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Regulated, greenhouse gas, and particulate emissions from lean-burn and stoichiometric natural gas heavy-duty vehicles on different fuel compositions

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HIGHLIGHTS

- Natural gas composition impacts the emissions from lean-burn engines.
- Lower THC, CH_4, and NO_x emissions for stoichiometric vs. lean-burn engines.
- NH_3 emissions produced important increases for the stoichiometric engines.
- Lubricant oil combustion was the main source for particle number formation.
- Higher carbonyl emissions for lean-burn vs. stoichiometric engines.

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ABSTRACT

The gaseous and particulate matter (PM) emissions from three heavy-duty natural gas vehicles, including a lean-burn bus with an oxidation catalyst and two stoichiometric Class 8 trucks with three-way catalysts were evaluated. Testing was performed on a range of three to seven different test fuels with varying Wobbe and methane numbers. The lean-burn vehicle showed general trends of higher emissions of nitrogen oxides (NO_x) and non-methane hydrocarbons (NMHC), and lower emissions of total hydrocarbons (THC), methane (CH_4), and formaldehyde, and improved fuel economy for the fuels with low methane numbers. The stoichiometric trucks showed some trends toward lower THC, CH_4, and NO_x emissions with the low methane number fuels, whereas some increases in NMHC, carbon monoxide (CO), and ammonia (NH_3) emissions were also observed. Results of the particle size distributions revealed bimodal size distribution profiles for all three vehicles, with a predominant nucleation mode close to 10 nm for the lean-burn bus and one of the stoichiometric trucks.

1. Introduction

Recent forecasts for natural gas (NG) resources in the United States (US) suggest that NG will be abundant and low cost for many decades, giving reason to study the efficiencies and the environmental impact of the multiple paths for its use [1]. The US government is continually pushing the use of natural gas engines in order to reduce foreign oil dependence and achieve lower greenhouse gas (GHG) emissions. The most important GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), with the transportation sector being the main contributor of the overall GHG emissions in the US [2]. Therefore, the introduction of natural gas as a potential alternative to conventional liquid fuels in the heavy-duty vehicle segment (vehicles with gross vehicle weight ratings ranging from 3.9 to 15 tons and over), which consumes a large amount of fuel, is a fast growing market. In California, the use of NG has been increasing for a number of years, due predominantly to expanded power and home heating needs. Currently, California supplies 85–90% of its needs with NG imported domestically from the Rockies, from southwest states, such as Texas, and from Canada [3]. As innovations in horizontal drilling and hydraulic fracturing are unlocking vast unconventional reserves of US domestic NG, however, the composition of imported domestic

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NG supplies could change. NG quality varies with geographic location and season as well as the degree it is processed. So far, the shale revolution is providing US domestic NG at extraordinarily low prices, which could change the economics for processing valuable natural gas liquids (NGLs), such as ethane, propane, butanes, pentanes and hexanes plus. This could lead to natural gas with high Wobbe numbers and lower methane numbers being injected into the pipeline, which could affect the combustion pathways that lead to the formation of carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and other harmful pollutants.

Natural gas vehicles (NGVs) have been implemented in a variety of applications as part of efforts to improve urban air quality, particularly within California [4–6]. Most NGVs utilize fuel cylinders containing NG that has been compressed at high pressure (~250 bars), reducing its volume by 99% compared to standard atmospheric conditions; this allows significantly greater driving range between fueling events [7]. Although NG use is widespread in California and the US due to electricity generation and domestic heating, a dedicated NG refueling infrastructure for heavy-duty NGVs is still lacking. However, the use of NG powered transit buses, school buses, and waste haulers in densely populated urban areas remains an attractive alternative to petroleum diesel, since travel distances are relatively short and a central refueling network already exists.

Two technologies have been widely being used for NG heavy-duty engines, namely lean-burn combustion and stoichiometric combustion. Older technology NGVs are equipped with lean-burn engines and oxidation catalysts to effectively control CO and formaldehyde emissions. Current heavy-duty NGVs are equipped with spark-ignited stoichiometric combustion engines, with water cooled exhaust gas recirculation (EGR) technology, and three-way catalysts (TWC) in order to meet the more stringent 2010 NO_x emission standards from the US Environmental Protection Agency (USEPA). Stoichiometric combustion engines with TWC are superior to lean-burn combustion engines with oxidation catalysts for reducing NO_x emissions [8,9]. However, stoichiometric engines with TWCs produce higher CO emissions than lean-burn engines [9]. PM emissions from both stoichiometric and lean-burn combustion NG engines are very low due to the almost homogeneous combustion of the air–gas mixture, and the absence of large hydrocarbon chains and aromatics in the fuel [10].

