Natural Gas as a Transportation Fuel: Best Practices for Achieving Optimal Emissions Reductions

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INTRODUCTION

Natural gas is used as a transportation fuel in many countries around the world, and its use in vehicle applications is growing. Besides displacing imported petroleum fuels, one of the primary benefits of using natural gas as a vehicle fuel is the potential to substantially reduce exhaust emissions of harmful pollutants such as particulate matter (PM) and nitrogen oxides (NOx). Studies have shown that NOx reductions of 50–80 percent and PM reductions of 80–95 percent are possible when heavy-duty vehicles are operated on natural gas instead of diesel fuel.[1] Similar reductions can be achieved in light-duty cars and trucks. In some cases, using natural gas to power a vehicle will also lower total greenhouse gas (GHG) emissions.

Switching to natural gas does not by itself guarantee low emissions of conventional pollutants or GHGs. Environmental benefits depend on the type of engine technology used and how it is deployed (e.g., as a retrofit of an existing gasoline engine or as a purpose-built natural gas engine)—in fact, some natural gas conversions can actually increase total emissions.[2]

To maximize the benefits of any natural gas vehicle program, several factors must be considered, including natural gas fuel quality, vehicle engine technology, retrofits versus new vehicles/engines, and safety. All of these issues will be discussed in this paper.

A country or region's current pattern of fuel usage is also important when evaluating the potential benefits of a natural gas vehicle program. For example, Brazil currently produces significant amounts of ethanol from domestically grown sugar cane for use as a vehicle fuel, primarily in light-duty cars. It also produces enough gasoline to meet its needs, but is highly dependent on imported petroleum to supply diesel fuel for heavy-duty vehicles. At the same time, Brazil's natural gas production ranks fifth in Latin America and recent discoveries suggest that the potential exists to increase production substantially. Brazil is also a highly urbanized country, with significant transportation-related air quality problems in its major cities. As such, Brazil could potentially reap significant environmental, public health, and economic benefits from increasing its use of domestic natural gas reserves for transportation.

A significant portion of Brazil's light-duty fleet already runs on domestically produced ethanol. The criteria pollutant emission reductions that can be achieved by switching from gasoline or ethanol to natural gas are also generally modest. Therefore, the greatest potential benefit from additional natural gas usage in Brazil's transportation sector will accrue by focusing on heavy-duty buses and trucks that currently operate on diesel fuel.

[1] Balon et al, 2000 and Kojima

[2] Weaver, 2003 and Nyland et al, 2000

Technology Overview

Natural gas can be used as a transportation fuel in several different ways. It can be used to generate electricity that in turn powers trains or trolley buses; theoretically, naturally gas can also be chemically modified into a synthetic liquid diesel fuel. As a potential alternative vehicle fuel, however, attention has generally focused on direct uses of natural gas in specially designed or modified internal combustion engines. When used as a vehicle fuel, natural gas can be carried on board as a cryogenic liquid (LNG), but it is much more common to carry it on the vehicle as a high-pressure compressed gas (CNG).[3]

Internal combustion engines designed to operate directly on natural gas can be configured a number of different ways. The choice of engine technology can dramatically affect both the efficiency and the emissions characteristics of natural gas vehicles.

Compressed Natural Gas (CNG)

At present, the most common use of natural gas in transportation applications involves carrying CNG aboard a vehicle to power an internal combustion engine. CNG is produced from low-pressure pipeline gas using large electric- or gas-driven compressors. Typically, each fueling station would have its own compressor(s) fed by a low-pressure gas pipeline.[4]

The higher the pressure, the further a CNG vehicle can drive between fill-ups. In the United States and Europe, typical CNG vehicles are fueled to pressures between 2,000 and 4,000 pounds per square inch (psi) in order to provide acceptable minimum driving range. The size and cost of CNG fueling stations is highly dependent on the allowable fueling time per vehicle, as well as the number of vehicles to be fueled each day.

