ENVIRONMENTAL ASSESSMENT OF PROPANE AS A MOTOR VEHICLE FUEL

Report[1] prepared by

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EXECUTIVE SUMMARY

This report deals with the environmental assessment of propane (LPG or liquefied petroleum gases) as a motor vehicle fuel. The use of propane is compared with gasoline and natural gas, another popular gaseous alternative fuel.

Both natural gas and propane were introduced in Canada and the United States (US) as indigenous alternative transportation fuels during the oil crisis of 1970s. During 1980s and 1990s, these fuels were preferred for their emissions performance and environmental merits, and were promoted as clean transportation fuels compared to gasoline. The alternative fuels got the support of federal and state governments both in Canada and the US in terms of special grants and tax rebates to promote their use. Currently the use of propane and natural gas is being supported under the Energy Policy Act in the US and the Alternative Fuels Act in Canada.

In spite of over two decades of successful experience, and numerous benefits offered by them, the current use of propane and natural gas still remains under 2% level compared to gasoline use. Based on the past history it can be concluded that alternative gaseous fuels would not be able to replace gasoline as mainstream transportation fuels in the near future, but these can play an important role in niche markets. These niche markets include dedicated fleet vehicles, which accumulate a lot of mileage over a short period of time, such as police cars, taxicabs, and other business fleets.

Compared to gasoline, both propane and natural gas offer lower emissions of carbon monoxide, toxic hydrocarbons and ozone precursors. On the life-cycle basis, they produce less greenhouse gas emissions than gasoline. In addition, these fuels also cost less than gasoline on energy equivalent basis.

When compared amongst them, propane and natural gas offer similar environmental benefits. Data based on the complete life-cycle evaluation suggest that as a clean transportation fuel, propane is better or as good as natural gas. On the operations side, propane offers greater benefits than natural gas. These include lower fuel price, lower conversion cost of gasoline engines, better fuel distribution infrastructure, longer range and comparable performance to gasoline.

Based on critical assessment of available environmental data, it can be concluded that as an alternative fuel, propane should be given the same privileges as natural gas by all levels of governments, administrators, and fleet operators.

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1. INTRODUCTION

Motor vehicles using internal combustion (IC) engines predominantly operate on gasoline and diesel fuel. The combustion of these fuels under ideal conditions should produce carbon dioxide (CO_2), water, and oxides of nitrogen (NOx). Carbon dioxide and water are the products of complete combustion from hydrocarbon fuels whereas oxides of nitrogen are formed by the combination of oxygen and nitrogen from the air at high temperatures encountered during the combustion process. However, in reality the combustion of fuels is never complete and thus significant quantities of carbon monoxide (CO), hydrocarbons (HC) and particulates are also produced in IC engines. Besides these tailpipe or exhaust emissions, there are HC emissions resulting from the evaporation of fuel, which are known as evaporative emissions. Many components of hydrocarbon emissions are toxic and carcinogenic. After the exhaust and evaporative emissions get into the ambient air, reactive species of HC react with NOx in the presence of sunlight to form ground level ozone or photochemical smog.

Thus motor vehicle emissions degrade air quality, contribute to the greenhouse effect, acid rain and tropospheric (ground level) ozone, and add toxic materials such as lead (from leaded gasoline), benzene, 1-3 butadiene, formaldehyde, acetaldehyde and particulates to the ambient air.

The solution to the problem, in simplistic terms, is to (a) produce less exhaust and (b) to produce less damaging exhaust. Smaller and fuel efficient vehicles generate less exhaust and alternative fuels such as compressed natural gas (CNG) and liquefied petroleum gas (LPG or propane), when compared to gasoline, can produce less damaging exhaust.

In Canada, the interest in gaseous alternative fuels (CNG and LPG) started in 1970s as a result of the Middle East oil crisis. The development of alternative, indigenous fuels was considered as a means to achieve energy security and diversity. As time progressed and people became more concerned with the harmful effects of motor vehicle emissions, the use of gaseous fuels was anticipated to provide ambient air quality benefits, especially reduction of greenhouse gases, toxic air pollutants, ozone precursors and carbon monoxide. More recently, the potential of these fuels for wealth generation through economic development, job creation and export opportunities has also been emphasized.

This document focuses on the environmental assessment of propane as a motor vehicle fuel. In most cases emissions performance of propane is compared with CNG and gasoline.

2 HISTORY OF GASEOUS FUELS IN CANADA

Canadian federal government support for gaseous fuels began in early 1980s and continues to the present time. The programs were designed to assist propane and natural gas industry to overcome early barriers in the marketplace and to establish these fuels as viable alternative transportation fuels (ATF) in Canada. Several provincial governments also instituted supporting initiatives to complement the federal programs. The success of these programs over the past two decades has primarily been due to the excellent cooperation between the federal government, provincial governments and industry.

The federal government support programs can be classified into three categories.

1. Fiscal measures.
2. Research and development support.
3. Use of gaseous fuels in the federal fleet.

2.1 Fiscal Measures

The first, and one of the strongest elements of federal government support to propane and natural gas, was the decision to exempt these fuels from the federal excise tax. The excise tax on gasoline is 10 cents per liter and on diesel fuel it is 4 cents per liter. The excise tax waiver has been in effect since the inception of the alternative fuels industry in Canada. Federal support was also provided in the form of financial grants for market development, field demonstrations, and public awareness and promotional activities.

