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A comparative life cycle assessment of diesel and compressed natural gas powered refuse collection vehicles in a Canadian city

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HIGHLIGHTS

- Life cycle analysis is performed on two alternative refuse collection vehicle technologies.
- Real-time operational data obtained by the City of Surrey in British Columbia are utilized.
- The life cycle energy use is similar for diesel and CNG RCVs.
- A 24% reduction of GHG emissions (CO_2-equivalent) may be realized by switching from diesel to CNG.
- CNG RCVs are estimated to be cost effective and may lead to reduced fuel costs.

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ABSTRACT

Consumers and organizations worldwide are searching for low-carbon alternatives to conventional gasoline and diesel vehicles to reduce greenhouse gas (GHG) emissions and their impact on the environment. A comprehensive technique used to estimate overall cost and environmental impact of vehicles is known as life cycle assessment (LCA). In this article, a comparative LCA of diesel and compressed natural gas (CNG) powered heavy duty refuse collection vehicles (RCVs) is conducted. The analysis utilizes real-time operational data obtained from the City of Surrey in British Columbia, Canada. The impact of the two alternative vehicles is assessed from various points in their life. No net gain in energy use is found when a diesel powered RCV is replaced by a CNG powered RCV. However, significant reductions (approximately 24% CO_2-equivalent) in GHG and criteria air contaminant (CAC) emissions are obtained. Moreover, fuel cost estimations based on 2011 price levels and a 5-year lifetime for both RCVs reveal that considerable cost savings may be achieved by switching to CNG vehicles. Thus, CNG RCVs are not only favorable in terms of reduced climate change impact but also cost effective compared to conventional diesel RCVs, and provide a viable and realistic near-term strategy for cities and municipalities to reduce GHG emissions.

1. Introduction

Rising oil prices and growing environmental concerns are driving research into alternative, cleaner, and more efficient ways of producing and using energy (Rose, 2013). According to Natural Resources Canada (2008), the transportation sector is the largest source of greenhouse gas (GHG) emissions in Canada, accounting for more than one third of Canada's total GHG emissions. Additionally, criteria air contaminants (CACs) from the transportation sector are posing significant environmental and health risks for Canadians, particularly for approximately 80% of the population who live and/or work in urban areas (Transport Canada, 2006).

In order to minimize the impact of emissions from the transportation sector, consumers and organizations are seeking viable low-carbon alternatives to conventional gasoline and diesel vehicles. The compressed natural gas (CNG) powered vehicle is a viable alternative to conventional gasoline and diesel powered vehicles and can significantly reduce emissions from the transportation sector. Two studies of CNG and gasoline engines have shown significant reductions of all combustive emissions (Jang

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and Lee, 2005; Zhang et al., 2011). However, Aslam et al. (2006) observed an increase in NO_x emissions. This increase in NO_x is, despite significant reductions in other emissions is also observed in studies comparing CNG to diesel fuel (Jayaratne et al., 2009; Kathuria, 2004; Ravindra et al., 2006). A possible explanation for the increase in NO_x is given by Nylund et al. (2004) who argue that if no special measures are taken, NO_x emissions will be higher than for diesel engines. CNG engines need to operate in a lean-burn operation or in stoichiometric combustion in combination with a three-way catalyst to reduce emissions.

However, to validly evaluate and assess the energy, emissions, and economic effects of alternative fuels and vehicle technologies, a holistic or comprehensive approach has to be considered. The approach, often referred to as life cycle approach, or life cycle assessment (LCA), must include all the steps required to produce a fuel, to manufacture a vehicle, and to operate and maintain the vehicle throughout its lifetime including disposal and recycling at the conclusion of its life cycle. This particular approach provides a better understanding of alternative choices in fuels and vehicle technologies and makes informed selections for the long-term possible. Conversely, without a life cycle approach, false conclusions can be drawn, particularly for alternative vehicle technologies that employ fuels with distinctly varied primary energy sources and fuel production processes. Numerous studies have been conducted on alternative vehicle technologies from the life cycle perspective, often estimating fuel cycle emissions and energy use associated with various transportation fuels and technologies. On the topic of comparative LCA, fuel cell vehicles are compared with conventional vehicles (Collela et al., 2005; Granovskii et al., 2006; MacLean and Lave, 2003; Pehnt, 2001, 2003; Zamel and Li, 2006) and electric vehicles (Cuenca et al., 1998). Others have performed comparative LCAs of different hydrogen production pathways (Row et al., 2002; Spath and Mann, 2001).

LCAs comparing CNG to diesel vehicles have concluded different results, partially due to locale specific data. Comparing CNG and diesel light duty vehicles, Weiss et al. (2000, 2003) have done an LCA study showing higher efficiency and reduction of CO_2 emissions for CNG and a 13% reduction of life cycle energy consumption for diesel compared to gasoline. However, if the diesel fuel is derived from natural gas (Fischer–Tropsch (FT) diesel), an increase in energy demand offsets any GHG reduction in vehicle usage. Previous studies on comparative LCAs of heavy duty CNG and diesel vehicles were focused on transit buses (Ally and Pryor, 2007; Karman, 2006; Kliucininkas et al., 2012; Ryan and Caulfield, 2010). Karman (2006) found significant reductions of CO_2 emissions for vehicles in the city of Beijing, China, when switching to CNG, but stressed the importance of locale specific data for an LCA. Kliucininkas et al. (2012) found a higher environmental impact for CNG compared to diesel in Kaunas, Lithuania, due to a higher consumption of CNG per traveled distance with related upstream emissions. Ryan and Caulfield (2010) found a significant decrease of all pollutants except CO in CNG buses compared to diesel buses on the Euro V norm in Dublin, Ireland. Ally and Pryor (2007) compared CNG, diesel, and H_2 fuel cell driven vehicles and showed that CNG required more energy per distance traveled and resulted in slightly higher GHG emissions compared to diesel driven vehicles. However, vehicles driven by CNG showed lower emissions related to smog, acidification, and soil/water contamination (NO_x, CO, SO_2, and non-methane volatile organic compounds) for Western Australia. On presenting LCA impacts, Kliucininkas et al. (2012) used “milli ecopoints” (mPt) per kilometer traveled. One point is interpreted as one thousandth of the annual environmental load (damage) of one average European inhabitant. Sorensen (2004) has monetized (in Euros) the environmental, social, and other impacts. However, the majority of LCAs present their findings in the quantity of greenhouse gases and pollutants per kilometer traveled for vehicles as well as energy consumed to evaluate efficiency.

