Energy Policy 122 (2018) 253–259

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Natural gas vehicles in heavy-duty transportation-A review☆

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ARTICLE INFO

Keywords:
Natural gas emissions
Greenhouse gas

ABSTRACT

In comparison to legacy engine technology, natural gas vehicles have become cleaner and more efficient. Improved fueling infrastructure has supported the growth of natural gas vehicles in the heavy-duty sector. The heavy-duty transportation industry greatly favors the use of diesel engine technology compared to alternative fuel strategies. Local regulations and economic incentives, however, have helped to spur adoption of natural gas vehicles in certain heavy-duty vocations. Studies have shown lower distance-specific oxides of nitrogen (NOx) emissions from the stoichiometric three-way catalyst (TWC) equipped natural gas engines compared to diesel engines equipped with diesel particulate filters (DPF) and selective catalytic reduction (SCR). This review details the progress in natural gas engine technology, presents changes to emissions rate due to technology advancements, and compares natural gas engine emissions to those of modern diesel engines.

1. Introduction

The United States Energy Information Administration (US EIA) estimates that about 29% of the total U.S energy consumption was used by the transportation industry (EIA, 2017). The demand for petroleum-based fuels for transportation continues to escalate with increases in both movements of people and goods. Gasoline and diesel account for 76% of the total energy consumed by the transportation industry. Natural gas contributes to only 4% of the total energy consumed by the transportation industry (EIA, 2017). The availability of domestic natural gas reserves, improved fueling infrastructure, and state incentives help promote the increased integration of natural gas vehicles into the transportation sector. Natural gas vehicles have increased in many captive heavy-duty fleet applications such as refuse trucks, transit buses, school buses, and delivery trucks.

Natural gas is a clean-burning fuel that is characterized by soot-free combustion when used in internal combustion engines. The high-octane properties of natural gas promote its use in spark-ignited engines rather than diesel engines. The octane number designation for liquid gasoline fuels cannot be applied to natural gas as its value exceeds the maximum scale of the octane number (Kramer et al., 2015). Typically, methane's autoignition property is designated by methane number (MN) which is referenced to a mixture of hydrogen/methane fuel. A value of 100 refers to 100% methane, while a value of zero indicates 100% hydrogen. Natural gas MN in the US is typically over 90, which translates to a motor octane number (MON) close to 130 (Karavakalis et al., 2016). Due to its high resistance to autoignition, natural gas in compression ignition requires the use of a dual-fuel combustion system with a diesel pilot injection to initiate combustion. Natural gas in a dedicated spark-ignited platform combusts soot-free (Ayala et al., 2002; Yoon et al., 2013). Alternatively, dual-fuel combustion with a diesel pilot injection will have higher soot emissions (Thiruvengadam et al., 2010). Older natural gas engines were based on a diesel engine block retrofitted with a spark-ignition platform. Retrofitted engines are fueled with natural gas which operates on a lean-burning combustion cycle aided by simple two-way oxidation catalysts. Current technology engines have been redesigned to a dedicated spark-ignited platform with cooled exhaust gas recirculation (EGR), stoichiometric fueling, and a three-way catalyst that is able to achieve the stringent U.S. Environmental Protection Agency's (US EPA) oxides of nitrogen (NOx) and particulate matter (PM) standards of 0.20 and 0.01 g/bhp-hr, respectively.

The performance of natural gas fuel in the heavy-duty sector is often evaluated against diesel fuel, which is the primary source of energy used by the transportation sector. The general opinion within the trucking industry suggests that natural gas fueled-vehicles fail to meet the reliability of their diesel-fueled counterparts in terms of vehicle range and overall durability. (Truckinginfo, 2014). Stringent emissions regulations might sway the balance towards the adoption of natural gas fuel in urban vehicle vocations, such as refuse trucks, transit buses, and delivery vehicles. A cost-effective emissions control system in the form

☆ *This article is part of a Virtual Special Issue entitled "The Potential of Natural Gas as a Sustainable Transportation Fuel".*

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https://doi.org/10.1016/j.enpol.2018.07.052
Received 5 September 2017; Received in revised form 25 July 2018; Accepted 26 July 2018
0301-4215/

of a three-way catalyst (TWC) can prove to be an economical alternative to a diesel emissions control strategy that uses diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and selective catalytic reduction (SCR). This paper will review current natural gas engine technologies and their associated emissions, comparison of regulated and greenhouse gas (GHG) emissions factors between modern diesel and natural gas engines, natural gas fuel quality and its impact on engine performance, and the technology pathways for future low NOx emissions standards.

2. Natural gas engine technology and emissions rates

Heavy-duty natural gas engines have undergone significant advancements in their engine design and emissions control strategies to conform to stringent US EPA 2010 emissions standards. Legacy natural gas engine technology was often built around a diesel block with simple changes to the fueling system to accommodate a port-fueled, lean-burn, spark-ignited engine platform. Early models operated without any aftertreatment system (Ayala et al., 2002), while subsequent models were equipped with a two-way oxidation catalyst to control high hydrocarbon and carbon monoxide (CO) emissions. A study showed that the use of oxidation catalyst reduced CO emissions by close to 62% relative to uncontrolled CNG vehicles. Furthermore, the CO emissions from uncontrolled CNG vehicles were twice that of uncontrolled diesel vehicles (Hesterberg et al., 2008). Similarly, uncontrolled CNG vehicles exhibited 18 times the hydrocarbon (HC) emissions emitted from uncontrolled diesel vehicles, while the use of oxidation catalysts on CNG vehicles reduced their HC emissions profile by over 50%. It is to be noted that a major fraction of the HC emissions observed in CNG engines is composed of methane. This is a direct result of incomplete combustion and the inability of an oxidation catalyst to remove methane efficiently. While CNG vehicles exhibit immediate benefits in PM reduction compared to diesel technology, it was evident from legacy vehicle data that the use of an oxidation catalyst is imperative to lowering emissions of CO and hydrocarbons. Furthermore, studies also showed that the lean-burn engine platform did not result in any NOx reduction benefits compared to diesel technology (Ullman et al., 2003; Yoon et al., 2013). Therefore, from a legacy engine technology standpoint, CNG vehicles were viewed only as an alternative to lower soot emissions.

