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Greenhouse gas emissions from heavy-duty natural gas, hybrid, and conventional diesel on-road trucks during freight transport

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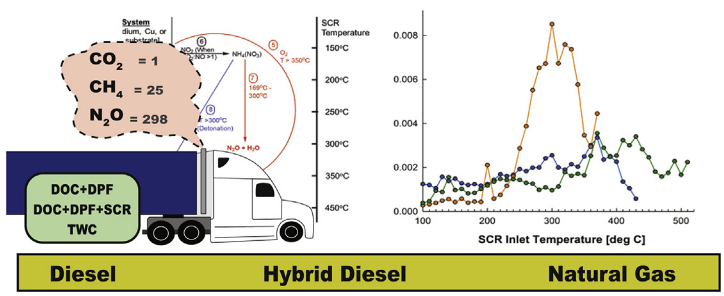
HIGHLIGHTS

- Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) measured from trucks.
- Seven trucks were measured on-road including diesel, hybrid diesel, and natural gas.
- N_2O was ten times higher for diesel trucks with selective catalytic reduction.
- CO_2 equivalent (CO_2-eq) considers relative warming potentials of all three gases.
- Natural gas and hybrid diesel vehicles had lower CO_2-eq for selected routes only.

GRAPHICAL ABSTRACT



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ABSTRACT

Heavy-duty on-road vehicles account for 70% of all freight transport and 20% of transportation-sector greenhouse gas (GHG) emissions in the United States. This study measured three prevalent GHG emissions – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – from seven heavy-duty vehicles, fueled by diesel and compressed natural gas (CNG), and compliant to the MY 2007 or 2010 U.S. EPA emission standards, while operated over six routes used for freight movement in California. Total combined (tractor, trailer, and payload) weights were 68,000 ± 1000 lbs. for the seven vehicles. Using the International Panel on Climate Change (IPCC) radiative forcing values for a 100-year time horizon, N_2O emissions accounted for 2.6–8.3% of total tailpipe CO_2 equivalent emissions (CO_2-eq) for diesel vehicles equipped with Diesel Oxidation Catalyst, Diesel Particulate Filter, and Selective Catalytic Reduction system (DOC + DPF + SCR), and CH_4 emissions accounted for 1.4–5.9% of CO_2-eq emissions from the CNG-powered vehicle with a three-way catalyst (TWC). N_2O emissions from diesel vehicles equipped with SCR (0.17–0.30 g/mi) were an order of magnitude higher than diesel vehicles without SCR (0.013–0.023 g/mi) during highway operation. For the vehicles selected in this test program, we measured 11–22% lower CO_2-eq emissions from a hybrid compared to conventional diesel vehicles during transport over lower-speed routes of the freight transport system, but 20–27% higher CO_2-eq emissions during higher-speed routes. Similarly, a CNG vehicle emitted up to 15% lower CO_2-eq compared to conventional diesel vehicles over more neutral-grade highway routes, but emitted up to 12% greater CO_2-eq emissions over routes with higher engine loads.

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1. Introduction

Anthropogenic greenhouse gas (GHG) emissions have increased since the pre-industrial era, and in 2015, over 100 nations have agreed upon and adopted approaches (i.e. *The Paris Agreement*) to limit warming to less than 2 °C to prevent additional and irreversible economic, ecological, and infrastructure damage (IPCC, 2014; Meinshausen et al., 2009; United Nations 2015; Solomon et al., 2009; Tol; Walther et al., 2002). The United States is the second-highest GHG-emitting nation in the world, and in recent years emits about 15% of global GHG emissions (JRC, 2016). Several actions are already underway within the United States to reduce GHG emissions. In California, the Global Warming Solutions Act (AB 32) requires that California achieve 1990 emission levels by 2020 (CARB, 2014), Senate Bill (SB) 32 requires 40% below 1990 levels by 2030 (California, 2016), and Executive Order S-3-05 requires 80% below 1990 levels by 2050 (Schwarzenegger, 2005).

Mobile sources (including cars, trucks, off-road equipment, and others) currently account for 36% of California's GHG emissions (CARB, 2014). New passenger cars sold in the United States must emit ~5% lower GHG emissions for each model year (MY) between 2017 and 2025 (CARB, 2012). Another major source is heavy-duty (HD) on-road vehicles weighing greater than 14,000 lbs., where the federal Phase I and II GHG requirements are expected to reduce the sector's GHG emissions by nearly 40% for MY 2027 vehicles compared to a MY 2014 baseline (U.S. EPA, 2011; U.S. EPA, 2015a). The engines that power HD on-road vehicles have standards set for three GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Methane is a short-lived climate pollutant (average lifetime = 12.4 years), with global warming potential (GWP) equal to 25 times higher than CO_2 over a 100-year time horizon; N_2O is also a potent GHG with a longer lifetime (121 years) and a GWP of 298 over a 100-year time horizon (IPCC, 2013). N_2O is not only a heat-trapping pollutant, but also is the largest known remaining anthropogenic threat to the stratospheric ozone layer (Kanter et al., 2013). The agriculture sector is the predominant global control target for N_2O, but emissions reductions are also needed from mobile sources (Shcherbak et al., 2014). CO_2 emissions are regulated for MY 2014 and newer heavy-duty on-road engines depending on the application of the truck in which it will be operated (627–432 g CO_2 per brake-horsepower-hr [bhp-hr]), and CH_4 and N_2O standards (both 0.1 g/bhp-hr) apply to MY 2015 and newer engines (Table S1). The engine dynamometer Supplemental Emission Test (SET) assesses performance of engines sold in tractors over various steady-state torque and engine speeds. In addition to the engine standards, the Greenhouse Gas Emission Model (GEM) assesses compliance to applicable vehicle CO_2 or fuel economy standards (64–92 g CO_2/ton-mile of payload for tractors operating in freight applications, Table S2).

