Introduction

A comprehensive study prepared for the Transportation Table entitled *Alternative and Future Fuels and Energy Sources for Road Vehicles* reviewed production processes and resource supply issues affecting fuel production, estimated fuel production costs, and quantified fuel cycle emissions of potential alternative fuels. It also estimated the cost-effectiveness of emission reductions by fuel type, and identified and discussed barriers, analytical uncertainties, and data gaps.

The study employed a fuel cycle analysis, which includes the upstream emissions arising from the production of a commercially available vehicle fuel and the emissions resulting from its use in an on-road vehicle. An existing fuel-cycle model, the Delucchi model, was modified for use in the study to provide emission predictions that more accurately reflect Canadian conditions and the current knowledge of emissions from the energy sector. Up to date information on production, transportation, distribution and use of alternative and future fuels was used for this purpose. Baseline fuel consumption rates for light and heavy duty vehicles included in the study were those forecast in the Energy Outlook 1996-2020 by Natural Resources Canada for the years 2000, 2010 and 2020.

The consultant for the Transportation Table analyzed the following fuel options. Also included in the study were hydrogen and electricity as potential vehicle fuels, however these options are only likely to become feasible for widespread adoption in the medium to longer term, and are thus omitted from this discussion.

Reformulated gasoline fuels are conventional petroleum fuels that would undergo further refining so that the fuels would produce fewer emissions upon combustion in vehicles. This includes low and very low sulphur gasoline, gasoline with ethanol at low blends (10% ethanol), and possibly gasoline additives/detergents.

Reformulated diesel fuel is produced by further refinement of conventional diesel fuel so that it exhibits cleaner-burning properties, producing fewer emissions. This also includes the use of detergent additives in diesel fuel. Like gasoline, reformulating diesel fuel will principally reduce the sulphur content of the fuel.

Ethanol is an alcohol fuel produced from the fermentation of sugars or starches of biological materials – grains, wood, and agricultural or forestry residues. Unlike petroleum fuels that have finite feedstocks, ethanol is essentially a renewable fuel that can be produced from annual agricultural crops and forest harvests. The analysis of ethanol involves a pure ethanol fuel.

Methanol is an alcohol fuel produced from natural gas through various reforming processes. It can be produced from other carbon-based feedstocks, such as coal or biomass, but natural gas is typically used to produce methanol.

Natural gas is essentially methane that is usable as a vehicle fuel in either a compressed or liquefied format. Because it is a gas at ambient temperatures, natural gas must been contained under pressure or cooled significantly so that it liquefies if it is to be used in vehicles.

Liquefied petroleum gas is essentially propane, although it does typically contain constituent ethane, butane, and pentane (all hydrocarbons), and is a by-product of petroleum refining or natural gas processing.

Dimethyl ether can be produced from natural gas via several pathways and is being studied as a potential substitute for diesel applications. Considerable research remains to be done concerning this fuel.

Biodiesel is another potential substitute for diesel fuel. It can be produced from various sources, including animal fats or virgin or recycled vegetable oils, and is then used as a fuel either in its pure form or blended with conventional diesel.

Fuel Sources

There is a range of energy sources available for conversion into transportation fuels. Shown in the table below are the general classifications of road transportation fuels and the sources of energy required for the production of each fuel. Also indicated by the table is the current status of each energy source/fuel type combination.

Table 1: Fuel Production Pathways

	Coal	Oil	Natural Gas	Gas Liquids	Traditional Agricultural Crops	Cellulosic Biomass	Hydro	Solar	Wind	Nuclear
Gasoline	C	C	C			R				
Diesel	C	C	C			R				
LPG		C		C						
CNG			C							
LNG			C							
DME			C							
Methanol	C		C			D				
Ethanol					C	D				
Biodiesel					C					
Hydrogen			C			R		R		
Electricity	C	C	C			C	C	C	C	C

Source: Alternative and Future Fuels and Energy Sources for Road Vehicles

C = commercial process
D = under development
R = research stage

LPG = liquid petroleum gas (propane)
CNG = compressed natural gas
LNG = liquefied natural gas
DME = dimethyl ether

There are other routes available for producing certain fuels that are not the primary pathways currently utilized, either because of cost or technological limitations. At present these other routes do not appear to offer fuel cycle GHG emission reduction potential over the dominant or primary production routes, however this situation may change as research and development progresses.