Propane Vehicle Program (PVP), which began in 1980 as an initiative under the National Energy Program, provided grant of $400 to anyone converting a vehicle to operate on propane. The program targeted 90,000 propane conversions over the 5-year period ending in March 31, 1985. While the program fell somewhat short of its original target, it was considered a success with more than 71,000 vehicles converted to propane by the scheduled program termination date. The PVP is credited for establishing propane as a viable alternative fuel in Canada. Currently there are an estimated 103,000 vehicles operating on propane from coast to coast, supported by over 3,000 fueling stations across Canada[1].

In 1983 in response to industry solicitation, federal government launched the Natural Gas Vehicle Program (NGVP) and Natural Gas Fuelling Station Program (NGFSP). The NGVP provided a grant of $500 for the conversion of a vehicle to natural gas operation. The higher grant was given to natural gas recognizing the fact that the cost of conversion to CNG is higher than conversion to propane. Another difference between natural gas and propane related to the fuelling of the vehicles. The propane industry was in a position to react quickly to establish a refueling infrastructure due to its modest cost, on the other hand natural gas industry could not do the same thing because the cost of CNG refueling station was five to ten times higher than that of a propane station. Therefore, the NGFSP provided a grant of $50,000 towards the capital cost of each CNG public refueling station. A typical CNG fuelling station costs in excess of $300,000.

Growth in numbers of natural gas vehicles (NGV) was considerably slower than for propane, and by the middle of 1980s when the National Energy Program funding was terminated, only a few thousand NGV were on the road in Canada. Thus it was clear that the industry had still not reached a sustainable level. The federal government decided to continue the natural gas grant under the Market Development Incentives Program (MDIP) to allow more time for the industry to develop.

** Number shown in the superscript refers to the reference given at the end of this report.*

A number of modifications were made to the natural gas grant program in an attempt to further stimulate the NGV market. These included extending the refueling station grant to private stations, a grant of $1,000 (later reduced to $500) for the installation of a natural gas vehicle refueling appliance (VRA) for home or commercial applications, and an augmented grant of $1,000 for the purchase of a factory produced or Original Equipment Manufacturer (OEM) authorized natural gas vehicle. Presently there are about 20,000 natural gas vehicles in Canada, most of them operating in British Columbia, Alberta, Ontario and Quebec. About 135 public and 75 private refueling stations, and approximately 1,000 vehicle refueling appliances serve this fleet.

Many provinces also followed the lead of the federal government in providing tax relief for gaseous fuels. For example, in the province of British Columbia (B.C.) the incentives for these fuels included conversion grants of $200 to $700 per vehicle (now discontinued), a sales tax exemption on conversion equipment, and an exemption from the B.C. motor fuel tax. In the province of Ontario, gasoline is subjected to a provincial tax of 14.7 cents per liter. However, natural gas is exempt from this tax while propane is taxed at 4.3 cents per liter. Ontario also refunds a portion of the 8% retail sales tax on new vehicles, which operate on natural gas or propane, including vehicles those are converted within 180 days of their purchase. The rebate is up to $750 for a propane vehicle, and up to $1,000 for natural gas vehicle.

In addition to tax incentives and grants, the federal government has conducted a variety of market development and demonstration initiatives for propane and natural gas. These have included demonstrations of new market-ready vehicles and equipment technologies on school and transit buses, OEM and after market light-duty vehicles, advanced on-board fuel tanks and new natural gas fuelling compressors.

2.2 Research and Development Support

Research and development (R&D) support has been an integral part of the federal government's policy on alternative fuels. The funding for R&D support has come from various programs that include Panel on Energy Research and Development (PERD), Green Plan, Enerdemo, and Market Development Incentives Program (MDIP). Early in the R&D cycle, when the risks are greatest, federal support is highest and the government plays the leadership role. As the technologies mature and approach commercialization, the industry assumes the leadership and takes more of the financial burden.

In the case of propane, R&D support was provided to OEMs (primarily Chrysler) to market OEM vehicles and propane ready engines, including Chrysler's liquid fuel injection van. Federal R&D has also contributed to the development of a generic electronic engine control system, and stop-fill valves for propane tanks.

In the area of natural gas, the government has supported R&D through the Canadian Gas Association (CGA) research initiatives, as well as directly with industry and private laboratories. Example of successful projects include:

- An electronic gaseous fuel injection system (GFI) for use in the conversion of vehicles to natural gas,

- A refueling probe that permits self-service of natural gas at public refueling stations, and
- Light weight NGV fuel tanks.

Support for heavy-duty natural gas powered engines, and subsequent demonstrations of these technologies in urban transit buses, has resulted in over 200 natural gas buses in operation in several Canadian cities, and sales of natural gas buses to many transit authorities in the US.

2.3 Use of ATF in the Federal Fleet

The federal government has been promoting the conversion of its own fleet to alternative transportation fuels (ATF) since the early 1980s, by offering appropriate financial support to departments with suitable vehicles. About 5,000 vehicles were converted to propane and natural gas under this program. During the development of "Green Plan" in the early 1990s, it was planned that 10% of federal fleet vehicles be capable of operating on alternative fuels by the year 1997.

The government's commitment to the use of ATF became even stronger in June 1995 with the passage of Bill S-7 (Alternative Fuels Act), which provided aggressive legislative targets for the adoption of ATF vehicles by all federal government departments and agencies.