For NGVs, one issue that has been shown to be important with respect to emissions is the effect of changing the composition of the fuel. This is part of a broader range of issues which are classified under the term interchangeability, which is the ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions. Changes in the NG composition used in NGVs can affect the reliability, efficiency, and exhaust emissions. Previous studies conducted with small stationary source engines, heavy-duty engines/vehicles, and light-duty vehicles have shown that NG composition can have an impact on emissions [11–14]. Karavalakis et al. [15] showed higher NO_x emissions when they tested a 2002 lean-burn NG waste hauler on lower methane number/higher Wobbe number fuels. Hajbabaei and colleagues [16] reported NO_x and non-methane hydrocarbon (NMHC) emission increases for fuels with low methane contents when they tested two transit buses equipped with lean-burn NG engines. However, they did not find any fuel effect on NO_x emissions when they tested a bus with a stoichiometric combustion engine and a TWC. The effect of NG composition on exhaust emissions was also confirmed by Feist et al. [17] where they found NO_x and total hydrocarbon (THC) emissions increases with higher Wobbe number fuels under lean-burn engine combustion, while the stoichiometric engines showed no clear trends for NO_x and THC emissions with different fuels.

The present study builds on the work of Karavalakis et al. [15] and Hajbabaei et al. [16] discussed above. Specifically, these earlier studies showed that fuel composition can have important emissions impacts in lean-burn NG engines in refuse haulers and transit buses, while stoichiometric TWC-equipped NG engines in a transit bus and a refuse hauler did not show significant emissions differences for different NG fuels. This study aims at evaluating the impact of NG composition on the criteria emissions, carbonyl compounds, and particulate matter emissions from a legacy lean-burn NG engine school bus with an oxidation catalyst and two current technology stoichiometric combustion NG Class 8 trucks (vehicles with gross vehicle weight ratings ranging from 15 to 27 tons) equipped with TWCs. Given the emissions changes seen in the legacy lean-burn NG refuse hauler and transit bus, it is important to evaluate the potential emissions impacts of NG fuel composition for school buses that represent an important vehicle category that are commonly equipped with legacy lean-burn NG engines that has not been studied in terms of emissions impacts with changing NG composition. Similarly, while transit buses and refuse haulers with stoichiometric TWC-equipped NG engines have not shown strong fuel effects, it is important to also evaluate the impacts of NG fuel composition for class 8 trucks equipped with stoichiometric NG engines and TWCs, which were not included in the previous studies but represent an important segment of the heavy-duty NGV fleet that operate in urban port areas, such as the Ports of Los Angeles and Long Beach. Testing was conducted on a range of seven fuels with varying Wobbe numbers and methane numbers. Gaseous and particulate emission results are discussed in the context of changing fuel composition, along with the influences of the driving cycle and engine technology.

2. Experimental

2.1. Test vehicles and fuels

One school bus equipped with a 2005 lean-burn John Deere 8.1 L 6081H engine and an oxidation catalyst and two Class 8 trucks equipped with stoichiometric engines and cooled exhaust gas recirculation (EGR) systems and TWCs were employed in this study. The stoichiometric NGVs included a truck with a 2012 Cummins Westport ISL-G 8.9 L engine and a truck with a 2013 Cummins Westport ISX12-G engine. The test weights for the vehicles were 16.8 tons for the school bus and 28 tons for the two Class 8 trucks.

Seven fuels were employed for this study including three high methane number fuels and four high Wobbe number fuels. Fuels H1 and H2 represent historical baseline gases for Southern California and they are based on actual pipeline data. Fuel H1 was representative of Texas Pipeline gas and served as the baseline fuel, while Fuel H2 was representative of Rocky Mountain Pipeline gas. Fuel LM3 is representative of Peruvian liquefied natural gas (LNG) that was modified to meet a Wobbe number of 1385, which is a typical pipeline specification, and a methane number of 75. Fuel LM4 was representative of Untreated Middle East LNG with a high Wobbe number (above 1400). Fuel LM5 and Fuel LM6 were hypothetical fuels with compositions designed to evaluate whether two fuels with the same Wobbe number and methane number, but different compositions, would produce different exhaust emissions. Fuel H7 was a compressed natural gas (CNG) blend produced from a LNG fuel tank. Fuel H7 had almost no inert components because inerts were removed during the liquefaction process. The main properties of the test fuels are presented in Table 1. Note that not all fuels were tested on each vehicle; testing for the John Deere vehicle was conducted on all seven fuels, since previous studies showed strong fuel effects on tailpipe emissions