The current state of LCA studies of heavy duty vehicles as relating to refuse collection vehicles (RCVs) is, however, largely absent. Therefore, there is a significant need to conduct LCA studies of RCVs and evaluate the results in light of existing studies on transit buses that also employ heavy duty engines. Interestingly, there are conflicting reports of the climate change (or global warming) impact with respect to GHG emissions from CNG and diesel buses. Karman (2006) showed a small decrease of GHG emissions of CNG while Ally and Pryor (2007) showed an increase. The LCA on RCVs presented here is contextualised with respect to above-mentioned transit bus studies to show how a reduction of GHG emissions and climate change impact can be achieved by switching from diesel to CNG RCVs for different vehicle types.

The present study involves a municipal organization in British Columbia, Canada, known as the City of Surrey (hereafter referred to as the City). The City has about 300 vehicles in its engineering vehicle fleet, ranging from light duty passenger and commercial vehicles to rangers (pickups), heavy duty commercial vehicles, buses, and RCVs. The City became interested in finding viable low-carbon alternative fuel vehicles to replace incumbent gasoline and diesel vehicles in order to meet or exceed its goal of reducing GHG emissions from fleet vehicles by 20% by the year 2020. In this regard, the City wants to undertake a holistic or pragmatic approach that can assess low-carbon alternative fuel vehicles from various points in their life cycle. In an attempt to assess viable low-carbon alternative fuel vehicles, this study focuses on heavy duty RCVs powered by CNG as a potential replacement of the diesel powered RCVs presently operated in the City.

The objective of the present study is to conduct a life cycle analysis of a CNG powered RCV and compare it with a diesel powered RCV, utilizing the reliable and real-time operational data provided by the City and its contractor. The findings of this study will enable decision-makers to make an informed selection of CNG vehicles over conventional diesel vehicles based on realistic estimations of life cycle emissions, cost, and energy use.

2. Life cycle assessment methodology

The methodology used to assess different vehicle technologies from various points in their life cycle is often referred to as life cycle assessment (LCA). LCA is a ‘cradle-to-grave’ approach of assessing systems or technologies by compiling an inventory of relevant inputs and outputs, assessing the potential environmental impacts associated with identified inputs and outputs, and interpreting the results of inventory and impact phases to help make informed decisions (Scientific Applications International Corporation (SAIC), 2006).

A typical life cycle of a vehicle technology is shown in Fig. 1. The life cycle can be classified into two major categories: the fuel cycle and the vehicle cycle. In the fuel cycle, the following stages result, starting from the feedstock production where energy is used and greenhouse gases are released. At this stage in CNG production, for example, the associated input of energy to extract natural gas and the emissions output related to the extraction are accounted for. As for diesel, the extraction of crude petroleum is considered. Next in the fuel cycle is feedstock transport, in which the associated costs of transportation are documented. As with our example, natural gas is transported to gas processing facilities via pipelines or tank trucks requiring energy as well as producing emissions. Conversion of crude oil feedstock to practical fuels is a very energy intensive step of the fuel cycle, generating significant

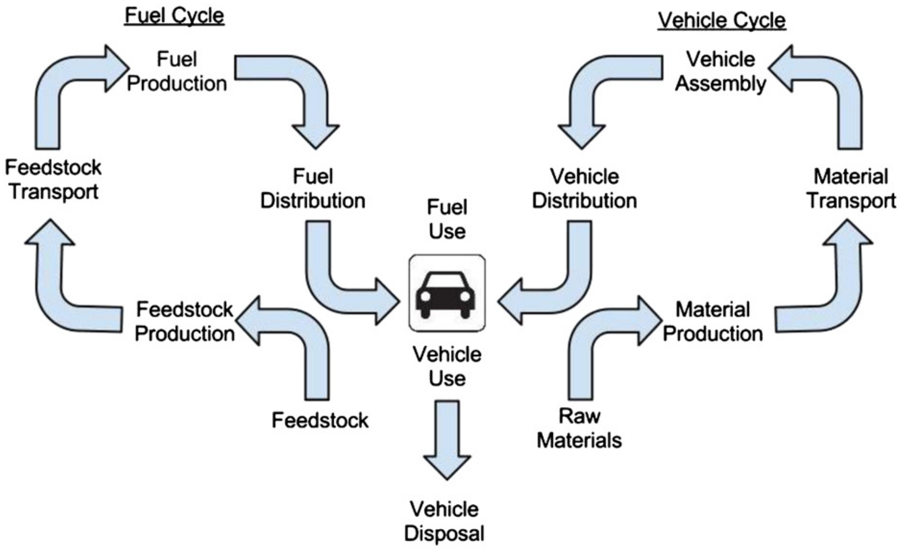

Fig. 1. Typical life cycle of a vehicle technology.

amounts of emissions. However, natural gas purification results in significantly less energy use and emissions. Lastly, the fuel needs to be transported to be available for use by the vehicle. Emission and energy use associated with fueling trucks are thus accounted for in the fuel distribution stage. In this LCA, the fuel cycle shares similar inputs and outputs with the vehicle cycle at the ‘‘Fuel Use’’ stage (Fig. 1).