After the Kyoto Protocol, the government of Canada initiated a comprehensive program called "FleetWise" that was aimed to decrease the environmental impact of the federal fleet while increasing its operational efficiency. Managed by Natural Resources Canada (NRCan) and steered by an interdepartmental committee that included NRCan, Treasury Board, Environment Canada, and Public Works and Government Services Canada, FleetWise was an example of the government of Canada's efforts to protect the environment. It also met a variety of objectives that were set out in the *Alternative Fuels Act*, which requires that the federal vehicles use alternative fuels where cost effective and operationally feasible; Bill C-83, *An Act to Amend the Auditor General Act*, which formalized the government's commitment to sustainable development; and the *Treasury Board Motor Vehicle Policy*.

3 ALTERNATIVE FUELS ACT

The Alternative Fuels Act (AFA) received Royal Assent on June 22, 1995, and took effect on April 1, 1997. The purpose of the Act is to accelerate the use in Canada of alternative transportation fuels (ATF) in motor vehicles in order to reduce the emissions of carbon dioxide and other greenhouse gases, and to reduce dependence on petroleum based fuels for transportation. The Act targets the federal vehicle fleet and helps make the government a leader in the use of ATF.

Under this Act[2], federal government departments and agencies must purchase alternative fuel vehicles, where they are cost-effective and operationally feasible, according to the following schedule:

- 50% of all vehicle purchases in 1997-98,
- 60% of all vehicle purchases in 1998-99,
- 75% of all vehicle purchases in 1999-2000, and every year thereafter,
- By the year 2004, 75% of the entire federal fleet is to operate on alternative fuels, where cost-effective and operationally feasible.

Under this Act, alternative fuels include ethanol, methanol, propane, natural gas, hydrogen, and electricity. The term motor vehicle fleet includes automobiles, passenger vans, buses, light duty trucks, and medium duty trucks. The Act cites that the above-mentioned alternative fuels are less damaging to the environment than conventional fuels. Therefore, if gasoline vehicles converted to propane or natural gas meet the applicable emission standards, they qualify under this Act for the federal fleet use.

Specifically, the Act requires that departments and agencies review each new vehicle acquisition in terms of its estimated annual fuel consumption and primary operational tasks, and determine whether using ATF would be both cost-effective and operationally feasible. This has been interpreted to mean that, if a new vehicle is less expensive to operate on ATF than on a conventional fuel, and the vehicle can fulfill its operational duties, then it is included in the group of new acquisitions that are capable of operating on ATF.

The fourth annual report on the application of the AFA[3], pertinent to fiscal year 2000-01, concludes that the availability of ATF vehicles and associated ATF infrastructure has not yet materialized to the extent first envisaged when the AFA was passed in June 1995. The federal government has encountered many obstacles that place practical limitations on the use of alternative fuels and ATF vehicles. In time, as these obstacles are overcome, there will be greater opportunity to acquire more ATF vehicles for federal fleet and make greater use of alternative fuels across the federal government.

Many government departments seem reluctant to use aftermarket conversions from gasoline to propane or natural gas, based on the past history of lack of reliability and poorer performance of converted vehicles. If a robust and environmentally viable propane conversion system is offered in the marketplace supported by propane availability at a reasonable cost, such departments and agencies can be persuaded about the merits of converting their gasoline vehicles to propane.

4 US LEGISLATION SUPPORTING THE USE OF GASEOUS FUELS

In the United States, the Energy Policy Act (EPAct) was passed in 1992 to accelerate the use of alternative fuels in the transportation sector. The US Department of Energy’s (DOE) primary goals are to decrease the nation’s dependence on foreign oil and increase energy security through the use of domestically produced alternative fuels. DOE's mission is to replace 10% of petroleum based motor fuels by the year 2000, and 30% by 2010.

The Act defines alternative fuel as natural gas, LPG (propane), alcohol fuels (methanol, ethanol and higher alcohols), hydrogen, fuels derived from biomass, liquid fuels derived from coal, and electricity.

Federal, state and alternate fuel provider fleets are currently mandated by EPAct. Fleets that own, operate, lease or control at least 50 light-duty vehicles (gross vehicle weight of 8,500 lbs. or less) in the US are covered. Of the fleet vehicles, 20 or more must be operating with in any affected area with a population of 250,000 or more (1980 US census). The vehicles must also be centrally fuelled or capable of being centrally fuelled. A fleet must meet all three requirements to be covered by EPAct.

Private sector companies that make alternative fuels, such as natural gas and propane companies, electric utilities, are required to introduce alternative fuel vehicles into their fleets as follows:
30% in model-year 1997
50% in model-year 1998
70% in model-year 1999
90% in model-year 2000 and thereafter

The minimum federal fleet requirements for light-duty alternative fuel vehicles are as follows:
5,000 in fiscal year (FY) 1993
7,500 in FY 1994
10,000 in FY 1995
25% in FY 1996
33% in FY 1997
50% in FY 1998
75% in FY 1999 and thereafter

Purchase of light-duty vehicles by state governments are required to be alternative fuel vehicles based on the following schedule:
10% in model-year 1997
15% in model-year 1998
25% in model-year 1999
50% in model-year 2000
75% in model-year 2001 and thereafter

In December 1996, it was recognized that the goals of the Energy Policy Act would not be met by voluntary commitments. Therefore, the provisions of the Act were extended to municipal and private fleet owners, and law enforcement vehicles.

Beginning June 30, 1993, the federal government provided financial incentives for purchasing alternative fuel vehicles, allowing a tax deduction (immediate depreciation) of up to $2,000 for light-duty vehicles, in the year the vehicle was purchased. For medium-duty trucks and vans, and heavy-duty trucks and buses the tax deductions were higher. In addition to the federal government, many state governments also provided incentives and mandates for using alternative fuel vehicles. For the US, the current statistics[4] on the vehicles using propane, natural gas, and all alternative fuels combined are shown in Table 1. The estimated consumption of gaseous alternative fuels and conventional fuels are given in Table 2. The data indicate that the use of propane on energy equivalent basis is only about 0.2% of gasoline use.

