TECHNICAL PAPER

ISSN:1047-3289 *J. Air & Waste Manage. Assoc.* 61:427–442
DOI:10.3155/1047-3289.61.4.427

Regulated and Unregulated Emissions from Highway Heavy-Duty Diesel Engines Complying with U.S. Environmental Protection Agency 2007 Emissions Standards

Imad A. Khalek, Thomas L. Bougher, and Patrick M. Merritt
Southwest Research Institute, San Antonio, TX

Barbara Zielinska
Desert Research Institute, Reno, NV

ABSTRACT
As part of the Advanced Collaborative Emissions Study (ACES), regulated and unregulated exhaust emissions from four different 2007 model year U.S. Environmental Protection Agency (EPA)-compliant heavy-duty highway diesel engines were measured on an engine dynamometer. The engines were equipped with exhaust high-efficiency catalyzed diesel particle filters (C-DPFs) that are actively regenerated or cleaned using the engine control module. Regulated emissions of carbon monoxide, nonmethane hydrocarbons, and particulate matter (PM) were on average 97, 89, and 86% lower than the 2007 EPA standard, respectively, and oxides of nitrogen (NO_x) were on average 9% lower. Unregulated exhaust emissions of nitrogen dioxide (NO_2) emissions were on average 1.3 and 2.8 times higher than the NO_2 emissions reported in previous work using 1998- and 2004-technology engines, respectively. However, compared with other work performed on 1994- to 2004-technology engines, average emission reductions in the range of 71–99% were observed for a very comprehensive list of unregulated engine exhaust pollutants and air toxic contaminants that included metals and other elements, elemental carbon (EC), inorganic ions, and gas- and particle-phase volatile and semi-volatile organic carbon (OC) compounds. The low PM mass emitted from the 2007 technology ACES engines was composed mainly of sulfate (53%) and OC (30%), with a small fraction of EC (13%) and metals and other elements (4%). The fraction of EC is expected to remain small, regardless of engine operation, because of the presence of the high-efficiency C-DPF in the exhaust. This is different from typical PM composition of pre-2007 engines with EC in the range of 10–90%, depending on engine operation. Most of the particles emitted from the 2007 engines were mainly volatile nuclei mode in the sub-30-nm size range. An increase in volatile nanoparticles was observed during C-DPF active regeneration, during which the observed particle number was similar to that observed in emissions of pre-2007 engines. However, on average, when combining engine operation with and without active regeneration events, particle number emissions with the 2007 engines were 90% lower than the particle number emitted from a 2004-technology engine tested in an earlier program.

IMPLICATIONS
To meet the 2007 EPA heavy-duty highway PM emissions standard, engine manufacturers have elected to equip engine exhaust with a high-efficiency C-DPF. Because of the use of the C-DPF, the PM emissions were 86% below the 2007 standard, and many unregulated gas and particle-phase emissions compounds were substantially lower than those emitted from pre-2007-technology engines. Significant air quality benefits can be expected as the C-DPF technology, or other equivalent technology, continues to be applied to future highway engines and to other nonroad and stationary diesel engines.

INTRODUCTION
Model year 2007 heavy-duty highway diesel engines sold in the United States must comply with the 2007 U.S. Environmental Protection Agency (EPA) particulate matter (PM) emission standard of 0.01 g/hp-hr, a 90% reduction from the 1994 limit of 0.1 g/hp-hr.[1] The 2007 highway engines must also comply with a phased-in oxides of nitrogen (NO_x) limit of approximately 1.2–1.5 g/hp-hr, a 38–50% reduction from the 2004 limit. This will be followed by a NO_x limit of 0.20 g/hp-hr for 2010 heavy-duty highway diesel engines. Compliance with carbon monoxide (CO) and nonmethane hydrocarbon (NMHC) emissions limits of 15.5 and 0.14 g/hp-hr, respectively, is also required.

Complying with 2007 emission limit challenges required on-highway heavy-duty diesel engines to adopt design and external equipment changes, most notably the addition of a high-efficiency catalyzed diesel particle filter (C-DPF) in the exhaust system to trap PM. A C-DPF requires periodic cleaning to prevent an unacceptable exhaust system pressure increase as the C-DPF collects PM. The cleaning process is called "regeneration" and it is achieved by several techniques. For engines in this investigation, diesel fuel injection into the diesel oxidation catalyst (DOC) or igniting a burner within the exhaust system achieved regeneration. The main goal of fuel injection or a burner is to elevate the exhaust stream temperature to oxidize soot trapped in the C-DPF to reduce engine exhaust back pressure. In addition to the exhaust