While conventional gasoline and diesel are the primary vehicle fuels used in Canada, there are several alternative fuels presently in use. Liquefied petroleum gas (LPG), compressed natural gas (CNG) and liquefied natural gas (LNG), ethanol and methanol as high and low level blends, and electricity are currently in use in Canada. In the future it is likely that for certain applications biodiesel, hydrogen, and dimethyl ether (DME) may be utilized. Like gasoline and diesel, these fuels can be modified to meet different specifications and could potentially be used in a variety of engine configurations.

Alternative Fuels

The following is a more detailed discussion providing estimates of potential fuel cycle GHG reductions and outlining some of the attributes and drawbacks associated with each fuel.

Reformulated Gasoline

Formulating a fuel for low GHG emissions will require that changes be made in the refining of gasoline. Low and very low sulphur gasoline, gasoline with 10% ethanol, and the use of additives are some of the gasoline specifications considered for their impact on fuel cycle GHG emissions, including energy use during refining, compared with conventional gasoline.

By 2005, Canadian regulations will limit the sulphur content of gasoline to a 30 ppm average, down from 350 ppm at present. The sulphur content in gasoline is related to emissions of particulates and reduces the performance of emission control systems. While options for lowering the level of sulphur in gasoline require more energy to be expended in the refining process, more energy efficient processes are being developed.

Reducing sulphur in gasoline to 30 ppm (low sulphur gasoline) will decrease GHG and other emissions from vehicles. Of significant note is the reduction in nitrous oxide (N_2O); a 60% reduction in fuel cycle emissions. In terms of its global warming potential 1 kg of N_20 is equivalent to 310 kg of carbon dioxide (CO_2). Lowering the sulphur content in gasoline further to 1 ppm (very low sulphur gasoline) is assumed to result in no additional change in N_2O emissions.

It is estimated that the reduction of N_2O emissions through low (30 ppm) and very low (1 ppm) sulphur gasoline does not fully offset the additional CO_2 emissions from the energy required to desulphurize the fuel. Compared to conventional gasoline, low sulphur gasoline will result in a 1% increase in fuel cycle GHG emissions, and very low sulphur gasoline in a 3.2% increase in net GHG emissions. This is likely to change, as refiners become more efficient at removing sulphur from gasoline.

10% ethanol blends in gasoline are commonly produced from corn and agricultural residues (cellulose), and demonstrate a reduction in fuel cycle GHG emissions ranging from 4.2% (corn) to 6.9% (cellulose). Given current technologies, 10% ethanol blends exhibit a larger reduction in GHG emissions than reformulated gasoline.

Reformulated Diesel Fuel

As with gasoline, processes are under development for reformulating diesel fuel. The *Alternative and Future Fuels study* compared conventional low sulphur diesel to reformulated diesel and diesel produced via the Fischer-Tropsch process. The Fischer-Tropsch process enables diesel fuel to be produced from natural gas. Research on reformulating diesel fuel has focussed on engine design modifications and fuel specifications to reduce vehicle emissions, specifically nitrogen oxides (NOx) and particulate matter (PM), however, there has not been significant research on reformulating diesel to reduce GHG emissions.

Reformulated diesel and Fischer-Tropsch (FT) diesel differ from conventional diesel fuel in sulphur and cetane content. Cetane in diesel fuel is analogous to octane in gasoline. Conventional diesel is 40 cetane and has a sulphur content of 500 ppm. Reformulated diesel (50 cetane; sulphur at 50 ppm) and FT diesel (70 cetane; sulphur at 1 ppm) both increase cetane content while reducing the amount of sulphur present in the fuel. Reducing the sulphur content of diesel requires more energy during the refining process, increasing upstream fuel cycle emissions substantially. Although increasing the cetane content of diesel improves fuel efficiency and potentially reduces NOx and PM emissions, total fuel cycle emissions increase. The corresponding increase in fuel cycle emissions of GHG for the reformulated diesel is 1.6% and 15.3% for the FT diesel. Also FT diesel has a high paraffin content and does not have suitable cold weather flow properties for winter use in Canada.