Both the production and operation of the vehicle need to be accounted for in the LCA. The materials that are extracted from the earth required to produce the vehicle are accounted for in the ‘‘Vehicle Material Production’’ stage. In the standard RCV internal combustion engine and fuel storage systems, aluminum and steel are needed for production. These materials can be extracted from the ground or from old vehicles via recycling. The LCA accounts for the energy required for these operations as well as emissions generated. Next, these materials are transported to RCV assembly plants where energy is required for production, with emissions correlating directly to RCV production. Further emissions are produced and energy is required for the transport of the RCVs to end users and for disposal or recycling at the end of their lifetimes.

An LCA of a vehicle technology can be relatively laborious and time and data intensive. As one can see from observing the fuel pathway from resource extraction and the stages of vehicle production from raw materials above, much time can be spent in gathering the inventory data. Consequently, it may be advantageous to use established tools that can access the necessary data from databases and assist with the main analysis. The scope at any stage can branch out to secondary or tertiary energy and environmental effects; therefore, one must also list the assumptions and boundaries of the analysis to give the reader the scope of the LCA conducted. The following sections will elaborate more on the modeling and analysis tools employed and the assumptions made in the present study.

3. Description of analysis

As mentioned in the previous section, a complete LCA of a vehicle technology should consider all the steps of the fuel cycle and the vehicle cycle shown in Fig. 1. It can be conducted by either developing custom-made in-house models or using existing LCA tools developed by various organizations. According to the United States Environmental Protection Agency (2011), there are approximately 30 LCA tools developed for different applications. Among them, two LCA tools were developed in North America for transportation applications: GHGenius and GREET. While GHGenius is a complete LCA package for various fuels and vehicle technologies, GREET (the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model developed by Argonne National Laboratories) is mainly a fuel cycle model for different vehicle technologies. Recently, the developers of GREET also released a vehicle cycle model for light duty vehicles; however, the vehicle cycle model for heavy duty trucks is yet to be released (Wang et al., 2007; Wang, 2008). Therefore, in the present study, GHGenius is selected to conduct a complete comparative LCA study of CNG and diesel powered RCVs. The following subsections provide a brief overview of the GHGenius model and summarize the key assumptions pertaining to the present study.

3.1. GHGenius

GHGenius is a Canadian life cycle modeling tool for transportation fuels and vehicle technologies developed and maintained by Natural Resources Canada. The model complies with ISO 14040 and 14044 standards for LCA. It is a derivative of the life cycle emissions model (LEM) developed by Delucchi (1998). It has more than 200 vehicle, fuel, and feedstock combinations and predicts life cycle energy use and emissions for the past, present, and future years using historical data or correlations for changes in energy and process parameters. Additionally, it has economic tools incorporated to estimate cost-effectiveness of different fuel and vehicle combinations (Natural Resources Canada's GHGenius Model 3.19a, 2005; (S&T)^2 Consultants Inc., 2006).

Some of the salient features of GHGenius compared to other LCA tools include the availability of a comprehensive Canadian database in the model, including all the steps of the life cycle in the model starting from raw material acquisition to end-use, and generation of very detailed data output from model simulations. In addition to light duty vehicles, provisions are available for heavy duty vehicles suitable for the RCV analysis. Hence, GHGenius is selected as a primary life cycle analysis tool for this study. The main methodology and assumptions used by GHGenius in the context of the present study are explained in the following subsections (O'Connor, 2010; (S&T)^2 Consultants Inc., 2005, 2006).

3.2. GHG emissions and energy projections

In GHGenius, GHG emissions are calculated in terms of grams of pollutant per kilometer of vehicle travel. GHG emissions can then be displayed in terms of grams of equivalent CO_2 emissions using the Intergovernmental Panel on Climate Change (IPCC) (2007) 100 year global warming potential (GWP). The IPCC GWP is a relative measure of how much heat each gas contributes to climate change as compared to the standard carbon dioxide. The GWP for methane and nitrous oxide is 21 and 310, respectively, for 100 years. The greenhouse gases included in the calculation of grams of CO_2-equivalent emissions are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The sum of grams of CO_2-equivalent at various points of the life cycle is then added to the grams of CO_2 released during the operation of the vehicle. In the end, results are provided for the total life cycle GHG emissions from the usage and production of the vehicle and fuel.

GHGenius estimates the total energy used during the life cycle in joules per kilometer driven. It aggregates data on the energy use during the fuel distribution, fuel production, feedstock recovery, and transmission stages. As for the fuel use stage, it uses parameters such as the vehicular efficiencies in liters per kilometer driven for each fuel (diesel and natural gas in our study) and the heating values in megajoules per liter to calculate the amount of energy required for operation. The sum total of energy used by each vehicle can then be displayed in total joules per kilometer traveled.

On the topic of emission standards and data, the standards for light duty passenger cars are normalized by vehicle driving distance, g/km; however, for heavy duty vehicles, standards are defined by engine energy output, g/kWh. Emission certification is performed by running stand-alone engines on an engine dynamometer. The emission standards adopted in 2000 in the USA and Canada are similar to those in Europe known as the “Euro Norm” for heavy duty vehicles (Nylund et al., 2004). “Euro Norm” ranges from “Euro I Norm” to “Euro VI Norm” which is the strictest and most recent emission standard. In the present case, both CNG and diesel engines are evaluated under “Euro V Norm” emission standards (Cummins Westport, 2012a,b; U.S. EPA, 2012). Using data on these engines and diesel emissions made available by Environment Canada, GHGenius utilizes MOBILE6.2C to obtain adjustment factors to convert the certified levels to real world conditions. In addition, GHGenius allows user input of fuel consumption and percentage of highway driving for further flexibility. The GHGenius Manual Volume 1 in Section 47.17 and 47.23 details the MOBILE6.2C data on heavy duty diesel and CNG engines, respectively (($S\&T)^2$ Consultants, 2012a, b).

