the cylinder for DI or IDI injection schemes. Such late-cycle injection could be utilized for the technology assumed in cases 10 and 13 listed in Table 5. Late-cycle injection is a known method for achieving charge stratification, both for gaseous and liquid fuels. It has the potential to extend the effective lean limit of operation for the engine, therefore boosting efficiency.

A major drawback is seen for this type of system because of the necessity of supplying high-pressure NG to the fuel system. Injection when the piston is nearing TDC will require high-pressure gas to overcome the in-cylinder pressure. A reasonable late-cycle injection scheme for NG would be to inject near 60° before TDC. The NG pressure requirements would be near 500–600 psi.[36] Assuming that it is not practical to somehow boost CNG pressure when the storage tank pressures drop to 500–600 psi, the useful storage capacity of a CNG tank will drop significantly (14–17% for a 3600-psi tank). A larger and more expensive CNG tank would be required to maintain vehicle range. Because this appears to go directly against the goals of OAAT, methods of charge stratification using relatively low-pressure gas are recommended. It may be possible to develop a gaseous fuel unit injection system that uses lower pressure gas but increases injection pressure through some sort of piston-stroke scheme.

5.4 THE IMPORTANT ISSUE OF REGULATED EMISSIONS

A much-touted feature of NG fueling is the potential for very low regulated emissions. In fact, light-duty CNG vehicles employing a stoichiometric fueling scheme with a TWC are able to meet the federal ILEV and CARB ULEV standards[10,11,23,24,37] and may have emission levels well below these standards. Unfortunately, this excellent environmental performance does not extend to lean-burn technology.

A major unanswered question involves what emission levels can be reached by lean-burn NG engine technology for light-duty vehicles. Essentially, this is a "go/no-go" issue, and emission standards must be met for lean-burn NG technology to be applied. Clearly NG has advantages over current gasoline and diesel fuel as a lean-burn fuel. NG can be effectively combusted using leaner mixtures than gasoline and/or can tolerate more EGR; therefore, lower levels of engine-out NO_x should be achievable. Furthermore, NG engines emit HCs mainly as methane, which remains unregulated and will form less particulates than current petroleum fuels. For these reasons, NG has a better chance of being environmentally compliant as a lean-burn fuel.

Data available concerning lean-burn, light-duty, NG engines are very limited. Apparently, no study has been published with test data showing that emissions standards can be met for the FTP-75 cycle. The Turbo Sprint data[11] show that the lean-burn fueling scenario used did not come close to meeting standards, with NO_x being a factor of 7 too high for ULEV/ILEV standards (about 1.4 g/mile). This work did not include an optimization effort to meet emission standards. NO_x emissions are the main problem for lean-burn engines.[11,19,28]

Emissions data are available for heavy-duty NG engines. Published data including recent work at Southwest Research Institute on an 8.1-L heavy-duty engine indicate that emissions levels well below ULEV standards for heavy-duty engines are achievable without a catalyst.[19,38] This work has focused on engine and control system optimization, and NO_x levels of about 0.77 g/bhp-h were achieved.[19] Although there is no valid way to use emission results from a 8.1-L engine tested on the heavy-duty FTP transient cycle to predict what is achievable on a smaller engine for the FTP-75 cycle, a very crude estimation can be made. A compact car would travel about 3 miles for an engine shaft output of 1 bhp-h. Using this value (and ignoring large differences between tests and engines), a crude estimate for NO_x emissions of 0.26 g/mile can be made. This estimate could easily be in error by a factor of 2, but it represents some indication that meeting FTP-75 ULEV/ILEV standards is a possibility. Note that the 8.1-L NO_x data were achieved without a catalyst and without use of EGR.

5.5 RECOMMENDED ENGINE TECHNOLOGY FOR FURTHER CONSIDERATION

The list of engine options in Table 5 can now be narrowed. Certainly, if a 10% improvement in engine efficiency compared to current gasoline engines is a major criterion, the NG lean-burn options (cases 8 and 10 in Table 5) and the CI options (cases 12 and 13) easily qualify. Of these, it has been argued to drop the CI engine technology and technologies requiring high-pressure gas supplied from the storage tank. For any stratified charge technology (case 10), consideration should be given only if low-pressure gas utilization can be established.