Natural Gas Fuel Quality

Natural gas vehicles tend to be more sensitive to changes in fuel composition than other major users of natural gas such as electric power plants, and require higher fuel quality than is sometimes available through pipelines.[5] Requirements for fuel quality vary

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[3] Natural gas will liquefy at very low temperature (- 260^{O}F). In places where it is impractical to build pipelines, natural gas is often liquefied at the wellhead and transported to market as LNG in special highly insulated containers. Because LNG fuel tanks are much more expensive than CNG tanks, vehicles usually carry NG fuel as CNG rather than as LNG. In areas not served by a NG pipeline, vehicles could be fueled directly with LNG, or the LNG could be gasified at the fuel station and compressed onto vehicles.

[4] Theoretically, compressor stations could be centralized, with multiple fuel stations served by high pressure pipelines from the compressor station, but this is not typical.

[5] When extracted, natural gas generally contains 70-90% methane. The balance of the gas is usually other hydrocarbons like ethane, propane and butane; water; nitrogen; carbon dioxide; and hydrogen sulfide. Natural gas from different wells will have widely different composition. The extracted gas typically goes through a number of processing steps at or near the wellhead to remove most of these other materials. While the composition of “natural gas” sold to consumers varies widely from market to market, it typically contains 85% to 99% methane.

somewhat among engine manufacturers, but most currently specify between 85 and 90 percent *minimum* methane content, between 2 and 9 percent *maximum* propane content, and between 1 and 5 percent *maximum* butane content. These specifications are based primarily on light-duty stoichiometric engines; most heavy-duty vehicles, including those with lean-burn or turbo-charged engines, are even more sensitive to fuel composition. Specifying that natural gas for vehicle applications must have minimum 95 percent methane content will provide a reliability safety factor and is an appropriate goal for programs aimed at promoting natural gas as a transportation fuel.

When evaluating the use of natural gas as a transportation fuel, it is important to identify the composition of available pipeline gas (both in terms of average composition and in terms of maximum daily and seasonal variations). Local gas suppliers can generally upgrade fuel quality to meet the standards required for transportation uses, but this will often increase fuel costs. Suppliers may be unwilling to make the necessary upgrades if transportation users continue to account for only a small portion of total natural gas sales.

If fuel quality standards are not met, variations in fuel composition can upset the air-fuel ratio in the engine, leading to higher emissions and in some cases lower efficiency. In extreme cases, performance problems or engine damage can result. Because natural gas engines are spark-ignited, the "knock resistance" of the fuel (i.e., its resistance to premature compression ignition) is also important. Significant concentrations of the heavier hydrocarbons (propane, butane) in natural gas can increase the tendency to knock, resulting in loss of engine power and progressive engine damage. This could potentially be a seasonal problem, depending on how natural gas suppliers handle seasonal demand peaks.[6]

Several additional fuel components are important when natural gas is used as a vehicle fuel. These include water content, sulfur content, and compressor oil carry-over.

- *Water content* must be limited in order to preclude the formation of liquid water, ice, and particulates within the vehicle's fuel system at low operating temperatures. Water, ice, or particulates can plug fuel lines, regulators or valves, leading to vehicle performance problems. If the pipeline gas has high water content, it can be removed at the CNG fuel station by installing gas dryers in conjunction with the natural gas compressors.
- *Sulfur content* must be minimized in order to maximize the emissions and GHG benefits of natural gas vehicles. While the sulfur content of natural gas is typically much lower than the sulfur content of gasoline and diesel fuel, even very small amounts of sulfur can poison the catalysts used to control hydrocarbon emissions from natural gas engines. Catalytic oxidation of exhaust methane (a potent GHG) is particularly affected by sulfur. In the United States, pipeline natural gas typically has very low sulfur content but sulfur-based odorants are often added to the fuel to increase awareness and safety in the event of a leak. If available natural gas has high

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[6] In areas with significant seasonal variations in demand, natural gas producers often inject a mixture of propane, butane, and air into the normal natural gas stream to increase its total volume while maintaining consistent energy content, in order to meet peak demand needs.

sulfur content, sulfur levels can be reduced by further processing at the wellhead or by better control of odorant additions, depending on the source of the sulfur.

