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A study of regulated and green house gas emissions from a prototype heavy-duty compressed natural gas engine under transient and real life conditions

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ABSTRACT

A newly designed Compressed Natural Gas prototype engine was benchmarked against its parent Euro V compliant engine in terms of gaseous emissions and with particular view on regulated and Green House Gas emissions. The main technological innovation included a new cylinder head equipped with a Variable Valve Actuator system designed to increase the efficiency compared to the reference throttled engine. The objective of the study was to examine the effect of this system on the operation of the prototype engine. Engine stand-alone tests represented the first step of this analysis. Afterwards, both engines were installed on the same truck and tested under different operating conditions. Vehicle tests included measurements on a chassis dynamometer as well as on-road with the aim of verifying real-world emissions. CO_2 emissions and Brake Specific Fuel Consumption of the prototype were lower compared to the reference engine, with this phenomenon being more pronounced on-road. Furthermore, reduced NO_x and CO emissions were observed under all operating conditions. On the other hand, the introduction of the prototype engine had a negative effect on CH_4 emissions. Despite that the prototype was initially designed to fulfill the EURO V standards, no pollutant exceeded the EURO VI limits over homologation cycles.

1. Introduction

An increase of total energy consumption of about 36% compared to 1995 had been recorded worldwide in 2010, and despite that current statistics show a clear deceleration of the primary energy consumption at a 10-year annual average level of 2.1% [1], predictions still indicate that energy consumption will further increase in the forthcoming future [2]. As far as GHG (Green House Gas) emissions are concerned, the combustion of fossil fuels for transport purposes is the second largest source of CO_2 emissions worldwide, accounting for about 26% in the US (United States) and 27% in the EU (European Union) of total GHG emissions in 2013 [3]. Similar figures have also been reported in China [4]. Despite that GHG emissions in other sectors decreased between 1990 and 2013, transport emissions increased significantly at the same period due to the increased amount of personal and freight transport. It is calculated that the transportation sector accounted for over half of the net increase in total US GHG emissions from 1990 to 2011 [5]. The need for a strategy addressing CO_2 from the transport sector has been recognized by the EC (European Commission) already in its 2010 Strategy on Clean and Energy Efficient Vehicles. Moreover, the EC's 2011 White Paper on transport [6] describes a pathway to increase the sustainability of the transport system with technological innovation, enabling the transition to a more efficient and sustainable European transport system.

Furthermore, stringent legislated reductions of exhaust gas emissions have already been implemented. The EURO VI emission regulation requires HD (Heavy-Duty) diesel and NG (Natural Gas) engines to reduce their NO_x, CH_4, and PM (Particulate Matter) emissions by about 75%, 55%, and 67%, respectively compared to the corresponding EURO V limits. At the same time consumers expect improved engine performance and fuel consumption as these are key market criteria in the HDV market [7]. Vehicle and engine manufacturers need to come up with technical solutions that will

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Nomenclature

A/F	Air Fuel Ratio
BSFC	Brake Specific Fuel Consumption
CBD	Central Business District
CH_4	Methane
CLD	Chemiluminescent Analyzer
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRF	Fiat Research Center
CVS	Constant Volume Sampler
EC	European Commission
ECU	Electronic Control Unit
EEV	Enhanced Environmentally Friendly Standard
EGR	Exhaust Gas Recirculation
EIVC	Early Intake Valve Closing
ETC	European Transient Cycle
EU	European Union
GHG	Green House Gas
GPS	Global Positioning System
HDV	Heavy Duty Vehicles
HFID	Heated Flame Ionization Detector
JRC	Joint Research Center
LIVO	Late Intake Valve Opening
LPG	Liquefied Petroleum Gas
NDIR	Non-Dispersive Infrared Sensor
NG	Natural Gas
NMHC	Non Methane Hydrocarbons
NO_x	Nitrogen Oxides
OBD	On-Board Diagnostics system
OC	Oxidation Catalyst
PEMS	Portable Emission Measurement System
PM	Particle Matter
PN	Particle Number
SS	Steady State
THC	Total Hydrocarbon
TWC	Three Way Catalyst
UDDS	Urban Dynamometer Driving Schedule
US	United States
VELA	Vehicle Emissions Laboratory
VVA	Variable Valve Actuator
WHM	William H. Martin
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle

result in powertrains compliant to the new emission standards and counter balance the tradeoff in fuel consumption. Taking under consideration rapidly growing energy demands, increasing public concern regarding GHG emissions, as well as the introduction of more stringent regulation regarding exhaust emissions, HDV manufacturers and operators have already been engaged in further investments in fuel and emissions reduction technologies.