The only other possible option in Table 5 is for stoichiometric, turbocharged, or DI SI engines. It is doubtful that a 10% efficiency advantage can be established, especially if the comparison is with a fuel-efficient NA gasoline engine. It appears that this engine option does not meet the OAAT goals mentioned earlier. From a research standpoint, this is also a less challenging technology, although significant development work may be warranted. Excellent environmental performance is expected when a TWC system is employed.

Another possibility is to control an engine so that it uses stoichiometric fueling under certain conditions and switches to lean-burn operation at low loads for conditions that generate little NO_x. This essentially represents a combination of case 6 with case 8 or 10 as given in Table 5.

The recommended NG engine technologies that warrant further consideration are given below.

1. SI, lean-burn with turbocharging, and PFI. If charge stratification is feasible, it should also be considered.
2. SI, lean-burn with DI early-injection (homogeneous charge) fueling. Turbocharging is optional; the possibility of charge stratification should be evaluated.
3. SI, lean-burn with IDI stratified charge (prechamber) fueling if it is beneficial to do so with low-pressure NG.
4. SI, lean-burn with DI or IDI late-cycle, high-pressure injection if a unit injection system to boost gas pressure is possible.
5. Control an SI engine to use stoichiometric fueling under certain conditions and lean-burn operation at low loads. A combination of stoichiometric fueling with a TWC system and one of the preceding lean-burn engine descriptions is proposed.

Although it may seem that the technology options have been narrowed significantly, a number of technical options and research issues can be identified within the general engine technologies chosen.

6. R&D NEEDS

It is rarely an easy task to foresee the "best" R&D approach to advance a complex technology such as the IC engine. This chapter attempts to describe the leading topics to be pursued to advance higher efficiency NG light-duty engines and to move toward the applicable DOE and OAAT goals. The topics discussed relate to the engine technologies recommended in Sect. 5.5, and, accordingly, research issues specific to CI engines are not included.

It must be emphasized that no lean-burn NG engine technology will have an impact unless the applicable emission standards can be met, regardless of efficiency gains and other performance factors.

6.1 ENVIRONMENTAL COMPLIANCE

As stated earlier, lean-burn NG engines must meet the CARB ULEV and Federal Tier 2 emission standards. Because of a lack of relevant testing, it is not possible to know how challenging environmental compliance might be. Developing a lean-burn engine with appropriate controls and running tests to develop an emission data base should be a high priority and would be a guide for further R&D. With such data as a guide, a variety of design issues could be explored to begin optimizing dedicated lean-burn NG engines. Design parameters may include valve placement and timing, turbulence and mixing, CR, fuel injection, and spark timing.

Advancements in lean-burn catalyst systems optimized for NG would be beneficial and would be an enabling technology to help meet environmental regulations.

6.2 DEVELOPMENT OF ROBUST CONTROL SYSTEMS AND SENSORS

Efforts to develop advanced controls for light-duty applications will be needed if lean-burn NG engines are going to meet CARB ULEV and Federal Tier 2 emission standards. Optimization of the operation of a lean-burn NG engine will require development of advanced control systems that address the special needs of this technology. For lean-burn NG engines, the lean limit (misfire limit) is affected by the amount of water vapor (humidity) in the intake air.[19,29] Water vapor acts as a diluent and has other effects (including effects on the oxygen sensor), such that a humidity sensor integrated into the control system appears beneficial.[19,29] Excellent control over the air and fuel flows is also essential, and the need for highly sensitive wide-range oxygen sensors is apparent. Related to this is the need to have excellent control over EGR.

6.3 MODE SWITCHING BETWEEN STOICHIOMETRIC FUELING AND LEAN BURN

A possible method of meeting emission standards, while retaining some advantages of a lean-burn engine, would be to control an engine to switch between near-stoichiometric operation and lean burn at the appropriate operating conditions. At higher load conditions that generate substantial NO_x, it may be desirable to use stoichiometric fueling to enable a TWC system to work effectively. At lower loads when low NO_x production is expected, the engine can switch to a lean-burn operating mode to limit throttling losses. Obviously, a sophisticated control system would be necessary.