This paper summarizes the CO_2, N_2O, and CH_4 emissions from seven modern technology HD vehicles during real-world operation along major freight corridors in California. The on-road trucking industry hauls about 70% of all freight in the United States (U.S. EPA, 2015a), and therefore a sustainable freight system with low overall GHG emissions must ensure on-road trucks are achieving intended benchmarks. This assessment includes one diesel engine certified to the MY 2007 emission standard, one hybrid diesel vehicle with a MY 2011 engine, four MY 2013 or 2014 conventional diesel engines, and one MY 2013 compressed natural gas (CNG) engine. Total vehicle weight was 68,000 ± 1000 lbs. to correspond to median freight hauling loads (39,250 lbs. of payload = 19.63 tons). This study reports emissions from 96 total trips lasting 1–2 h each, all starting and beginning from a stop, for six route classifications (Figs. S1 and S2). Three of the six routes were defined by repeat trip over the same geographical locations (Local Drayage, Near-Dock Drayage, and Urban Arterial). For the other three routes (Hill Climb, Interstate, and Regional Highway), trips were performed in many locations throughout California, and classification was determined operationally.

2. Methods

2.1. Test vehicles and trailer

Table 1 lists the vehicles, engines, certification information, and fuels for each vehicle in the study. Vehicles were selected to represent four emission technology groups: (1) one conventional diesel certified to the MY 2007 emission standards with DOC + DPF aftertreatment; (2) four conventional diesel engines (MY, 2013 through 2014) certified to the MY 2010 emission standards with a DOC + DPF + SCR aftertreatment system; (3) one hybrid diesel engine (MY, 2011) certified to a transition family emission limit (FEL) of 0.46 g NOx/bhp-hr using a DOC + DPF but no SCR; and (4), one stoichiometric compressed natural gas (CNG) engine (MY, 2013) certified to the MY 2010 emission standard using a TWC. All seven engines utilized exhaust gas recirculation (EGR) as part of the emission control system. All seven engines had certification PM emissions of at least three times below the current standard (0.01 g/bhp-hr), and CO + non-methane hydrocarbon (NMHC) emission of at least two times below current standards (15.5 g CO/bhp-hr and 0.14 g NMHC/bhp-hr) as reported elsewhere by Quiros et al. (2016). Odometer readings were below the regulatory useful life limit of 435,000 miles for Vehicles 1–5, 7, and 185,000 miles for Vehicle 6.

All tractors pulled the mobile laboratory (TEMS) affixed to a flatbed trailer along with an on-board power generator, and other emissions measurement equipment. Previous works have evaluated the TEMS system (Kappanna et al., 2013) and the sampling configuration used in the study (Quiros et al., 2016). The trailer was not equipped with any aerodynamic drag-reducing equipment, such as trailer skirts as required by U.S. EPA SmartWay program requirements, although the flatbed trailer used in this study may have exhibited some drag-reducing properties due to its low ground clearance. The TEMS is equipped with a constant volume sampler (CVS) set to approximately 1800 cubic feet per minute (CFM).

2.2. Instruments and data processing

Diluted CO_2 was measured using a MEXA 7200d (Horiba Ltd., Japan) laboratory-grade bench analyzer reporting other criteria gases used for regulatory compliance testing. Total molar flow rates for dilute CO_2 measurements were obtained from the total flow of the CVS.

N_2O and CH_4 emissions were measured in real-time using an MKS Instruments Inc. (San Jose, CA, USA) MultiGas 2030-HS High Speed Fourier-Transform Infrared (FTIR) gas analyzer. Minimum detectable concentrations (MDC) for N_2O and CH_4 were 0.25 and 0.5 ppm, respectively. N_2O and CH_4 were measured from the raw exhaust, and CO_2 was measured from the CVS in the mobile laboratory. Exhaust flow was measured using a pitot-tube high-speed electronic flow module (EFM-HS) manufactured by Sensors, Inc. (Saline MI, USA). The Engine control unit (ECU) data broadcast over the controller area network using the SAE J1939 protocol were recorded to measure engine torques, engine speed, temperatures at various locations of the engine and aftertreatment system, and other parameters. Raw emissions data were post-processed according to CFR guidelines for performing drift correction (1065.672), performing dry-to-wet conversion of analyzers operating downstream of a chiller (1065.659), and for performing dilution-air background correction (1065.667).