In an effort to push for better fuel consumption various countries (US, Japan, China) have already set up CO_2 monitoring and labeling schemes for HDVs [8], while in the US the new phase two legislation foresees binding CO_2 targets for the near future. Europe is working on a comprehensive monitoring and reporting mechanism for single vehicle CO_2 performance that intends to cover most of the HDV market. Although currently European HDVs outperform in terms of fuel consumption the US ones [9], it is expected that the earlier introduction of limits in the US market will reverse this picture in the next decade [7]. Given the commitment of Europe to curb transport generated CO_2 emissions, additional measures, at vehicle, operator and fleet level, which will push towards an improvement in the energy efficiency of the transport sector, should be expected for the years to come.

Apart from new, and thus technologically advanced, vehicles and powertrains the improvement of fuel efficiency and environmental performance of existing HDVs is being investigated. In this direction alternative fuels have been found to play a key role as a viable alternative to conventional fossil fuels [10]. Gas fueled vehicles, powered either by CNG (Compressed Natural Gas), or other gaseous fuels such LPG (Liquefied Petroleum Gas), are considered to be an overall sustainable option for curbing CO_2 emissions and fuel consumption from HDVs [10]. NG is a gaseous fossil fuel, consisting predominantly of methane and various other gaseous species such as ethane, propane, butane, as well as inert diluents such as molecular nitrogen and carbon dioxide [11]. NG fueled HDVs are already available in the market since several years [12]. CNG engines have been employed in public use HDVs (i.e. transit and school buses, garbage collection trucks) as an alternative to diesel engines mainly due to their environmental benefits [11]. Furthermore, CNG engines are preferred due to economic related advantages such as lower market price [13] and much less exposure to fluctuating petroleum fuel prices [14]. Another important political aspect has to do with the high public visibility and acceptance of such measures. On the other hand, practical disadvantages like reduced vehicle range due to on-board storage limitations and a limited refueling infrastructure compared to petroleum fuels exist [4]. However, the use of NG vehicles in cities and suburban areas still remains attractive due to relatively short travel distances and centralized refueling for many fleets [11]. It is estimated that CNG is the second most common fuel source for transit buses after diesel [5]. According to Yoon et al. [15] the NG urban bus population (including compressed and liquefied NG) has more than doubled in the US during the last decade, while in the state of California they increased from 24% of the total bus fleet in 2001 to 45% in 2011 [16]. Other studies also report increasingly usage of new buses and trucks powered by CNG engines in China [17], the US [18] and Europe [19]. Finally, CNG trucks for garbage collection purposes have been extensively used in the US for more than a decade [20,21], as well as in other areas worldwide such as in Asia [22] and Europe [23,24].

There are both positive and negative aspects associated with the application of gaseous fuels in HDVs in terms of pollutants emissions. It is mentioned that the transition from diesel to NG fuels results in significant reductions of NO_x emissions [13]. For instance, 2 CNG trucks were found to emit 3–4 times lower NO_x when compared to a reference EURO V/EEV diesel vehicle [25]. Hesterberg et al. [26] reported lower NO_x from several CNG transit buses equipped with a TWC (Three-Way Catalyst) compared to diesel buses of the same classification. Fontaras et al. [27] also found significantly lower on-road NO_x emissions from 3 CNG garbage trucks when compared to a reference diesel truck. Further to NO_x, most researchers have found that CNG trucks and buses emit less CO and NMHC (Non-Methane Hydrocarbons) than diesel HDVs [11,15]. However, this largely depends on parameters such as the specific technology tested and the condition of the vehicles [28]. In case of older vehicles PM emissions of CNG engines appear to be up