3.3. GHG impact assessment

GHGenius can assess the cost-effectiveness of alternative fuels and vehicles compared to conventional fuels and vehicles. This calculation is particularly useful in comparing vehicle related GHG reduction strategies with fuel related strategies on a common basis. The function to calculate cost-effectiveness integrates the relative costs of alternative fuels and vehicles with the estimated GHG emissions. As a result, the cost-effectiveness function estimates costs in terms of GHG emissions reduction ($ per unit CO_2-equivalent) achieved by an alternative fuel/vehicle technology using the following equation:

$$E_c=\frac{\left(\sum_{y=1}^{n}\frac{P}{F}\left\{VKT_y((F_aFCR_a)-(F_cFCR_c))\right\}\right)+(P_a-P_c)+\frac{P}{A}OM+C_o}{VKT_t(GHG_c-GHG_a)} \tag{1}$$

where, $\sum_{y=1}^{n}$ is the sum of the annual terms for the economic lifetime of n years at an assumed discount rate; P/F and P/A are factors to calculate the present value of a future cost and the present value of a series of future constant annual costs assuming an economic lifetime n and a discount rate i; F_a and F_c are the consumer fuel prices of the alternative and conventional fuel per liter excluding taxes ($/L); FCR_a and FCR_c are the fuel consumption ratings of the vehicle using alternative and conventional fuel (L/km); VKT_y and VKT_t are vehicle kilometers traveled per year and total distance traveled over the economic lifetime of the vehicle (km); P_a and P_c are the purchase prices of the alternative and conventional vehicles excluding taxes; GHG_a and GHG_c are life cycle greenhouse gas emission factors for the alternative and conventional fuels (CO_2-equivalent g/km); OM are the constant annual non-fuel operating and maintenance costs over the life ($); and C_o are other costs ($).

The result of the cost-effectiveness function can be a positive or negative number. If the cost-effectiveness calculation results in a positive number, the alternative fuel (CNG in the present study) powered vehicle costs more than the conventional fuel (diesel) powered vehicle per aliquot of GHG emissions reduced. Alternatively, if negative cost-effectiveness results from the model, the alternative fuel powered vehicle has a lower life cycle cost per unit GHG emissions reduced compared to the conventional fuel powered vehicle. Further details on the cost-effectiveness parameters are available in $(S\&T)^2$ Consultants Inc. (2005).

3.4. Goal, scope, and assumptions

The scope of the present LCA is consistent with the scope of GHGenius including all parts of the fuel cycle: feedstock production and recovery, leaks and flaring, feedstock transport, fuel production, fuel storage and distribution, and fuel dispensing at retail level. In its scope it includes on the vehicle cycle: vehicle operation, vehicle assembly and transport, and emissions from materials manufacturing. The functional metrics used to describe the results are (1) energy used (per km of travel), (2) greenhouse gases emitted (in CO_2-equivalent per km), (3) combustive emissions generated (per km), and (4) cost-effectiveness as described above. These four functional metrics are utilized to indicate the anticipated categorical impact of the different vehicles on (1) resource use (energy efficiency), (2) climate change, (3) air quality, and (4) economic viability, respectively. Other LCA impact categories such as ozone depletion, acidification, eutrophication, human health, and land use are beyond the scope of this comparative LCA. The contributions of each phase of the complete fuel and vehicle life cycles will be analyzed. The system boundaries and assumptions are:

- The secondary energy and environmental effects are not quantified. For instance, energy use and associated emissions during the production of crude oil and natural gas are quantified, but the energy used and emissions produced in the manufacturing of equipment required for oil and gas exploration and extraction and the material used in the construction of a refinery are not quantified.
- A penalty of 0.35% on fuel economy is applied for every 1% increase in vehicle mass for the CNG RCV (Cheah et al., 2007).
- The lifetime of the diesel and CNG RCVs is assumed to be 5 years based on data obtained by the City of Surrey and the non-fuel costs of operation and maintenance are assumed to be equal.
- Emissions associated with the materials manufacture and assembly are a function of the mass of the vehicle and the spectrum of materials in the vehicle.
- The fraction of city driving is assumed to be one, implying no highway driving for RCVs.
- The crude oil price is assumed to be equivalent to the average crude oil price of April 2011 ($122 US per 0.159 m^3 crude oil)

Table 1
RCV data collected from the City of Surrey and its contractor.

Parameter	Value
In-use city fuel consumption	12 L/h
Tare mass	15,000 kg
Maximum mass	23,300 kg
Stops per day	1400
Range requirement	100 km
Average daily distance traveled	54 km
Vehicle lifetime distance	90,000 km
Maximum operational lifetime	5 years
Capital cost of diesel RCV	$220,000 CDN
Capital cost of CNG RCV	$260,000 CDN

plus a distribution and retail cost of $0.055 CDN per liter (currency exchange rate 1.04 $US/$CDN) (Bloomberg, 2011; Fogt, 2011). Diesel and CNG fuel prices as of April 2011 are used ($0.93 CDN per liter and $4 CDN per GJ, respectively).