Following practices in Europe, detergent additives for diesel fuels are being applied for use in North America. Experience shows that these additives improve fuel economy and lower emissions. Clean engines produce less hydrocarbons, carbon monoxide, and particulates, while power and torque may increase, as might nitrogen oxide emissions.

Ethanol

There are various potential feedstocks available for ethanol production. Lignocellulosic material from coniferous and/or deciduous trees, and agricultural residues can serve as feedstocks in Canada today. Ethanol can also be produced from agricultural crops like cereal grains, corn and oilseeds. Nonetheless, there are resource supply and process technology issues for each feedstock. In addition, conventional gasoline-powered vehicles are not compatible with ethanol at higher blends like E85 (85% ethanol and 15% gasoline) or with pure ethanol. The analysis of fuel cycle GHG emissions for ethanol involves a pure ethanol fuel.

Ethanol from Lignocellulosics

The primary route for converting lignocellulosic material has been hydrolysis of cellulose to sugars, which then undergo fermentation to produce ethanol. There are four technologies currently being demonstrated to carry out this process: an enzymatic procedure; weak acid hydrolysis or concentrated acid hydrolysis; and, the organosolv method. A fifth technology is being developed in the U.S. to synthesize ethanol from carbon monoxide and hydrogen. The four technologies already underway should each be capable of ethanol yields of 350 litres per tonne of softwood and 375 litres per tonne of hardwood or agricultural residue on a commercial scale, though each of these processes are at different stages of development. It is expected that ethanol plants using lignocellulosic material will input 500 to 1000 tonnes of feedstock per day, producing 60 to 120 million litres annually.

The supply of feedstock for ethanol plants is tied to the price of the feedstock, with the first plants utilizing residues as feedstock. This potentially includes forest waste after harvesting and growing energy crops on marginal lands. Sawmill residues can be used but cogeneration plants and fibreboard plants compete for these materials. Agricultural cellulosic material is another possible feedstock, however crop rotations and strawboard plants would compete for the same resources. Nonetheless, agricultural residues offer significant potential as a feedstock. In terms of cost, sawmill residues are the least costly, then agricultural residues, with crops from marginal lands being the most costly.

Modelling fuel cycle GHG emissions for ethanol from agricultural residues produces significant emission reductions from upstream sources and vehicle exhaust compared to conventional gasoline. The reduction in total fuel cycle GHG emissions is estimated at 86%, with upstream emissions down 45% and CO_2 emissions from fuel carbon completely eliminated.

Ethanol from Agricultural Crops

At present more than 200 million litres of ethanol are produced annually in Canada from agricultural crops, while in the U.S. 5 billion litres are produced per year. Corn is the primary feedstock used in North America, except in western Canada where feed wheat is used, and production is generally via an enzymatic process. Canada is a net exporter of wheat at 15-20 million tonnes per year, while it is usually in a small import position for corn. The corn is primarily used as animal feed and could be diverted for ethanol production.

A study estimating potential ethanol production in Canada assumed that 10% of total spring wheat could produce 947 million litres of ethanol and that another 537 million litres could be produced from 20% of the annual corn crop. These input percentages, of wheat and corn, account for domestic and export demands on Canadian agricultural crops. Although it is estimated that 1.6 billion litres of ethanol that could be produced annually this represents only 4.5% of Canadian gasoline consumption. Moreover, this quantity of ethanol is eight times what is currently produced in Canada. Also of concern are GHG emissions associated with land use change that would involve converting grasslands and/or forested lands for agricultural purposes.

Compared with gasoline, ethanol from agricultural crops are expected to reduce fuel cycle GHG emissions, but to a lesser extent than ethanol from cellulosic material. A 52% reduction in fuel cycle GHG emissions for ethanol from corn is estimated, despite upstream emissions more than doubling (105%). More intensive production requirements, including fertilizers and other energy inputs, needed to grow crops account for the lower reductions.