- *Residual compressor oil*: Most compressors used to create CNG from pipeline gas are lubricated by oil. Some of this oil is carried over into the gas stream during compression and ends up in the vehicle fuel system. While a small amount of oil is beneficial to lubricate the vehicle's gas injectors, too much oil can interfere with the operation of the vehicle's gas pressure regulators, leading to expensive failures. This problem can generally be avoided by installing appropriate filters to remove the oil, both at the fueling station and on the vehicle.[7]

In order for CNG engines to achieve low emissions, operate at maximum efficiency, and maintain durability, minimum fuel quality standards should be enforced.

Natural Gas Engine Technology

Minimum Fuel Qualify Standards for NGVs	
Methane	95% *minimum*
Propane	2–5% *maximum*
Butane	1–5% *maximum*
Water	Dewpoint 6ºC below minimum expected ambient temperature
Sulfur	8–30 parts per million *maximum*

Natural gas can be used in typical internal combustion engines instead of petroleum-based liquid fuels such as gasoline and diesel fuel. Whether the natural gas is carried on the vehicle as CNG or LNG, the fuel system allows low-pressure natural gas to mix with air before entering the engine's cylinders. The gas/air mixture is compressed in the cylinder and then ignited by a spark or by other means. Because natural gas engines are typically spark-ignited, existing gasoline engines (which are also spark-ignited) can be easily converted to operate on natural gas. By contrast, diesel engines, which do not utilize spark ignition, generally cannot be easily converted to operate on natural gas.[8]

The two main engine technologies used in natural gas vehicles—stoichiometric and lean-burn technology—are described below. These technology options are not equivalent in terms of their efficiency, emissions characteristics, or fuel quality requirements.

Stoichiometric Natural Gas Engines

Stoichiometric engines operate with an air/fuel mixture in the cylinder that contains only enough oxygen to burn all of the fuel. After combustion, there is very little, if any, "extra" oxygen left over in the exhaust. Stoichiometric natural gas engines are very

[7] There currently is no generally agreed on value for maximum oil content of natural gas vehicle fuel, or a standard method to measure oil content. Properly designed coalescing oil filters on both the compressor station and the vehicle are usually sufficient to remove enough oil to avoid problems.

[8]Diesel engines are compression-ignition. To be converted to run on natural gas the cylinder head must be modified to allow installation of a spark plug.

similar to conventional gasoline engines and are used in the vast majority of light-duty natural gas vehicles worldwide.

Most stoichiometric natural gas engines achieve an overall level of efficiency that is similar to gasoline and ethanol engines, but significantly lower than that of diesel engines. Stoichiometric engines also have relatively low power, especially compared to most turbocharged diesel engines. They are therefore much more appropriate for cars than for trucks or buses.[9] Because of their low compression ratio, non-turbo-charged stoichiometric engines are relatively tolerant of natural gas impurities and can operate with a wider range of fuel quality than lean-burn engines.[10]

Lean-Burn Natural Gas Engines

Lean-burn engines operate by putting far more air into the cylinder than is needed to burn the fuel—the exhaust therefore contains a significant amount of excess oxygen. The excess air lowers the peak combustion temperature, which reduces NOx and PM emissions. This also allows for much higher compression ratios, which in turn results in increased efficiency compared to a typical, throttled stoichiometric engine. Lean-burn engines typically operate at lower RPM and have more power than stoichiometric engines—in this way they operate much more like diesel engines. Accordingly, most lean-burn natural gas engines are based on diesel engine designs. Virtually all of the natural gas engines used in trucks and buses in the United States are turbo-charged lean-burn engines.

Instead of using a spark to ignite the fuel/air mixture in the cylinder, some state-of-the-art lean-burn natural gas engines use diesel pilot ignition. This means that a small amount of diesel fuel is injected into the cylinder at the desired ignition point to ignite the natural gas/air mixture. Under compression, the diesel fuel ignites, which in turn ignites the natural gas.

Closed-Loop Fuel Control

In both stoichiometric and lean-burn natural gas engines, precise control of the air/fuel ratio is necessary to ensure low emissions and peak engine efficiency. In modern engines, this is achieved using a direct sensor to measure the oxygen content of the exhaust. Based on readings from the oxygen sensor, the engine's electronic control module adjusts the fueling rate to maintain optimal conditions within the cylinder. A "closed-loop" system can adjust for minor changes in fuel composition, as well as changes in atmospheric conditions.