TABLE 1. Alternative Fuel Vehicle Population in the US

	1999	**2000**	**2001(Estimate)**
Propane	267,000	268,000	269,000
Natural Gas	89,556	100,530	109,730
Total AFV	406,841	432,344	456,306

TABLE 2. Estimated Consumption of Vehicle Fuels in the US
(Thousands of gasoline-equivalent gallons)

	1999	**2000**	**2001**
Propane	242,141	242,695	243,196
Natural Gas	86,286	97,568	107,476
Gasoline	125,111,000	124,651,000	126,284,000
Diesel	35,796,800	36,779,340	37,581,010
Total	161,247,140	161,784,100	164,231,341

5 MOTOR VEHICLE EMISSIONS AND GASEOUS FUELS

In Canada and the US, the motor vehicle emission standards for light-duty vehicles regulate the emissions of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx) and particulates (only for diesel vehicles) on gram per mile basis. This effectively de-couples the amount of CO, HC and NOx emissions from a vehicle from the amount of fuel it consumes. The CO_2 emissions, on the other hand, directly depend on the fuel consumption. Therefore, CO_2 emissions can be reduced by increasing the vehicle fuel efficiency or by using less carbon rich fuels such as natural gas and propane.

Some of the reactive hydrocarbons participate in complex reactions with NOx in the presence of sunlight to form ground level ozone or photochemical smog. The US Environmental Protection Agency (EPA) has also identified five most important air toxic components that are present in motor vehicle exhaust. These include, benzene, 1,3 butadiene, formaldehyde, acetaldehyde, and polycyclic organic matter (POM).

5.1 Carbon Monoxide

Carbon monoxide is a colorless, odorless gas produced by incomplete combustion of carbonaceous fuels. When CO enters the human blood stream it reduces the delivery of oxygen to the organs and tissues of the body, especially to the brain. At low concentrations CO can cause discomfort for people with heart or lung disease. One of the first symptoms of CO poisoning is blurred vision and clumsiness. At high concentrations, CO can cause fainting that may even result in death.

CO most strongly affects the people exposed to exhaust emissions in confined areas and those who stay in polluted air for a long period of time, such as parking garage attendants, traffic control officers, and tunnel users. However, elevated CO levels can also occur over large metropolitan areas and affect the general population. The CO emissions from gasoline, and alcohol fuel vehicles increase substantially with decreasing ambient temperature. Thus CO emissions from gasoline vehicles in Canada during winter months are much higher than in summer.

5.2 Hydrocarbons

Bulk of the hydrocarbon emissions from gasoline-powered vehicles come under the category of volatile organic compounds (VOCs). One of the major concerns with VOCs is their contribution to ozone formation. Many hydrocarbons, especially aromatic compounds, are also carcinogenic in nature. As mentioned earlier, the US EPA has identified five components belonging to vehicle HC emissions as toxics.

5.3 Oxides of Nitrogen

Oxides of nitrogen are toxic, irritating gases that are emitted by all combustion processes. When combined with water they form acid rain. They also participate in the formation of ozone and acid aerosols. NOx can cause lung irritation and lower resistance to respiratory infection. It can also damage materials and vegetation.

5.4 Particulates

Particulate emissions from diesel vehicles have long been associated with cancer and respiratory diseases. More recently the particulates from gasoline vehicles, which are significantly lower than from diesel vehicles on gram per mile basis, have also received a lot of attention for its potential adverse health risks. As noted earlier, the particulate emissions from gasoline vehicles are not regulated at the present time.

A large portion of total particulate emissions from motor vehicles consists of fine particles, which are 2.0 micrometer or smaller in diameter. Many studies have shown that there is a better correlation between fine particles and morbidity than between total particulate matter and morbidity. The research is continuing to better understand the effect of particle size on human health.

5.5 Gaseous Alternative Fuels

Both natural gas and propane have a much simpler molecular structure than gasoline and diesel fuel, which are mixtures of numerous hydrocarbon species. Thus the products of incomplete combustion from gaseous fuels contain fewer reactive hydrocarbons (precursors to ground level ozone) and less quantity of toxic hydrocarbons. The gaseous fuels also use a completely sealed fuel system; therefore they do not produce any evaporative emissions. Gaseous fuels also produce extremely low particulate emissions compared to gasoline. Since these fuels are already in the gaseous state, they mix well with the combustion air and do not require any fuel enrichment during cold start, resulting in lower CO and HC emissions during this critical phase of engine operation.

Natural gas and propane both have higher octane numbers than gasoline; therefore dedicated engines can be designed for higher compression ratios, leading to higher fuel efficiencies compared to their gasoline counterparts.

The volumetric energy content of gaseous fuels is much lower than gasoline. Therefore with the same volume of fuel tank, compared to gasoline, CNG vehicle would have a range of only 25% while a propane vehicle would provide a range of about 74%.

The OEM production of gaseous fuel vehicles is rather limited, thus the majority of natural gas and propane vehicles now on the roads in Canada and the US are after-market conversions of gasoline engines. Converted vehicles can operate on gaseous fuel alone (dedicated or mono-fuel) or on gaseous fuel as well as on gasoline (dual-fuel). The emissions performances of the converted vehicles greatly depend on the quality of conversion. It should also be recognized that during the last decade the emissions performance and durability of gasoline vehicles have significantly improved and these vehicles have become progressively less polluting, therefore gaseous fuel conversions have to compete and match with the technical advances of gasoline vehicles.