Lean-burn engine technology even with the incorporation of exhaust gas recirculation (EGR), would not have been a suitable emissions control strategy to achieve the 2007 and newer US EPA heavy-duty engine standards. Specifically, an SCR aftertreatment would have been required to meet the 0.20 g/bhp-hr NOx standard. Consequently, heavy-duty natural gas engines equipped with a TWC were introduced to meet the US EPA 2010 emissions standards as early as 2007. TWC is highly efficient in controlling NOx emissions in a stoichiometric combustion platform (Baldassarri et al., 2006). An 8.9 L, Stoichiometric, cooled EGR, TWC equipped natural gas engine developed by Cummins Inc. exhibited significantly lower distance-specific NOx emissions compared to DPF-SCR equipped diesel engines (Yoon et al., 2013; Thiruvengadam et al., 2015; Quiros et al., 2016). Studies have also shown that although NOx emissions are near-zero levels with the use of TWC, stoichiometric natural gas engines are still characterized by high CO and methane emissions (Yoon et al., 2013; Thiruvengadam et al., 2015). However, equivalent brake-specific emission rates are well within the certification limit 15.5 g/bhp-hr for CO. Natural gas engines offer the advantage of using a single catalytic aftertreatment system for the abatement of NOx, while soot-free combustion results in PM emissions below the 0.01 g/bhp-hr standard without the use of a particulate filter. This is a significant advantage over its diesel counterpart that uses a series of PM and NOx aftertreatment systems to meet emissions standards. Furthermore, the use of multiple aftertreatment systems is associated with durability concerns, aftertreatment maintenance cost, use of additional reductant for SCR, fuel penalties associated with thermal management, and DPF soot regeneration processes. Vocations that are characterized by a highly transient stop-and-go type of activity can benefit from a stoichiometric TWC natural gas engine platform to realize a cost-efficient low NOx and PM vehicle technology.

Soot-free combustion from natural gas engines contributes to near-zero mass emissions of PM. Organic fractions of PM and metal-based nanoparticle emissions below the 25-nm size range have been observed to dominate the physical composition of PM from natural gas engines. These fractions, while not contributing significantly to mass emissions of PM, can result in high particle number emissions. A study observed that the exhaust nanoparticles in the size range between 6.04 and 25.5 nm strongly correlated to the mass of lubrication oil-derived elemental and metallic species characterized in the exhaust (Thiruvengadam et al., 2014). Findings from this study are in agreement with data collected on CNG transit buses in Finland (Pirjola et al., 2016). Particle size distribution measured from a newer model of the 8.9 L Cummins ISLG and a newly developed 12 L (ISX 12-G) stoichiometric engine also suggests the presence of lubrication oil-based nucleation mode particles (Karavakalis et al., 2016). The lubrication oil consumption results observed by Thiruvengadam et al. could be attributed to high vehicle mileage and consequence of engine piston seal deterioration. Interestingly, however, a relatively newer vehicle tested in the study published by Karavakalis et al. also indicates the possibility of in-cylinder combustion of lubrication oil. The results indicate that metallic and elemental nanoparticles could be an inherent characteristic of modern natural gas engines. Lowering additive content of lubrication oil used in natural gas vehicles and improving in-cylinder oil seals could lower metallic nanoparticle emissions from natural gas engines. Also, another study shows that particle number (PN) emissions downstream of TWC exceed European Union particle number (EU-PN) limits over the world harmonized test cycle (WHTC). Furthermore, it concludes that the high PN emissions to be composed of solid and metallic ash particles. The study suggested the use of exhaust particle filters as a possible approach to control PN emissions (Khalek et al., 2018).

The demands of the trucking industry are high-torque output and power density from their powertrains. Diesel engines are unrivaled in delivering these key demands from the goods movement segment of the heavy-duty transportation sector. The adoption of natural gas-fueled trucks by the goods movement fleets has been slow. This inhibition can be primarily attributed to the lower torque output of spark-ignited engines coupled with lesser range, due to fuel tank energy density. The development of a dual-fuel (natural gas/diesel) compression ignition engine was aimed at matching diesel-like performance using a fuel system that delivers both natural gas (close to 95% substitution rate) and a small quantity of diesel fuel to serve as combustion initiator (Faghani et al., 2017). Although any diesel engine can be converted to operate as dual-fuel technology, the high-pressure direct injection (HPDI) technology utilized a patented fuel injection system to introduce both diesel and natural gas directly into the combustion chamber using a single injector body. The HPDI system patented by Westport Innovations utilized a base-diesel engine (Cummins ISX 15 L) retrofitted with the HPDI fuel injection technology. From an operator perspective, the HPDI engines provided the same operating characteristics as a traditional diesel engine. HPDI dual-fuel engines also provided a mileage range that suited intercity goods movement application with a mileage of close to 400 miles. The lean diesel-like combustion meant that NOx control can be achieved only with the use of an SCR aftertreatment system. DPF and SCR equipped heavy-duty HPDI engines have shown an order of magnitude lower NOx emissions compared to similar technology diesel engine (Thiruvengadam et al., 2015). Lean combustion also resulted in a low HC emissions profile in the exhaust.

3. Certification Vs. in-use NOx emissions rates

Heavy-duty engines are certified on an engine dynamometer over