Less sophisticated "open-loop" systems do not rely on a real-time sensor to provide feedback. They control fueling to the cylinder using a simple carburetor, or by relying on fixed "maps" within the engine control module that assume an average fuel composition

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[9] If turbo-charging is used, efficiency and power can be increased enough to make stoichiometric engines usable for trucks and buses. This appears to be the direction that European engine manufacturers are taking with heavy-duty natural gas engines.

[10] This is not true of turbo-charged or high compression stoichiometric engines, which require equivalent fuel quality as lean-burn engines to operate properly.

and average atmospheric conditions. Use of these systems will result in much higher in-use emissions compared to closed-loop fuel control systems.

Dual-Fuel Engines

A stoichiometric natural gas engine is very similar to a gasoline or ethanol engine. In fact, it is easy to design an engine that can operate equally well on any of these fuels. The vast majority of the natural gas vehicles in the world are actually "dual fuel" vehicles created by adding a natural gas tank and fuel system to an existing gasoline or ethanol powered car. After the conversion, the engine can operate using either the original fuel or natural gas. Dual-fuel vehicles usually have increased range compared to dedicated CNG vehicles. The flexibility to use more than one fuel provides the vehicle operator with security when driving in areas where CNG infrastructure is not fully deployed. It also allows the vehicle operator to switch fuels based on differential fuel costs, thereby allowing for lower overall operating costs.

Though less common, it is also possible to create a dual-fuel vehicle that can operate on either diesel fuel or natural gas by modifying an existing diesel engine.[11]

Fuel and Engine Choices, and their Impact on Emissions

There are three basic categories of pollutants that are of greatest concern in terms of motor vehicle emissions: particulates (PM); ozone-forming compounds such as non-methane volatile organic compounds (VOC) and nitrogen oxides (NOx); and greenhouse gases (GHGs). At a local level, carbon monoxide (CO) emissions can also be of significant concern.

Particulates

If properly maintained, all gasoline, ethanol, and natural gas engines produce almost no particulate emissions.[12] Diesel engines, by contrast, typically produce significantly higher levels of particulates even when they are new and properly maintained.

Ozone-Forming Compounds

Ozone forming compounds include NOx and non-methane volatile organic hydrocarbons (VOCs). Unfortunately, all internal combustion engines produce significant NOx and VOC emissions regardless of the fuel burned. In fact, the use of natural gas does not, by itself, guarantee that NOx and VOC emissions will be low.

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[11] Dual fuel diesel/natural gas vehicles should not be confused with natural gas *diesel pilot ignition*. In a true diesel pilot ignition system, only a small amount of diesel fuel is metered into the cylinder, and the majority of power is derived from ignition of the natural gas. These engines cannot operate using diesel fuel alone.

[12] The small amount of fine particulates produced by these engines usually results from contaminants in the fuel, and from engine oil burned in the cylinder along with the fuel. As these engines age and their cylinder liners wear out, particulate emissions can increase significantly based on increased engine oil entering the cylinders.

On the contrary, NOx and VOC emissions from a simple stoichiometric natural gas engine can be as high, or higher, than emissions from an equivalent gasoline, ethanol, or diesel engine. However, the stoichiometric operation of these engines also allows for the use of a three-way exhaust catalyst like those used on modern gasoline engines. These catalysts dramatically reduce NOx and VOC emissions. *Thus, the use of closed-loop fuel controls and three-way catalysts in conjunction with stoichiometric natural gas engines is likely to result in the lowest overall emissions of any engine/fuel combination.*

Compared to stoichiometric engines, lean-burn natural gas engines have inherently lower NOx emissions. *In fact, lean-burn natural gas engines have the lowest engine-out NOx emissions of any engine/fuel combination*. However, the high oxygen content of the exhaust from these engines makes a three-way catalyst ineffective in terms of producing further NOx reductions. Therefore, a stoichiometric engine that is equipped with a three-way catalyst, whether it burns gasoline or natural gas, will have lower NOx emissions than a lean-burn natural gas engine.

Lean-burn engines also potentially have much higher hydrocarbon and sometimes higher CO emissions, where much of the hydrocarbon emissions consist of unburned fuel in the form of methane. Adding an oxidation catalyst muffler can control the CO and a portion of the hydrocarbon emissions. However, current oxidation catalysts are generally not optimized for reducing methane emissions.