4. Data collection

A significant portion of any life cycle analysis requires collection of reliable data. The quality of data has a profound impact on the quality of the results predicted or estimated by an LCA tool. GHGenius has access to data for Canada from reports produced by Statistics Canada, Natural Resources Canada (NRCan), Environment Canada, and the National Energy Board for the production of power, crude oil, refined petroleum products, and natural gas. Additionally, GHGenius allows the user to provide data for certain steps in the process to provide the highest degree of flexibility possible in the model without compromising the quality of the results predicted.

In the present study, considerable time is invested to collect reliable real-time data for the different stages of the life cycle of diesel and CNG RCVs. The data collected from the City and its contractor on the RCVs are tabulated in Table 1. The in-use city diesel fuel consumption is calculated based on the reported RCV operational time of 9 h per day, making 1400 stops along the way, and requiring 12 L/h. The average RCV speed is estimated at 6 km/h, including the idling time at each stop, based on the average daily driving distance of 54 km. The relatively demanding and energy-intensive duty cycle in the present case features more frequent stops than in other reports (Blohm et al., 2004), underlining the importance of collecting data specifically for each project directly from the source. The lifetime of an RCV in terms of distance traveled is calculated based on the daily trip distance multiplied by the days used per year for the projected lifetime of 5 years.

The CNG consumption is calculated on a relative basis to the diesel engine. The energy efficiency of the Cummins Westport CNG engines modeled in GHGenius is 86–87% of that of a diesel engine. Consequently, an additional approximate 16% of fuel energy is required to achieve the same distance with a CNG motor as with a diesel motor.

5. Results and discussion

The GHGenius LCA modeling framework combined with the assumptions listed above and the data collected from the City of Surrey is employed to estimate the energy use, emissions, and cost of the diesel and compressed natural gas (CNG) powered heavy duty refuse collection vehicles (RCVs) over the complete life cycle of their production and operation. Fig. 2 shows the estimated energy use of diesel and CNG powered RCVs. The x-axis represents the various stages of the fuel and vehicle cycles, while the y-axis represents energy use as a function of distance traveled by an RCV for its total lifespan of 90,000 km. Interestingly, it is found that the energy use during fuel/vehicle operation of a CNG powered RCV is approximately 17% higher than the diesel powered RCV for the fixed lifetime of both RCVs. This result is comparable to Ally and Pryor (2007) in the cases where primary energy demand is higher for CNG. This increase is due to the low energy density of CNG fuel compared to diesel fuel. However, there is negligible difference (approximately 3%) in the total energy use during the complete life cycle of both RCVs, implying no net gain in energy use by replacing a diesel powered RCV with a CNG powered RCV. This is because of higher energy use during crude oil extraction (feedstock recovery stage) and fractional distillation (fuel production stage) of diesel fuel compared to the CNG fuel, which in turn offsets the lower energy use of diesel powered RCV during fuel/vehicle use stage. However, the main advantage of CNG based vehicles is the reduction of overall GHG and particulate emissions.

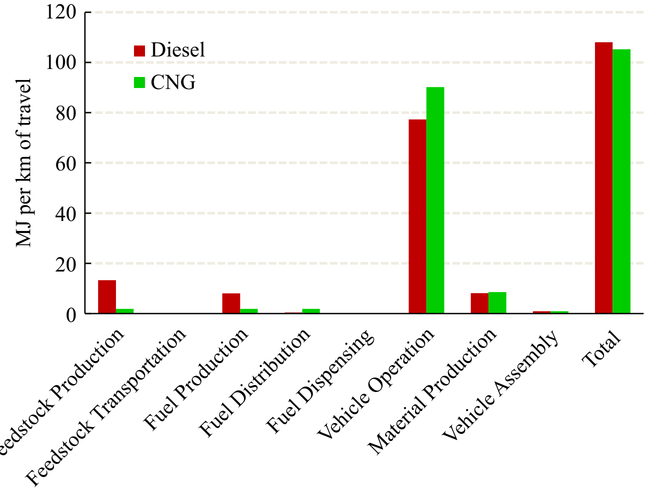

Fig. 2. Estimated energy use during different life cycle stages of diesel and CNG RCVs.

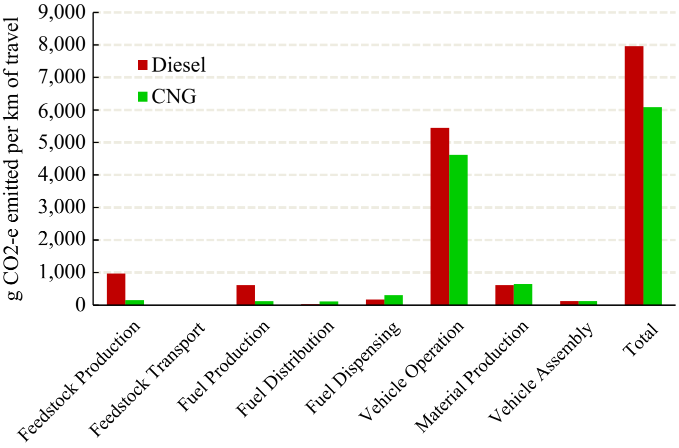

Fig. 3. Equivalent CO_2 emissions during different life cycle stages of diesel and CNG RCVs.

The equivalent CO_2 emissions during different life cycle stages of diesel and CNG powered RCVs is shown in Fig. 3. It can be seen that the total life cycle GHG emissions emitted by a CNG powered RCV are roughly 24% less than for the diesel powered RCV; in other words, replacing a diesel powered RCV with a CNG powered RCV results in a significant reduction of GHG emissions. Also, it can be seen that the vehicle operation stage (fuel use) is the single largest contributor to GHG emissions for both RCVs, accounting for 70–75% of total GHG emissions. CNG is essentially methane, which comprises the highest hydrogen-to-carbon ratio of all hydrocarbons. Diesel, in contrast, comprises a mix of predominantly carbon-rich compounds as a result of fractional distillation of petroleum. When the two are combusted in an internal combustion engine, methane produces less carbon dioxide, carbon monoxide, and other carbon-containing emissions. Moreover, the GHG emissions in the diesel fuel cycle (feedstock and fuel production) are significantly higher than those of CNG due to the relatively energy-intensive petroleum extraction and fractional distillation processes known to release significantly more emissions than the extraction and purification of natural gas. Notably, GHG emissions from refuse collection fleets can be reduced significantly by CNG RCV implementation.