Results from B.C.'s vehicle emissions inspection and maintenance program (AirCare) revealed a much higher failure rate for propane and natural gas vehicles than gasoline vehicles[5]. The main reason for these failures was poor quality conversions using inadequately matched components. The recent R&D investments in conversion technologies, and initiatives to enforce conversion standards, are helping to mitigate these problems.

Trevor Jones[6] has done a good comparative analysis of alternative fuels. His paper concludes that based on emissions and environmental considerations gaseous fuels are superior to liquid fuels. While comparing propane with natural gas, the following points were made:

- Natural gas has a slight edge over propane in reducing the localized pollution; lower emissions of toxic HC and ozone precursors, comparable CO and NOx emissions.
- Natural gas and propane have comparable CO_2 –equivalent emissions.
- Natural gas has considerable disadvantages for general passenger car use. It has poor range, low availability at the stations, high conversion cost, a decrease in power and, when the expense of commercial filling stations is factored in, it is almost twice as expansive as propane.

- Natural gas tanks are much heavier and more expansive than propane tanks. CNG is typically stored at 3000 psi versus propane at 200 psi.
- Propane filling still requires a certificate unlike natural gas, which can be easily refueled from a self-serve station.
- There is a perception, especially in the US, that propane supply is not enough to satisfy any large-scale vehicle fuel demand. In reality it is not true. Propane is a by-product of natural gas processing and refinery operation, so its production is related to the production of natural gas. At the present time surplus propane can easily fuel about 10% of gasoline vehicle fleet in Canada.
- Propane is available anywhere in Canada and almost anywhere in the US. Many people use propane for cooking and heating in rural areas, and are quite familiar with it.

TABLE 3. Some Features of CNG and LPG

	CNG	**LPG**
Chemical Structure	CH_4	C_3H_8
Primary Component	Methane	Propane
Main Source	Under ground reserves	A by-product of natural gas processing or petroleum refining
Energy Content per Gallon	29,000 Btu	84,000 Btu
Energy Ratio Compared to Gasoline	3.94 to 1 or 25% at 3000 psi	1.36 to 1 or 74%
Physical State	Odorless gas lighter than air. In case of leak will rise to the ceiling	Volatile liquid. Vapor when released from the cylinder, heavier than air. In case of leak will pool up on ground
Average Price Compared to Gasoline	Less	Less

Note: Data taken from Reference 4.

6 COMPARISON OF VEHICLE EMISSIONS

Comparing vehicle emissions for different transportation fuels is always a challenging task. It is almost impossible to use the same type of engines and vehicles for each fuel. In addition, some of the alternative fuel vehicles are not optimized for the new fuel or may use after-market conversions. Hence their emissions performance may not be optimum as compared to gasoline vehicles. The data shown in this report have been taken from major studies comparing the vehicle emissions for various alternative fuels with gasoline.

The hydrocarbon emissions from alternative fuels vary both in quality and quantity compared to those from gasoline engines. The reactivity or ozone forming potential of alternative fuels, relative to conventional fuels, is calculated using smog chamber experiments, emissions testing, and photochemical modeling. Often, similar chemical species are lumped together in order to simplify the calculations. The reactivity of each group of species is then used to estimate emission inventories for use in more extensive photochemical modeling or to compare the measured vehicle emissions of alternative fuels to those from conventional fuels. Table 4 shows the relative reactivity of various fuels based on measurements made at the California Air Resources Board (CARB)[7].

TABLE 4. Relative Reactivity of Emissions from Gaseous Alternative Fuels and Gasoline

Fuel Type	Reactivity/gram (exhaust + evaporative NMVOC)
Gasoline (Indolene)	1.0
Natural Gas	0.44
Propane	0.83

NMVOC = Non-methane volatile organic compounds

The study sponsored by the Gas Research Institute[8] in the United States compared the full fuel cycle emissions of alternative fuels for light duty vehicles. The alternative fuels considered were natural gas, LPG, E85, M85, and electricity. The tailpipe emissions from vehicles projected for the year 2000 are shown in Table 5. Before making any comparisons, it should be noted that natural gas vehicle emissions used in the study were based on emissions from a California certification test, while the other vehicle emissions were based on more lenient US Tier 1 standards. The numbers for natural gas shown in parentheses are the emission rates that would occur if the natural gas vehicle used the same emission standards as the others.

It should be further noted that the emissions figures given in Table 5 are based on emission standards rather than actual emissions from in-use vehicles. They are also based on an over simplified assumption that all vehicles, irrespective of fuel type, just meet the emission standards. In reality gaseous fuels (natural gas and LPG) would produce lower CO and reactive organic gas (ROG) emissions.

TABLE 5. Vehicle Exhaust and Evaporative Emissions (grams/mile) Year 2000

Fuel Type	ROG (Reactive Organic Gas)	CO	NOx
Gasoline	0.444	3.4	0.4
Natural Gas	0.021 (0.25)	0.4 (3.4)	0.04 (0.4)
Propane	0.25	3.4	0.4

In 1996, Canadian Energy Research Institute (CERI) conducted a study on Alternative Transportation Fuels in Canada[9]. This study summarized the current status of alternative fuels in Canada and their opportunity for further market development. The technical and economic suitability of natural gas, propane, methanol, ethanol, and electricity relative to gasoline and diesel fuel were addressed. A detailed analysis of the full fuel cycle emissions attributable to each fuel was also provided. Table 6 shows the comparison of only vehicle tailpipe emissions for gasoline, natural gas and propane from CERI study.