Using diesel pilot ignition allows the engine to operate on an even leaner fuel/air mixture without the risk of ignition misfire, thereby further reducing NOx emissions.

Greenhouse Gases

Carbon dioxide (CO_2) is the most abundant greenhouse gas produced by internal combustion engines. Because natural gas contains less carbon and more hydrogen than liquid transportation fuels like gasoline, ethanol, and diesel fuel, natural gas engines produce less CO_2 for the same amount of energy consumed. However, there is a trade-off between fuel carbon content and efficiency. Because diesel engines are more efficient than natural gas or gasoline engines, switching a vehicle from diesel to natural gas will produce lower net CO_2 reductions than switching a gasoline vehicle to natural gas.

Methane—the main component of natural gas—is a powerful GHG, with approximately 21 times the warming potential of CO_2. Without the use of a methane-targeted oxidation catalyst, methane emissions from a natural gas vehicle will offset any CO_2 reductions. Indeed, the switch to natural gas can actually increase net GHG emissions in some cases, especially where dual-fuel retrofits of existing engines are not optimized for natural gas operation.

Emissions Summary

When switching from GASOLINE to NATURAL GAS:

- There will be no significant reduction in PM emissions. NOx, VOC, and CO emissions could increase or decrease depending on the engine control and after-treatment technologies applied. *To ensure a reduction in NOx, VOC, and CO* *emissions, closed-loop fuel control systems and three-way exhaust catalysts must be used.*

- There will be a reduction in CO_2 emissions, but this will be offset by an increase in methane emissions[13] such that net GHG reductions may not be as large as expected. *To ensure maximum reductions of GHG emissions, closed-loop fuel control systems and methane-optimized three-way exhaust catalysts must be used.*

When switching from DIESEL FUEL to NATURAL GAS:

- There will be a significant reduction in PM emissions, on the order of 95 percent.[14] NOx, VOC, and CO emissions could increase or decrease depending on the engine control and after-treatment technologies applied. Lean-burn natural gas engines without exhaust after-treatment typically have lower NOx emissions than diesel engines, but stoichiometric natural gas engines have higher NOx emissions unless closed-loop fuel control systems and three-way exhaust catalysts are used. VOC and CO emissions from a natural gas engine will be roughly equivalent to those from a diesel engine unless an oxidation catalyst muffler is used.[15]
- There will be a reduction in CO_2 emissions, but an increase in methane emissions. CO_2 reductions will be less than those achieved by switching from gasoline, due to the lower efficiency of a natural gas engine compared to a diesel engine. Depending on how much methane is emitted, net GHG emissions could either increase or decrease. *To ensure a net reduction in GHG emissions, closed-loop fuel control systems and methane-optimized oxidation catalyst mufflers must be used.*
- As diesel engine technology has advanced, the incremental emissions benefits of switching to natural gas fuel have diminished. Diesel emissions regulations enacted by the US Environmental Protection Agency will ensure that after 2007, emissions levels of PM, NOx, VOC, and CO from new diesel engines equipped with after-treatment technologies will be virtually equivalent to those from new natural gas engines with after-treatment. The diesel technologies required to achieve these low emissions levels are very sensitive to fuel sulfur content, and are not effective if diesel fuel sulfur is greater than 15 parts per million. *If appropriate diesel fuel is available, the use of these advanced diesel technologies will provide equivalent emissions benefits as a switch to natural gas for new vehicles.*

Retrofit vs. New Engines/Vehicles

As noted above, dual-fuel retrofits of gasoline vehicles account for the vast majority of natural gas vehicles in the world . While simple and relatively inexpensive to implement, these dual-fuel retrofits seldom achieve any significant net reductions in exhaust emissions of harmful pollutants or GHGs—in fact, such retrofits may increase these

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[13] Gasoline engines emit negligible amounts of methane.

[14] Equivalent PM reduction is possible from a state-of-the-art diesel engine, but requires the use of a diesel particulate filter and fuel with less than 50 ppm sulfur.

