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Life cycle emissions and cost of transportation systems: Case study on diesel and natural gas for light duty trucks in municipal fleet operations

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ABSTRACT

The green economy mandate seeks to reduce transportation emissions by replacing traditional fossil fuels with alternative low-carbon fuels. The present article provides a comparative “cradle-to-grave” life cycle assessment (LCA) of light duty commercial vehicles (LDCVs) powered by compressed natural gas (CNG) and diesel. The LCA scope is based on conditions for municipal vehicle fleet operation in a semi-urban Canadian city, suitable for adoption of alternative fuels such as CNG. An in-house application is developed to conduct the LCA with a combination of real-time vehicle fleet data and Natural Resources Canada's GHGenius as the inventory database. The results indicate that the net energy consumed is comparable for both fuels. Mixed results are obtained for criteria air contaminant (CAC) emissions, indicating the need for exhaust treatment for both vehicles. More importantly, a 34% reduction of GHG emissions is predicted by replacing the diesel vehicles with CNG vehicles. The analysis of fugitive methane emissions caused by newly developed hydraulic fracturing methods shows that CNG vehicles are still favorable. The lifetime fuel cost can also be reduced by about $30,000 per vehicle by switching to CNG. Therefore, fleet operators and policy developers are recommended to consider adoption of CNG-powered LDCVs.

1. Introduction

Climate change mitigation is the effort by individuals, governments, and corporations to reduce the negative effects of global warming. In the long term, this will primarily be accomplished by reducing the atmospheric concentration of greenhouse gases (GHGs) either by reducing the sources that produce them or increasing the sinks. The most important GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Grubb, 2003). The transportation sector is one of the main contributors with 27% and 28% of the overall GHG emissions in the United States (US Environmental Protection Agency and Office of Transportation and Air Quality, 2013) and Canada (Government of Canada and Environment Canada, 2013), respectively, and diesel engines still play a significant role in this sector. In addition, diesel vehicles are known to have a negative impact on the overall health of residents of major urban areas by increasing local air pollutants which increase health risks to its inhabitants. Mono-nitrogen oxides (NO_x) are produced during the combustion of fossil fuels in a vehicle. NO_x react to form smog and acid rain. Other criteria air contaminants (CACs) produced during combustion include sulfur oxides (SO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter (PM); all of which directly affect the health of residents (Bernard et al., 2001). As a result, there is a significant push by individuals and governments to mitigate these problems by switching to cleaner burning fossil fuels as an intermediate solution and eventually to zero emission fuels.

Natural gas is a promising alternative fuel in view of its relatively low carbon content (compared to other fossil fuels) and abundance in North America (Government of British Columbia and BC Ministry

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of Energy and Mines, 2012). Sufficient infrastructure is available to obtain and distribute natural gas, which essentially consists of methane. The development and use of compressed natural gas (CNG) fuel as an alternative to diesel and gasoline is supported by the motivation to improve the local environment and air quality in urban areas and to reduce carbon dioxide, a major contributor to global warming. Some studies have shown a reduction of all pollutants (Zhang et al., 2011; Jang and Lee, 2005). However, other studies have indicated an increase of nitrogen oxides (NO_x) (Aslam et al., 2006; Jayaratne et al., 2009; Kathuria, 2004; Ravindra et al., 2006). Nylund et al. (Nylund et al., 2004) suggested that special measures need to be taken with CNG engines. CNG engines are very clean when operated under stoichiometric, lean-burn combustion conditions paired with adequate exhaust treatment. In such cases, CNG vehicles can be an intermediate step to reducing pollution and mitigating emissions from the transportation sector. In addition, the CNG engine efficiency can be theoretically higher than for petroleum (Bakar, 2008). CNG is a methane based fuel which has a heating value of 900 kJ/mol. Methane combustion produces two moles of water and one mole of carbon dioxide. Compared to petroleum which has a higher heating value of 3300 kJ/mol (C_6H_6) and produces three moles of water and six moles of CO_2, CNG delivers 1.6 times more energy for the same amount of CO_2 emission. Newer engines may be able to utilize this higher carbon efficiency potential as the technology progresses.

A strong push was made for natural gas vehicles in the 1980s as a combined result of technically acceptable conversion technology, relatively inexpensive natural gas, and favorable public policy programs provided by the Canadian government (Flynn, 2002). In less than two years, however, the conversion momentum stalled as a direct result of limited infrastructure for supporting the converted vehicles and an insufficient number of refueling stations. The commercialization of CNG vehicles is presently much less constrained, since the number of public refueling stations has increased (Flynn, 2002). Lack of government support for CNG vehicles is another factor mentioned in the study for the commercialization failure. Currently, both the provincial and federal authorities in Canada provide considerable incentives in the forms of tax deduction and direct cash back for procurement of CNG vehicles (FortisBC Energy Inc, 2013). In addition, significant progress in engine technology development justified the OEM supply of CNG vehicles as a balance for the aftermarket products.