Methanol

Methanol is an alcohol fuel primarily manufactured from natural gas feedstocks through a steam-reforming process. Petroleum fractions and coal can also be used to produce methanol, and current research is investigating biomass and municipal solid waste as potential feedstocks. Alternative production processes are also under development but have not yet become commercially viable. In addition, researchers are investigating the suitability of methanol for hydrogen fuel cell technology.

Production costs and location of feedstocks stimulate developments in the methanol industry. Lowering production costs drives the design of new processing plants as producers seek to build larger processing units to use feedstocks more efficiently and lower capital costs. Feedstock acquisition remains the most significant cost involved with methanol production, resulting in many new plants being situated near remote gas fields. These gas fields would otherwise be economically inaccessible.

Natural gas is an abundant resource in Canada, with exports through 2010 to 2020 projected between 3500 and 3700 billion cubic feet annually. From this export gas supply 160 billion litres of methanol could be produced per year, which exceeds Canada's transportation demand. This would require substantial investment into facilities and infrastructure. The *Alternative and Future Fuels study* forecasts that the methanol required for initial market penetration will likely come from offshore sources, and that the domestic supply will be utilized once remote sources are exhausted. The current market is oversupplied and prices are low, so domestic producers would likely come on-line as supply drops and higher prices are achievable on the market.

Estimates of fuel cycle GHG emissions for methanol report a reduction of 6.5% compared with gasoline. Upstream GHG would increase slightly, but methanol displays cleaner emission properties than gasoline when used in vehicles. Dedicated methanol-powered vehicles or flexible fuel vehicles that can accommodate methanol do require specific engineering and equipment changes to conform to certain chemical properties that the fuel exhibits. Like other fuel processing technologies, research and development will improve the efficiency of production methods of methanol, thereby reducing upstream emissions.

Natural Gas

For nearly twenty years natural gas has been used as a vehicle fuel in Canada. It is commonly used as a heating fuel, and is a feedstock for chemical processes and the production of other fuels such as methanol, dimethyl ether, or various gas-to-liquid fuels. Importantly, natural gas can be used as a vehicle fuel without any further refining or chemical processing beyond what is required for heating applications. However, engine modifications are necessary to most effectively and efficiently use natural gas as a vehicle fuel.

Natural gas is composed primarily of methane, with trace amounts of other hydrocarbons not removed during the refining process. It is essentially a no-sulphur fuel and contains only a few parts per million of mercaptan to provide odour; natural gas is colourless and odourless and mercaptan is added to detect leaks. Because of its clean-burning properties natural gas is being considered as a vehicle fuel for more widespread usage. Projections of Canadian exports of natural gas, 3500 to 3700 billion cubic feet annually from 2010 through 2020, suggest that this resource is more than sufficient to supply Canada's transportation demand.

For use as a vehicle fuel, natural gas is either compressed or liquefied; compression to between 3000 and 5000 psi for compressed natural gas (CNG), or liquefied by cooling to –159°C for liquefied natural gas (LNG). Compression or liquefaction of natural gas is necessary in order for natural gas powered vehicles to achieve a relatively competitive range (distance travelled) compared to gasoline vehicles, however the range of gasoline vehicles is significantly greater at present. Also, because of the size and nature of the storage systems required for LNG, its use as a fuel is currently restricted to heavy-duty applications.

CNG has been used longer and more widespread in the United States and some European countries than in Canada, with markets emerging in Asia and South America. In comparison, LNG has had very limited usage anywhere in the world. The technology for refuelling and dispensing both CNG and LNG is improving, and on-vehicle storage requirements are being minimized and the safety improved. Refuelling with these fuels does however involve different procedures than gasoline refuelling, and any required change from what the public is accustomed to may meet resistance.

Fuel cycle GHG emissions for CNG and LNG exhibit reductions of 31.3% and 14.6% respectively, compared to gasoline. The emissions resulting from fuel use in vehicles is reduced 26% for both CNG and LNG, however upstream emissions are markedly different for these two fuel types. Upstream emissions from CNG are 46.7% lower than gasoline, but are 18.9% higher for LNG. Technological innovation will continue to make CNG and LNG attractive as alternative fuel options.