[15] An oxidation catalyst applied to a diesel engine will also reduce VOC and CO emissions, but cannot be used if fuel sulfur level is above 500 ppm.

emissions. This is primarily due to the fact that the existing engine technology is usually old and very few, if any, changes are typically made to upgrade the engine or optimize it for operation with natural gas fuel.[16]

The flexibility to switch between fuels with a dual-fuel car, while convenient for the operator, also tends to undermine the goal of displacing imported petroleum, since gasoline can still be used. Petroleum fuels have significant market power and low prices for gasoline, even over short periods of time, can starve a natural gas vehicle implementation strategy.

Dual-fuel retrofits of existing diesel engines have similar problems. While these types of retrofits can achieve significant and reasonably consistent PM reductions, NOx, VOC, CO, and net GHG emissions are likely to increase.

In order to ensure consistent and significant emission reductions, as well as consistent petroleum displacement, new engines that are designed and optimized for use with natural gas, together with dedicated natural gas fuel systems, must be used.

Fuel Safety Trade-offs

Gasoline: highly flammable vapor; leaks can contaminate ground & groundwater; transportation tankers introduce some risk on roadways; contains cancer-causing compounds; infrastructure exists.

Diesel: leaks can contaminate ground & groundwater; transportation tankers introduce some risk on roadways; infrastructure exists.

Natural Gas: explosion hazard from leaks; high pressure system on-board vehicle; leaks dissipate into air – no ground water contamination, but a powerful GHG

Safety

Natural gas has been used in the transportation sector for over 50 years, with the majority of natural gas vehicles introduced over the last 30 years. Every fuel has its own safety concerns and requires care to be utilized safely. Gasoline vapor is highly flammable, yet gasoline is the most prevalent transportation fuel in the world. Over the past 100+ years, improvements to the gasoline infrastructure and to vehicle systems have significantly reduced the risks associated with gasoline.[17] Diesel fuel is not nearly as flammable as gasoline, but is associated with similar health and environmental hazards.

From a safety perspective, the most significant difference between natural gas and other transportation fuels is that diesel and gasoline are stored at the fueling station and on-board the vehicle as liquids at atmospheric pressure. CNG, on the other hand, is typically stored in gaseous form under high pressure: at 2,000 psi or more on light-duty vehicles and at 3,000 psi or more on heavy-duty vehicles. These elevated pressures can pose a significant hazard in the event of a valve or tank failure.

[16] By, for example, adding closed-loop fuel control or a 3-way exhaust catalyst.

[17] Liquid gasoline, however, can contaminate ground and groundwater, and has proven harmful health affects (contains cancer-causing compounds).

The main safety concern associated with natural gas is the risk of explosion, which can occur in the case of leakage or tank/valve failure. Because natural gas is lighter than air, gas leaking in the open air will quickly rise and dissipate in the atmosphere to the point that there is no longer a danger of fire or explosion.

The hazard is greatly increased in cases where gas leaks occur in a confined space. This could occur, for instance, when natural gas vehicles are stored or maintained inside a building. In this situation, a flammable mixture of leaked gas can accumulate at ceiling level and pose a significant explosion hazard. Large-scale use of natural gas as a transportation fuel will therefore likely require changes to building codes, both residential and commercial.

Most on-board vehicle storage tanks for natural gas are made of steel.[18] A properly designed natural gas tank and associated piping and valve systems will provide very robust protection against leaks and rupture. Proper integration with other vehicle systems is also important, as the tank and piping must be protected from the effects of vibration, as well as from damage caused by impact in the event of a crash. *Purpose-built natural gas vehicles are usually as safe, or safer, than gasoline and diesel vehicles. Retrofits can introduce more significant safety risks unless careful attention is paid to design and installation, especially where the retrofits involve multiple vendors.*

Potential hazards associated with storing and maintaining natural gas vehicles indoors can also be mitigated by good design.[19] Maintenance facilities, for example, should be designed with methane detection systems, adequate ventilation to remove leaked gas, and without ignition sources (open-flame heaters, electrical equipment) at or near ceiling level.

Summary Best Practices for the Use of Natural Gas as a Transportation Fuel

The following is a summary of important considerations for the design and implementation of programs to promote the deployment of natural gas as a vehicle fuel in ways that will ensure maximum and durable emissions reductions, as well as vehicle reliability.