6.4 CHARGE STRATIFICATION

Charge stratification is desirable to extend the effective lean limit of operation to improve efficiency and lower NO_x generation. Because requiring a source of high-pressure gas (500–600 psi) will diminish vehicle range, methods of achieving charge stratification using a lower pressure gas supply (<150 psi) would be attractive. It is recommended that the following topics be evaluated for feasibility and potential impact.

It is known that some axial stratification is achievable with gasoline and NG using PFI techniques with special engine design features.[39,40] Application of such techniques for gas fueling should be examined further, but it is likely to be somewhat more difficult.

Use of low-pressure gas (early injection) to achieve useful intake charge stratification for DI and IDI systems may be possible. A parametric study of mixing and turbulence as a function of injection and combustion chamber design would be required.

Normally, charge stratification techniques involve late-cycle injection, which requires high-pressure gas. The possibility of using a unit-injection system for NG, in which a plunger action would significantly boost the gas pressure, should be examined. Such a system would be very different from any unit injector system in use, and lubrication would be an obvious problem. Alternative concepts to boost injection gas pressure when the supply pressure drops below a threshold value should be considered.

6.5 IGNITION SYSTEM IMPROVEMENT

Two reasons for advancing ignition system technology for lean-burn NG engines are to lower maintenance requirements and to extend the practical lean-combustion limit. In currently available lean-burn NG engines, higher spark energies are needed for reliable ignition (in comparison with gasoline engines); this causes the ignition system to be a relatively high-maintenance system. Ignition system reliability has been identified by GRI as a significant problem for NG lean-burn engines. Ignition quality problems are an issue for all fuels as engine operation approaches the practical lean-combustion limit and more robust ignition is seen as a method of extending the lean limit. The major benefit of pushing engine operation farther into the lean regime (or to allow greater amounts of EGR) is suppression of NO_x, which improves the likelihood of lean-burn technology meeting CARB ULEV and Federal Tier 2 emission standards. A secondary benefit is greater efficiency gains.

Novel concepts in the area of spark ignition or optimization of more conventional systems that would improve ignition quality and lower maintenance requirements should be evaluated. Goals should include longer component life, more reliable ignition near lean-limit conditions, extension of the lean limit, and more rapid flame kernel development (which can improve heat release rate). Two specific suggestions include (1) a fuel pretreatment system that uses an arcing system to crack the fuel and produce some hydrogen (such as the plasmatron developed by Massachusetts Institute of Technology), and (2) a special SI system that features a moving series of short duration arcs that sweep over a relatively large area.

6.6 INCREASED COMBUSTION CHAMBER TURBULENCE AND MIXING

A method to increase flame propagation rate, and therefore heat release rate, is to increase the level of turbulence and mixing in the combustion chamber at the time rapid combustion is desired. Low flame speed is especially troublesome for lean combustion. Optimization for lean-burn, homogeneous charge, NG engines would boost efficiency.

6.7 OTHER

Skip firing is a generic method for allowing part-load operation while avoiding throttling. A skip refers to simply not introducing any fuel into a cylinder on a certain cycle. Some pattern of skipping is established for light-load operation. Skip firing can become specific to NG if NG fueling is able to meet environmental standards for lean-burn engines, while other fuels cannot. In this case, skip firing will have special applicability to NG, and development could be pursued to increase efficiency.

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CONVERSION FACTORS

In the United States, English units are commonly used for quantities concerning vehicles, vehicle fuels, and related regulations. For convenience a table is given below to convert quantities in this report into the International System of Units (SI).

English unit	Factor[a]	SI unit
Btu	1.055	kJ
Btu/gal	278.7	J/L
gal	3.785	L
GGE (gallon of gasoline equivalent)	3.785	L
mile	1.609	km
miles/gallon (MPG)	0.4251	km/L
miles/GGE (miles per gallon of gasoline equivalent)	0.4251	km/(liter of gasoline equivalent)
lb/gal	0.1198	kg/L
lb/GGE (pounds force per gallon of gasoline equivalent)	0.1198	kg/(liter of gasoline equivalent)
lb	0.4536	kg
psi	6.895	kPa

[a] Multiply English quantity by given factor to obtain SI quantity.