In a previously published study, Karman (2006) showed 70 g per mile (44 g/km, or 2.5%) reduction of CO_2-equivalent life cycle emissions for the case of a CNG transit bus versus a diesel bus operated in Beijing, China. Further analysis shows that at the vehicle operation stage, CO_2-equivalent emissions increased (48 g/km, or 3.6%) due to high CH_4 emissions by the CNG bus. However, upstream emissions of diesel fuel were higher. In the presently employed version of GHGenius, when comparing RCVs, a much higher (1880 g/km, or 24%) reduction is obtained over the full life cycle. Notably, the total GHG emissions of the CNG and diesel trucks in the study presented here (6080 and 7960 g/km) are approximately 3.6 × and 4.6 × higher than those of the CNG and diesel buses in Karman's work (1700 and 1740 g/km), as a result of the higher fuel consumption for RCVs. The higher relative GHG emissions reductions in this study are mainly from the vehicle operation phase where recent advances in CNG engine technology are expected to improve the environmental value proposition of such vehicles. Moreover, methane emissions from CNG vehicle operation are less significant in the present version of GHGenius. The type of diesel fuel considered for the comparison also influences the results. Due to the energy-intensive sulfur removal process, the ultra-low sulfur diesel (ULSD) used in our work requires significantly more energy upstream than the low-sulfur diesel (LSD) used by Karman. The present work compares ULSD to CNG because this fuel has become a standard in the USA and Canada. In addition, several other parameters may contribute to the difference, such as percentage of city and highway driving, vehicle range, and fuel economy, all of which were revised in the simulation of GHGenius version 3.19a employed here.

In a similar study on CNG and diesel buses in Australia, Ally and Pryor (2007) showed 25% higher overall GHG emissions for CNG than for diesel. In a subsequent report (Ally, 2008), a breakdown of the LCA shows unusually high emissions from the CNG vehicle operation phase compared to other studies. This can be attributed to two different technologies for heavy duty CNG engine operation. The Australia buses are Mercedes-Benz CNG OC 500LE with CNG engines that are run under lean-burn combustion conditions. The buses available in Canada from which GHGenius utilizes its data are based on Cummins Westport ISL-G CNG engines, which burn at stoichiometric conditions. Pelkmans et al. (2001) showed that CNG engines that run at stoichiometric conditions produce less carbon dioxide than those run at lean-burn conditions. Overall, as indicated by the results presented here, recent improvements in CNG internal combustion engines enable significant GHG emission reductions compared to incumbent diesel and gasoline engines. Based on conditions for the City of Surrey, selection of a new CNG RCV over a diesel RCV is estimated to reduce GHG emissions by 169 t (metric tons) during its 5-year lifetime. It is noteworthy that the net impact per vehicle is more significant for RCVs than for most other municipal fleet vehicles due to their high energy requirements.

Fig. 4 shows criteria air contaminant (CAC) emissions during different stages of the diesel and CNG powered RCV life cycle. CAC emissions include carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOC), sulfur oxides (SO_x), and particulate matter (PM). As pointed out earlier, CAC emissions are posing significant environmental, health, and economic risks for all communities and citizens. For instance, according to Canadian Medical Association (CMA) predictions, there were 306 premature deaths in British Columbia due to CAC pollution in 2008, and related economic damages of over $900,000 CDN (Geduld, 2008). It can be seen from Fig. 4 that replacing a diesel powered RCV with a CNG powered RCV results in a considerable reduction in total CAC emissions, ranging from 21% reduction in VOC emissions (Fig. 4c) to 44% reduction in NO_x and SO_x emissions (Figs. 4b, d). While SO_x and PM are mainly reduced at the feedstock and fuel production stages, the CO, NO_x, VOC, and PM emissions are significantly reduced at the fuel dispensing and vehicle operation stages where a positive net impact on local, urban air quality can be achieved. At the location of vehicle deployment, a 54% reduction in overall CAC emissions can be obtained. This calculation by GHGenius already includes recent advances of diesel exhaust treatment via particulate traps to control PM emissions (Natural Resources Canada, 2012). Thus, replacing diesel with CNG powered RCVs would lead to cleaner air in urban areas.

The cost-effectiveness calculations integrate information on the relative costs of the CNG fuel and vehicle with GHG emissions results produced by GHGenius to arrive at the cost of GHG emission reductions. The calculations include the lifetime vehicle and fuel costs, including the purchase price, operation, and maintenance. In Fig. 5, a negative value is present indicating a net cost savings of the alternative CNG powered RCV relative to the conventional diesel powered RCV. In other words, a CNG powered RCV saves $650 and $330 CDN per realized tonne of CO_2 reduction, with and without consideration of diesel tax, respectively. It is noteworthy that both the federal and provincial governments in Canada offer significant tax incentives for using CNG in commercial vehicles. For instance, the Harmonized Service Tax (HST) in British Columbia is fully refunded for users of CNG vehicles (Government of British Columbia, 2011). However, the entire tax on diesel fuel is estimated to $0.30 CDN per liter ($0.04 and $0.26 CDN per liter federal and provincial excise tax, respectively) (Department of Finance Canada, 2006). Therefore, both scenarios (with and without diesel tax) are considered in the cost-effectiveness calculations. Fig. 6 shows the lifetime fuel cost of diesel and CNG fuels based on a 5-year lifetime, excluding tax. It can be seen that significant fuel cost savings on the order of $100,000 CDN per vehicle can be achieved by switching to CNG. Besides the tax incentives on using natural gas from governments, the operational cost reduction on fuel offers the consumers and organizations the best incentive to switch to CNG powered vehicles. Additionally, diesel engines with modern emission limits tend to wear sooner than engines built several decades ago. At the same time, the durability of CNG based engines has improved significantly as a result of the increasing interest in these engines and the resulting development activities worldwide (Cummins Westport, 2012a, b). As a consequence, the robustness of CNG engines is approximately on par with diesel engines. CNG combustion based RCV pilot projects at various municipalities worldwide have shown that this can be achieved (Gordon et al., 2003).