- *Fuel quality must be controlled to allow for clean and durable vehicle operation.*
  - Vehicle applications, particularly where they involve low-emitting, state-of-the-art technologies, require a different standard for natural gas quality than other natural gas uses such as electric power generation, including greater minimum

[18] Other advanced lightweight materials are also available at a price premium, such as fiber-reinforced aluminum.

[19] The most significant risks associated with natural gas used as a transportation fuel are usually introduced during fueling operations. Good design, including the use of appropriate safety systems, can reduce these risks to levels at or below those associated with gasoline fueling.

methane content and tighter restrictions on the proportion of heavier hydrocarbons such as butane and propane. If existing gas quality is not adequate for vehicle use, gas utilities may need to implement tighter controls to reduce variability in the composition of delivered fuel.

- While natural gas has inherently low sulfur content, even small amounts of sulfur can deactivate the catalysts used in the after-treatment devices required to achieve very low levels of pollutant emissions from natural gas engines. If sulfur levels in the available natural gas supply are too high, additional processing by the gas distribution utility may be required.
- Other natural gas quality issues that are important for vehicle use include water content and compressor oil carryover. Both of these parameters can be controlled through the proper design of vehicle fueling stations and do not generally require action by the gas utility.

❖ *Purpose-built natural gas engines, using the best technologies (closed-loop fuel control systems and exhaust after-treatment) are necessary to assure consistently low emissions and maximize the benefits of any natural gas vehicle program.*

- Switching light-duty cars from gasoline to natural gas is not likely to achieve substantial reductions in harmful tailpipe emissions (PM, CO, VOCs, and NOx) and GHGs unless the new vehicles incorporate state-of-the-art natural gas engines with closed-loop fuel control and three-way exhaust catalyst mufflers.[20] Less sophisticated technologies, including most dual-fuel retrofits, do not achieve significantly lower emissions than in-service gasoline engines.
- Switching current technology heavy-duty trucks and buses from diesel fuel to natural gas can produce significant and durable reductions in PM emissions, but reductions of other harmful tailpipe pollutants and GHGs are not likely to be achieved without using state-of-the-art natural gas engines. While there are several different natural gas engine technologies available for use in heavy-duty vehicles, all of them require sophisticated closed-loop fuel control and oxidation catalyst mufflers to achieve emissions of CO, VOCs, and NOx that are significantly lower than those of in-service diesel engines.[20]

❖ *Retrofitting existing gasoline and diesel engines so that they can operate on natural gas—particularly in the case of "dual-fuel" retrofits where the vehicle retains the ability to operate on conventional fuel—seldom achieves the desired goals of reducing oil dependence, reducing in-use tailpipe emissions, and reducing GHG emissions.*

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[20] While the same or similar technologies could also be applied to new gasoline and diesel engines to give equivalently low emissions, they generally require fuel with low sulfur content to be effective. The inherently low sulfur content of natural gas could potentially allow "leap-frogging" to the latest engine emission standards without the need to upgrade petroleum refining infrastructure for additional sulfur reduction.

- Because retrofit engines usually are not optimized for use with natural gas and generally employ older engine technologies, natural gas retrofits often cause tailpipe and GHG emissions from the original vehicle to *increase*.
- Dual-fuel flexibility, while convenient for vehicle operators, can significantly diminish the extent to which a retrofitted vehicle is actually operated on natural gas, especially when differential fuel costs favor gasoline or diesel fuel. As a result, even short periods of low prices for petroleum fuels can starve a natural gas implementation strategy.

❖ *Vehicles and fueling stations must incorporate proper design, including the use of appropriate safety systems.*

- Properly designed and maintained natural gas vehicles and fueling stations are as safe, or safer, than existing gasoline vehicles and fueling stations. However, the use of natural gas does introduce safety issues that are not encountered with liquid fuels, including hazards associated with high-pressure fuel storage and handling systems as well as explosive hazards where there is the potential for gas to leak and accumulate in confined settings (such as inside maintenance buildings). Large-scale use of natural gas as a fuel by the transportation sector must be accompanied by appropriate codes and standards for vehicles and buildings. These standards must be actively enforced.

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