Liquid Petroleum Gas (LPG)

Liquid petroleum gases (LPG) are ethane, propane, butane, and pentane, and often occur together. Propane and butane are the gases important for transportation applications and are made available as co-products from oil refineries or by-products from natural gas plants.

Of the total production of propane in Canada, approximately 86% is from natural gas plants, with the remaining 14% coming from 20 oil refineries. It is estimated that 85% of demand for propane is in Ontario, Alberta, and British Columbia, and that if propane and butane exports were diverted for domestic transportation uses LPG could substitute 20% of Canada’s gasoline requirement.

Fuel cycle GHG emissions are lower for LPG than gasoline, with substantial reductions in emissions demonstrated in the upstream fuel cycle. Total fuel cycle GHG emissions are reduced 24.3% compared with gasoline, while the upstream portion of the fuel cycle exhibits emission reductions of 64.4%.

Despite LPG emission qualities and a prominent refuelling infrastructure for propane already established; 3500 retail locations in Canada supplying 1 billion litres annually, propane use has been declining as propane conversions have not maintained pace with improvements in gasoline engine technology. In addition, as propane use declines so have the number of retail outlets as suppliers rationalize the refuelling network. As new technologies emerge (liquid injection systems) that enable vehicles to operate on a propane-butane blend, this would involve new refuelling networks and retiring older propane vehicles unable to perform on the new fuels.

Dimethyl Ether (DME)

Recently dimethyl ether (DME) has received attention as a potential alternative to diesel fuel. DME may be produced via several pathways, with natural gas as the source feedstock. Interest in DME is due to lower emissions in diesel applications, however the current production technology is costly and relatively energy inefficient. As well, some engine optimization is required to take advantage of the fuel's properties. Considerable research is being conducted to improve production processes and for matching the fuel's properties with engine design specifications.

The *Alternative and Future Fuels study* modelled fuel cycle GHG emissions for DME, although the model could not be developed as rigorously as most other fuels because of information problems. The model's findings suggest that fuel cycle GHG emissions would be reduced 10.9% compared with conventional diesel.

DME is not commercially available and distribution and marketing of this fuel will require the development of entirely new infrastructure. At present, there is no existing demand, no refuelling infrastructure, and no production capacity. The status of DME as an alternative to diesel fuel should improve as research and development progresses.

Biodiesel

Biodiesel is the methyl or ethyl ester made from a variety of products including animal fats and virgin or recycled vegetable oils derived from soybean, canola, corn, and sunflowers. Other potential feedstocks are oil of low quality oil seeds, used restaurant oil, and oils from wood pulp. Biodiesel can be substituted for diesel fuel in its pure form (100% biodiesel) or blended with diesel, with a 20% biodiesel blend being the most common usage of the fuel. It would require some specific formulation for use in winter in Canada.

The technology for producing and using biodiesel has existed for more than a century, but only recently has it been used commercially. Its use has primarily been in Europe, with limited production and use in the United States. Biodiesel is not commercially available in Canada.

Production of biodiesel can take several pathways; the majority of production occurring is a base catalyzed reaction that uses methanol, which is one of the most economic methods currently possible. Development of more cost-effective production techniques is ongoing.

Canadian production of oilseed crops is in the range of 8-10 million tonnes annually, of which 4 million tonnes is exported as seed to the U.S. and an additional 900,000 tonnes as oil. It is estimated that if current exports were retained and converted to biodiesel 2.8 billion litres could be produced annually, potentially substituting for 20% of annual diesel fuel consumed in Canada (14.5 billion litres).

From a fuel cycle analysis, biodiesel demonstrates a significant reduction in GHG emissions over conventional diesel. The reduction in fuel cycle GHG emissions from biodiesel is 65.4 % when produced using soybeans and 53.8% if produced from canola. The entire GHG savings is due to the elimination of carbon dioxide emissions from fuel carbon, since both biodiesel pathways result in increased upstream fuel cycle emissions.

Lawrence Schmidt
Jason Politylo
Infrastructure Policy and Planning
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