The GHGenius results mentioned above realistically demonstrate the benefits of using CNG RCVs versus conventional diesel RCVs. While the predictions for emissions and cost savings are expected to be reliable and consistent with other studies done

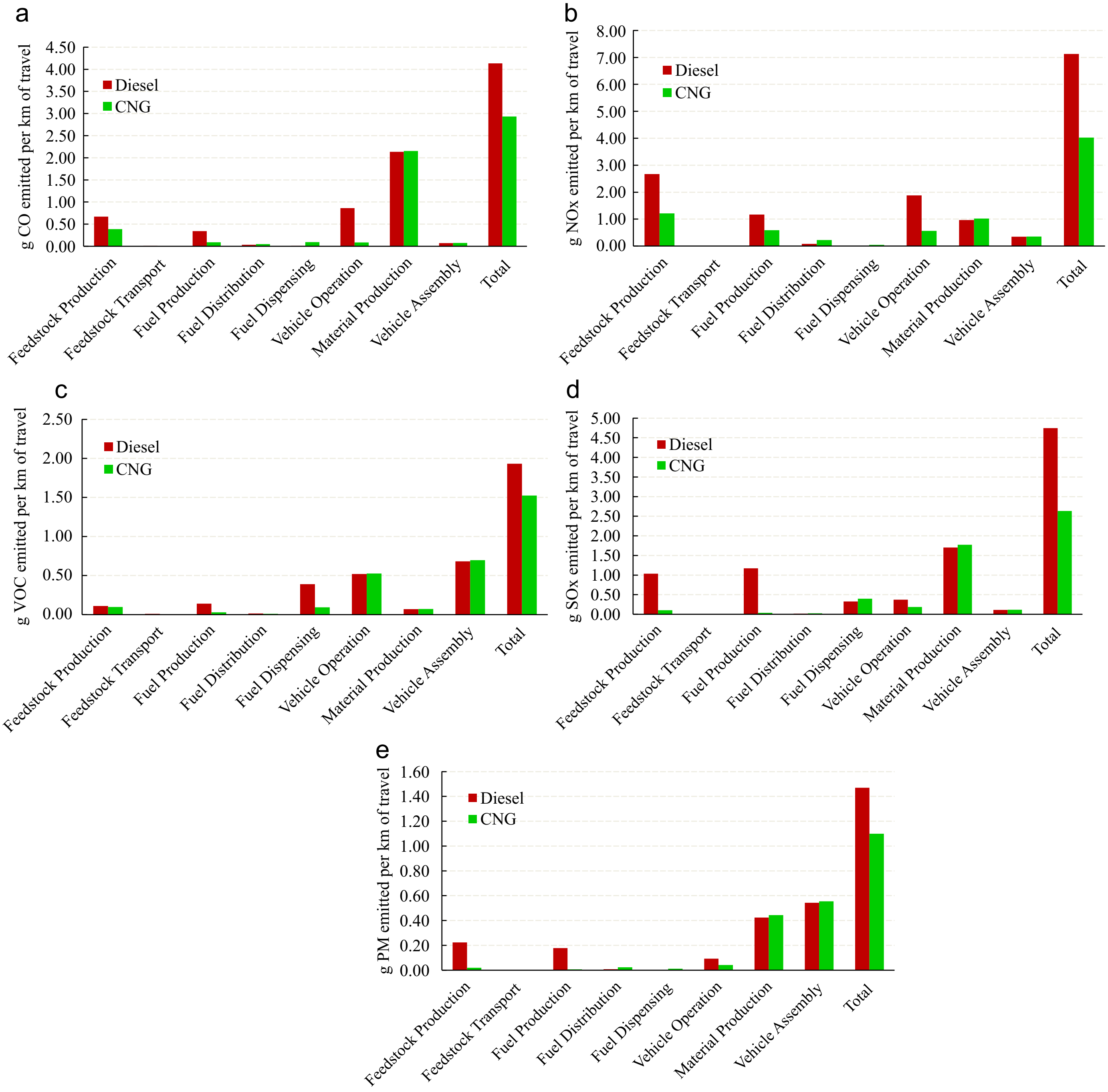

Fig. 4. Criteria air contaminant (CAC) emissions during different life cycle stages of diesel and CNG RCVs: (a) CO; (b) NO_x; (c) VOC; (d) SO_x; and (e) PM.

elsewhere, one may consider the uncertainties in conducting life cycle analysis mainly originating from the accuracy and appropriateness of the data used as input. GHGenius is sensitive to the quality of the data it uses. The models are kept updated by identifying trends and avoiding outliers as well as incorporating data from Statistics Canada with each release of new information. Specific data utilized in GHGenius are regionalized across Canada and in some cases generalized for North America. GHGenius developers acknowledge gaps in data, e.g., N_2O emissions related to feedstock production. Sensitivity analysis of new modules incorporated into the model are usually performed with respect to other LCA models such as GREET. GHGenius also includes a Monte Carlo simulator that can evaluate the sensitivity of different input parameters simultaneously. With respect to the crude oil price used (April 2011), major price variations in both diesel and CNG fuels are known to occur and the cost-effectiveness of CNG RCVs is expected to vary accordingly. In the present case of comparing CNG with diesel fuel, GHGenius provides a reliable platform to carry out the LCA.