TABLE 6. Comparison of Light-Duty Vehicle Emissions for Various Fuels (grams/km)

Pollutant	Gasoline	Natural Gas	Propane
CO_2	256.891	186.948	223.246
N_2O	0.002	0.005	0.012
CH_4	0.032	0.228	0.020
CO	3.094	1.375	0.239
NOx	0.182	0.515	1.219
VOCs	0.523	0.341	0.454
CO_2 Equivalent	258.134	193.336	227.454
Ozone	1.056	0.795	1.098

Note: *The global warming potential used to calculate emissions on a CO_2-equivalent basis are 21 for CH_4 and 310 for N_2O. Ozone pollutants are calculated as the sum of the emissions for CO (divided by 7), NOx (divided by 2) and VOCs. CO is divided by 7 and NOx by 2 because they are estimated to contribute seven and two times less, respectively, to ozone formation than VOCs.*

7 COMPARISON OF LIFE CYCLE EMISSIONS

Controlling only vehicle emissions without any consideration for upstream emissions may result in providing a wrong assessment of an alternative fuel. Life cycle emissions, which account for the total emissions for the entire life cycle of a fuel, include emissions during the production of a fuel, emissions during transporting and delivering the fuel to the market, and the emissions during its use in the vehicle. Life cycle emissions are of increasing significance as vehicle tailpipe emissions achieve lower and lower values.

There are many studies done on the life cycle emissions of various alternative fuels. The results from various life cycle studies can vary a great deal depending on the assumptions made for estimating the emissions. In this report, the data from two studies that are most relevant from the North American (Canada and the United States) perspective have been quoted. The first one is the “Light duty vehicle full fuel cycle emissions analysis” reported by the Gas Research Institute (GRI), Chicago, USA[8]. The second study[9], which is even more relevant for Canada, entitled, “Alternative transportation fuels in Canada: Prospects and policies” was conducted by the Canadian Energy Research Institute (CERI) in 1996. Again, it should be emphasized that the results from these two studies are quite different from each other, primarily due to the differences in fuel production practices in the two countries. For a better understanding of underlying assumptions and detailed calculations, readers are advised to look at references 8 and 9.

The GRI study compared the life cycle emissions for gasoline, reformulated gasoline, natural gas, LPG, E85, M85, and electricity for the years 1990 and 2000. In addition, the generation of electricity was based on two different power mixes, one for the United States as a whole and the other for the state of California. The use of different power mixes is significant for the use of electric vehicles, because while the US power mix is made up of 50 to 55% coal-fired power plants, the state of California power mix has no coal-fired plants. The results of the study for gasoline, propane and natural gas are shown in Tables 7 and 8. Before making any comparisons, it is important to note that the natural gas vehicle emissions used in the study are based on emissions from a California certification test, while the other vehicle emissions are based on more lenient US Tier 1 standards. The numbers for natural gas shown in parentheses are the emission rates that would occur if the natural gas vehicle used the same emission standards as others.

TABLE 7. Life Cycle Emissions Summary (grams/mile) - US Case

Fuel Type	ROG	CO	NOx	SOx	PM_{10}
Year 1990					
Gasoline	0.698	3.480	0.626	0.044	0.013
Propane	0.370	3.499	0.766	0.008	0.006
Natural Gas	0.116 (0.345)	0.461 (3.461)	0.537 (0.897)	0.299	0.006
Year 2000					
Gasoline	0.643	3.462	0.544	0.032	0.011
Propane	0.347	3.486	0.616	0.006	0.005
Natural Gas	0.104 (0.333)	0.462 (3.462)	0.290 (0.650)	0.076	0.005

TABLE 8. Life Cycle Emissions Summary (grams/mile) - California Case

Fuel Type	ROG	CO	NOx	SOx	PM_{10}
Year 1990					
Gasoline	0.698	3.480	0.626	0.044	0.013
Propane	0.330	3.462	0.547	0.008	0.005
Natural Gas	0.117 (0.346)	0.420 (3.420)	0.093 (0.453)	0.004	0.002
Year 2000					
Gasoline	0.468	3.462	0.344	0.032	0.011
Propane	0.138	3.451	0.314	0.006	0.004
Natural Gas	0.100 (0.144)	0.411 (3.411)	0.053 (0.213)	0.001	0.001

Abbreviations: ROG = reactive organic gas, SOx = sulphur oxides, PM_{10} = particulate matter less than 10 micrometers in diameter.

The CERI study[9] computed the life cycle emissions for alternative fuels by estimating and incorporating upstream emissions (associated with the production and transportation of primary energy feed-stocks); downstream emissions (associated with the production of fuel and transportation of fuel to the consumer); and vehicle emissions (associated with the use of fuel in the vehicle). The CERI data for life cycle emissions in the case of light duty vehicles using gasoline, propane and natural gas are given in Table 9.