While it seems that CNG vehicles generally provide a cleaner alternative to the incumbent diesel and gasoline vehicles, a comprehensive assessment including energy usage, emissions, and economic benefits has to be processed and evaluated for these vehicles. This holistic approach, known as life cycle assessment (LCA), is advantageous to consumers and especially to fleet operators that are seeking a reliable method to inform procurement decisions. LCA is a comprehensive approach to assess environmental and economic impacts at each step of a vehicle and its fuel “life” from raw materials and feedstock to usage and disposal or recycling. Without this comprehensive approach, false conclusions on environmental impact and economics may be reached, especially for emerging vehicle and fuel technologies (Pembina Institute, 2002).

In the context of transportation systems, most LCA studies published to date focused on light duty passenger vehicles (LDPVs), more commonly known as ‘cars’, and the emissions associated with different passenger car options. The effect of implementing natural gas-based fuel pathways on the CO_2 emission of LDPVs was studied by Hekkert et al. (Hekkert et al., 2005), who reported that hydrogen produced from natural gas is the most emission saving fuel pathway. A comprehensive LCA of different fuels for light duty vehicles showed that CNG engines have lower GHG emissions while diesel was found to use less energy (Massachusetts Institute of Technology and Energy Laboratory, 2000). Granovskii et al. (Granovskii et al., 2006) and Collela et al. (Collela et al., 2005) also adopted the LCA methodology to compare GHG emissions and energy use of hydrogen fuel cells versus internal combustion engines. Collela et al. (Collela et al., 2005) considered three different pathways for hydrogen production, including steam reforming of natural gas, gasification of coal, and water electrolysis using wind energy. The study showed that hydrogen fuel cell vehicles can significantly reduce CACs since most of these emissions are produced in the operation stage of vehicles powered by internal combustion engines. Akinnikawe and Ehlig-Economides (Akinnikawe and Ehlig-Economides, 2010) used LCA to carry out a well-to-pump and pump-to-wheel analysis of difference technologies for passenger vehicles, and recommended CNG fuel as a strategy to reduce energy use. LCA has also been applied to compare CNG and diesel buses (Karman, 2006) and assess various biofuels. MacLean and Lave (MacLean and Lave, 2003) conducted an LCA comparing all “green” options to replace traditional fuels, and concluded that no specific option can singularly dominate other alternatives. Larson (Larson, 2006) reviewed 800 LCAs of biofuel systems for the transport sector (including bioethanol, biodiesel, dimethyl ether, vegetable oil, and biomethanol) and concluded that GHG mitigation can occur under certain case-specific conditions. Lave et al. (Lave et al., 2000) concluded that CNG may reduce GHG emissions by up to 30% compared to gasoline and diesel, and proposed CNG as a potential intermediate to mitigate global warming emissions compared to fuel cells and bioethanol. With recent expansion of natural gas production in North America and elsewhere, a growing interest in CNG vehicles is observed.

The limited previous literature on light duty commercial vehicles (light trucks) either included such vehicles into a general light duty vehicle (LDV) category (Hekkert et al., 2005; Massachusetts Institute of Technology and Energy Laboratory, 2000; Ou et al., 2010; Kyle and Kim, 2011; Nigro and Jiang, 2013) or used ignition technologies (*i.e.*, spark ignition or compressed ignition) to distinguish the types of vehicles under study (MacLean and Lave, 2003; Ogden et al., 2004; Ou et al., 2009). The most recent studies presented scenario-based analyses using the life cycle methodology. Ou et al. (Ou et al., 2010) investigated energy use and GHG emissions of LDVs based on three hypothetical scenarios: 1) SBF: Second generation biofuel; 2) CBF: Coal-based fuel; and 3) PEV: Promoting electric vehicles. The fuel cycle emissions and energy use were presented in the form of “Life Cycle Factors” based on technical reports from the same authors (Ou et al., 2010, 2009). The total emissions of each scenario were then calculated using the emission factors and vehicle statistics without the details on GHG component emissions (N_2O, CH_4, and CO_2), CAC emissions, or any associated costs. Kyle and Kim (Kyle and Kim, 2011) calculated the fuel cycle CO_2 emission and energy use of LDVs during a long-term period (2005–2095) based on five technology scenarios and two climate change mitigation policies, considering upstream emission of CH_4 and tailpipe and upstream emissions of CO_2 for each scenario. Nigro and Jiang (Nigro and Jiang, 2013) recently summarized the concluding remarks of nine LCA studies on different fuel technologies including gasoline, ethanol (E85), natural gas, hydrogen, and electricity, and five vehicle types. The report highlighted the importance of analyzing a comprehensive range of fuel and vehicle pathways and a consistent set of scenarios to compare available technologies and fuels using the latest information.

While the results and recommendations of these studies are useful for transportation policy development, the analysis was simplified by combining light duty trucks and passenger vehicles into a single LDV category without providing any details on the contribution of each vehicle category to total GHG emissions and