6. Conclusions

A comparative life cycle analysis of diesel and CNG powered RCVs is conducted based on conditions relevant to a Canadian city. The study uses the most reliable and real-time operational data obtained from a municipal organization, providing services to Surrey, the second largest city in British Columbia, Canada.

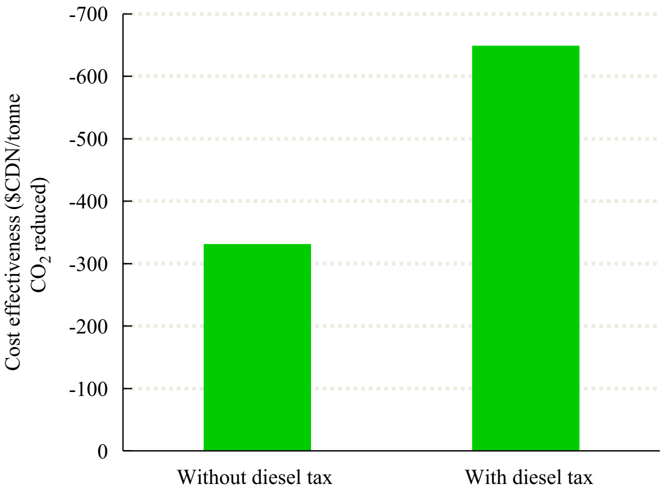

Fig. 5. Cost-effectiveness of replacing a diesel powered RCV with a CNG powered RCV.

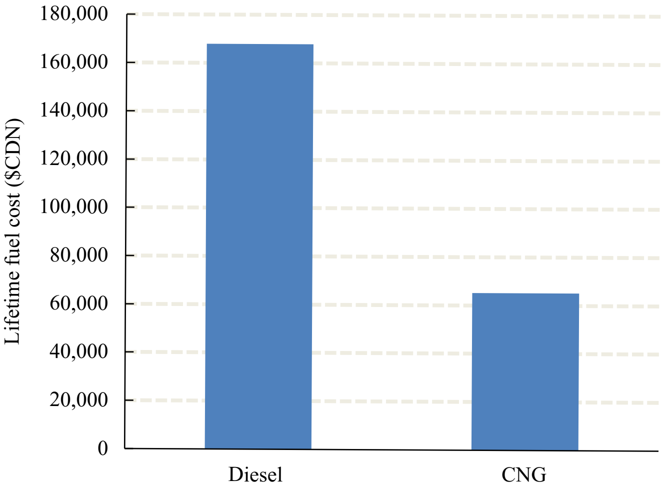

Fig. 6. Lifetime fuel cost of diesel and CNG powered RCVs.

Using GHGenius, a life cycle analysis tool, the potential impact of replacing a modern diesel powered RCV with a new CNG powered RCV is assessed from various stages in their life cycle. It is found that there is no net energy savings in replacing a diesel powered RCV with a CNG powered RCV. However, CNG powered RCVs result in significant GHG reductions compared to diesel powered RCVs, estimated to 24% based on the full life cycle. The CNG vehicle therefore has lower impact on climate change than the diesel vehicle. Moreover, CNG powered RCVs produce considerably less CAC emissions, which in turn enables locally improved urban air quality with a related potential reduction in health care costs associated with diseases caused by harmful CAC emissions. Additionally, the CNG powered RCV is found to be cost-effective in terms of tonnes of CO_2 reduced. Thus, CNG powered RCVs not only reduce the GHG and CAC emissions, but also provide significant cost savings over their lifetime.

Alternative propulsion systems exist. Powered by a fuel cell (FC), a hybrid combination of a fuel cell and batteries (HFC), or batteries alone (EV), electric motors may be used for propulsion (Rose, 2012). The fuel for the fuel cells, hydrogen, can be produced from natural gas, electrolysis, crude oil, or as a by-product of chlorine production. Batteries in a HFC are recharged by the fuel cell. However, the batteries in an EV are charged from the grid. In addition to these more developed technologies, hydraulic hybrids have come into the market recently, for example by Autocar's introduction of the E3 hydraulic hybrid RCV (Loveday, 2011). Data for LCA analysis of these technologies in an RCV are not readily available. In the framework of the LCA presented here, these technologies (FC, HFC, EV, and other hybrid concepts) can potentially be favorable to the CNG vehicle if the environmental impact of the production of the alternative drivetrain capacity does not offset the benefits of the more efficient vehicle usage. However, with respect to the goal of zero emissions, the FC, HFC, and EV are seen as the most likely long-term options for operation of refuse collection fleets. FC and HFC vehicles for this class of heavy duty vehicle with a usage pattern that involves a large number of stops per day and fast acceleration following each stop still have to be developed to be operational with the same reliability as diesel vehicles today. It can be predicted that EVs represent the favorable option in terms of both emissions during operation and overall emissions during the vehicle life cycle, on top of additional benefits such as noise reduction. However, battery-powered RCVs face the same challenges, but the first prototypes of battery powered RCVs are being tested. The results of this work suggest that using CNG powered RCVs can improve the operational economy and reduce overall emissions with an immediate impact. Combining hybrid battery electric and the CNG internal combustion engine technologies in an RCV is another interesting option that will be investigated in our future work.

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