TABLE 9. Comparison of Life Cycle Emissions (light-duty vehicles) (grams/km)

Pollutants	Gasoline	Natural Gas	Propane
CO_2	291.040	221.554	256.930
N_2O	0.002	0.007	0.013
CH_4	0.676	1.110	0.625
CO	3.130	1.633	0.457
NOx	0.270	0.717	1.373
VOCs	1.607	0.690	0.862
SO_2	0.189	0.252	0.268
CO_2 Equivalent	305.952	247.062	274.255
Ozone	2.189	1.282	1.613

Note: *The global warming potential used to calculate emissions on a CO_2-equivalent basis are 21 for CH_4 and 310 for N_2O. Ozone pollutants are calculated as the sum of the emissions for CO (divided by 7), NOx (divided by 2) and VOCs. CO is divided by 7 and NOx by 2 because they are estimated to contribute seven and two times less, respectively, to ozone formation than VOCs.*

In order to fully evaluate energy and emission impacts of vehicle technologies, the fuel cycle from wells to wheels and the vehicle cycle through material recovery and vehicle disposal need to be considered. Sponsored by the U.S. Department of Energy's Office of Transportation Technologies, Argonne National Laboratory has developed a fuel-cycle model called GREET[10] (Greenhouse gases, Regulated Emissions, and Energy use in Transportation). It allows researchers to evaluate various engine and fuel combinations on a consistent fuel-cycle basis.

GREET was developed as a multidimensional spreadsheet model in Microsoft Excel. This public domain model is available free of charge for anyone to use. The first version of GREET was released in 1996. Since then, Argonne has continued to update and expand the model. GREET 1.5a was released in January 2000. The model can be downloaded from the US Department of Energy website (www.afdc.doe.gov).

For a given engine and fuel system, GREET separately calculates the following:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal), and petroleum
- Emissions of CO_2-equivalent greenhouse gases - primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)
- Emissions of five criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NOx), particulate matter with size smaller than 10 micron (PM_{10}), and sulfur oxides (SOx).

Based on the results from GREET model, Table 10 shows the fuel-cycle energy and emissions changes of near-term technologies using dedicated CNG and LPG vehicles relative to baseline gasoline vehicles fueled with conventional unleaded gasoline. The numbers clearly indicate that LPG (propane) and CNG vehicles offer significant energy and emissions benefits compared to gasoline vehicles. Furthermore, in most cases, LPG vehicles provide greater energy and emissions benefits than CNG vehicles.

TABLE 10. Fuel-Cycle Energy and Emission Changes (GREET MODEL)
(Relative to Baseline Gasoline Vehicles Fueled with Conventional Gasoline)

	Percent Change Compared to Gasoline Vehicles	
	Dedicated CNG Vehicles	**Dedicated LPG Vehicles**
Total energy	+1.1%	-11.3%
Fossil fuels	-0.5%	-11.3%
Petroleum	-99.4%	-98.2%
VOC: Total	-70.5%	-62.5%
VOC: Urban	-74.1%	-58.7%
CO: Total	-34.8%	-39.6%
CO: Urban	-35.5%	-39.7%
NOx: Total	+26.6%	-17.2%
NOx: Urban	+22.4%	-4.8%
PM10: Total	-36.0%	-42.5%
PM10: Urban	-32.0%	-31.4%
SOx: Total	-33.6%	-87.4%
SOx: Urban	-96.2%	-98.1%
CH_4	+201.1%	+2.5%
N_2O	-23.7%	-1.2%
CO_2	-16.1%	-13.4%
GHGs	-10.2%	-12.7%

Note: Negative sign indicates a decrease compared to gasoline vehicles; positive sign shows an increase.

8 PROPANE AS A MOTOR VEHICLE FUEL

One of the most important potential markets for propane is in the transportation sector, which currently accounts for about 27% of the domestic propane demand. Propane can be used instead of gasoline in modified vehicles, especially in the niche markets[10]. Unfortunately, the auto-propane consumption in Canada has declined at an annual compound rate of 7.2% from 1990 to 1999. As a result propane use for road transportation has decreased from 36% of domestic propane share in 1990 to 26% in 1999. The decrease in auto-propane sale is a direct result of the declining number of propane conversions below the fleet replacement levels. The total number of propane vehicles has dropped from 150,000 in 1996 to an estimated 103,000 in 2001[1]. Currently propane-fueled vehicles use about 3.1 million L/day of propane, representing less than 2% of the total transportation fuels used in the country. The declining trends in auto propane use can be reversed if compatible and reliable conversion technology is used and propane availability is guaranteed at a reasonable price. The current surplus of propane production in Canada can easily replace 10% of gasoline consumption in the country.

There are more than 3000 auto propane fuelling outlets in Canada, which are located in major communities. In most parts of Canada, propane continues to be less expensive than gasoline on an energy equivalent basis. With the average conversion cost in the range of $3,000 to $5,000, depending upon the type of platform and conversion technology used, high usage propane vehicles can achieve a payback of conversion cost in a reasonable period of time.

Propane as a motor vehicle fuel offers many advantages. Based on emissions and environmental considerations it is superior to gasoline. When compared to natural gas, if not better, is it as good a gaseous alternative fuel. The following list summarizes the important features of auto-propane.

- Superior exhaust emission levels in many vehicles when compared to gasoline vehicle emission standards. Compatible with gasoline engines without a significant difference in power and performance.
- Evaporative emissions (VOC) are nil as the vehicle fuel system is sealed. No running or standing fuel loss from the vehicles.
- Small amounts of propane that escape to atmosphere at refueling points are 50% less reactive than gasoline vapors (lower ozone forming tendency).
- Extremely low sulfur content (does not contribute to acid rain).
- It is non-toxic.
- High Hydrogen to Carbon ratio (C_3H_8) produces less CO_2 on combustion.
- Cold-start emissions for propane are similar to warm engine operation, unlike gasoline engines, which have high cold-start emissions.
- In Canada, auto-propane has only one grade designated as HD-5.
- Octane number is 100 compared to 91 for premium gasoline.
- Simple hydrocarbon structure, low reactivity, consistent quality across Canada.
- Engine parts last much longer. Engine life itself is generally prolonged and exhaust system wears out much slower than for gasoline[11].

- The California South Coast Air Quality Management District has classified propane as a clean fuel.

Propane conversion makes a lot of sense for high usage fleet vehicles, such as RCMP fleet, provincial police vehicles, taxicabs, etc. The performance of propane vehicles would be comparable to gasoline, with the fuel cost savings resulting in rapid recovery of the conversion cost.

However, it should be recognized that the environmental performance of gasoline vehicles continues to improve for regulated emissions of CO, HC, and NOx. This is being demonstrated with the certification of growing number of vehicles for low emission (LEV) and ultra low emission (ULEV) California standards. Gasoline and diesel are not only getting cleaner, but vehicles are now being fitted with sophisticated on-board diagnostic systems to ensure that they continue to operate at optimal emission levels. While gaseous alternative fuels offer excellent environmental performance, it would be imprudent to assume that these fuels will continue to deliver substantial environmental benefits over gasoline indefinitely in the future, unless the conversion technologies also continuously improve and match with modern engines.

9 CONCLUSIONS

- Compared to gasoline, both propane and natural gas offer lower emissions of carbon monoxide, toxic hydrocarbons and ozone precursors. On the life-cycle basis, they also produce less greenhouse gas emissions than gasoline.
- Based on environmental considerations alone, propane is as good as, if not better than natural gas (CNG).
- On an overall basis when considering all aspects, i.e. emissions, vehicle performance, fuelling infrastructure and cost, propane is better than CNG.
- As a clean fuel, propane should be given similar privileges as CNG by all levels of governments, administrators, and fleet operators.
- Propane offers significant economic as well as environmental benefits over gasoline in niche markets, such as police cars, taxicabs, and other high usage fleet vehicles.
- Propane conversion technology has to compete and match with new generation of gasoline vehicles, which are rapidly improving their emissions performance by introducing cleaner vehicles such as LEV and ULEV.
- Governments at all levels should continue their support for the use of gaseous alternative fuels (propane and natural gas), since they are still the best options to provide energy security and environmental benefits compared to gasoline.

NOMENCLATURE

AFA	Alternative Fuels Act (Canada)
ATF	Alternative Transportation Fuels
B.C.	British Columbia
CARB	California Air Resources Board
CERI	Canadian Energy Research Institute
CGA	Canadian Gas Association
CH_4	Methane
C_3H_8	Propane
C_4H_{10}	Butane
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DOE	Department of Energy (USA)
E85	85% Ethanol and 15% Gasoline by Volume
EPA	Environmental Protection Agency
EPAct	Energy Policy Act (USA)
FTP	Federal Test Procedure
GFI	Gaseous Fuel Injection
GHG	Greenhouse Gas Emissions
GRI	Gas Research Institute
HC	Hydrocarbon
IC	Internal Combustion
L/day	Liters per day
LEV	Low Emission Vehicle
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas (Propane)
MDIP	Market Development Incentives Program
NGFSP	Natural Gas Fuelling Station Program
NGV	Natural Gas Vehicle
NGVP	Natural Gas Vehicle Program
N_2O	Nitrous Oxide
NOx	Oxides of nitrogen
NRCan	Natural Resources Canada
O_3	Ozone
OEM	Original Equipment Manufacturer
PERD	Panel of Energy Research and Development
PM	Particulate Matter
POM	Polycyclic Organic matter
PVP	Propane Vehicle Program
R & D	Research and Development
SO_2	Sulfur dioxide
SOx	Sulfur oxides
ULEV	Ultra Low Emission Vehicle
US	United States
VOC	Volatile Organic Compounds
VRA	Vehicle Refueling Appliance

REFERENCES

1. Canadian Propane Industry Statistical Review 2000, Propane Gas Association of Canada, Calgary, Alberta, September 2000.
2. Website, www.sen.parl.gc.ca/ckenny, Alternative Fuels: Summer 1997.
3. Report on the Application of the Alternative Fuels Act, fiscal year 2000-01, Treasury Board of Canada, 2001, Catalogue No. BT76-1/2001.
4. Data from the US Department of Energy Website, www.afdc.doe.gov.
5. Stewart, S. et al., “Correcting Emissions Problems in Existing Propane and Natural Gas Vehicles”, SAE Paper 952380.
6. Trevor Jones, “A Comparative Analysis of Alternative Motor Fuels for Canada in the 1990s”, Document Submitted to Environment Canada, 1992.
7. Rethinking the Ozone Problem in Urban and Regional Air Pollution, National Research Council of USA, National Academy Press, Washington, DC, 1991.
8. Light Duty Vehicle Full Fuel Cycle Emissions Analysis, Topical Report GRI-Gas Research Institute, Chicago, USA, April 1994.
9. Alternative Transportation Fuels in Canada: Prospects and Policies, Study No. 70, Canadian Energy Research Institute (CERI), Calgary, Canada, November 1996.
10. Michael Wang, “GREET1.5a: Changes from GREET1.5”, Center for Transportation Research, Argonne National Laboratory, January 2000, (www.afdc.doe.gov).
11. Alternative Transportation Fuels, Gaseous Fuels, ISBN: 0-0662-2081-4-5, Natural Resources Canada, 1996.

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