Science of the Total Environment 634 (2018) 909–921

Contents lists available at ScienceDirect

Science of the Total Environment

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

Real-world exhaust temperature profiles of on-road heavy-duty diesel vehicles equipped with selective catalytic reduction

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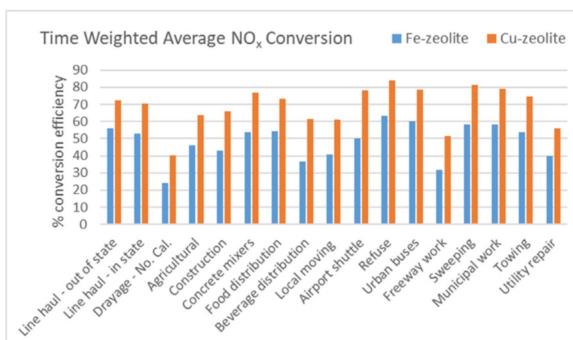
HIGHLIGHTS

- Real-world exhaust temperature data of 90 heavy-duty diesel vehicles (HDDVs) show high variability by vocational use.
- Exhaust temperature at selective catalytic reduction (SCR) inlet is found to be lower than 200 °C for 11-70% of the time.
- Copper zeolite SCR would be more effective at controlling NO_x emissions from HDDVs than Iron zeolite SCR.
- NO_x emissions from HDDVs equipped with SCR could be higher than expected for a significant part of their operations.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form 3 March 2018
Accepted 29 March 2018
Available online xxxx

Keywords:
Heavy-duty diesel vehicles
In-use emissions
Selective catalytic reduction
Exhaust temperature
Portable activity measurement system
NO_x control efficiency

ABSTRACT

On-road heavy-duty diesel vehicles are a major contributor of oxides of nitrogen (NO_x) emissions. In the US, many heavy-duty diesel vehicles employ selective catalytic reduction (SCR) technology to meet the 2010 emission standard for NO_x. Typically, SCR needs to be at least 200 °C before a significant level of NO_x reduction is achieved. However, this SCR temperature requirement may not be met under some real-world operating conditions, such as during cold starts, long idling, or low speed/low engine load driving activities. The frequency of vehicle operation with low SCR temperature varies partly by the vehicle's vocational use. In this study, detailed vehicle and engine activity data were collected from 90 heavy-duty vehicles involved in a range of vocations, including line haul, drayage, construction, agricultural, food distribution, beverage distribution, refuse, public work, and utility repair. The data were used to create real-world SCR temperature and engine load profiles and identify the fraction of vehicle operating time that SCR may not be as effective for NO_x control. It is found that the vehicles participated in this study operate with SCR temperature lower than 200 °C for 11–70% of the time depending on their vocation type.

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https://doi.org/10.1016/j.scitotenv.2018.03.362
0048-9697/

This implies that real-world NO_x control efficiency could deviate from the control efficiency observed during engine certification.

1. Introduction

On-road heavy-duty diesel vehicles are a major source of nitrogen oxides (NO_x) emissions in the United States (US), accounting for about 16%–18% of total NO_x emission inventory from all sources in the past decade (US Environmental Protection Agency, 2016). To help reduce NO_x emissions from this source, the US Environmental Protection Agency (EPA) and the California Air Resources Board (ARB) have adopted new diesel engine exhaust emissions standards that require model year (MY) 2010 and later on-road heavy-duty diesel vehicles to meet a NO_x emission standard of 0.20 g/bhp-hr over the transient Federal Test Procedure (FTP) engine dynamometer cycle. This is a 90% reduction from the previous standard for MY 2007–2009 engines. In addition, emissions from the engines are required to be within not-to-exceed (NTE) limits while operating within a specific engine operating region defined by a series of engine torque and speed conditions (US Environmental Protection Agency, 2004). This is intended to demonstrate in-use compliance under a wide range of driving conditions with a particular focus on highway driving.

Heavy-duty diesel engines in the US market have in most cases been using advanced engine exhaust aftertreatment, specifically selective catalytic reduction (SCR), to meet the 2010 NO_x emission standard (Jääskeläinen and Majewski, 2016). In SCR, NO_x is converted into nitrogen and water by the reaction with ammonia over a special catalyst. Typically, the exhaust gas temperature at SCR inlet (referred to as SCR temperature hereinafter) needs to be at least 200 °C for a significant level of NO_x conversion to occur (Slimarik et al., 2014; Cavataio et al., 2007). Heavy-duty diesel engines tested on the FTP cycle generally produce SCR temperature between 250 and 350 °C during the majority of the cycle (DieselNet, 2017). In addition, the NTE NO_x emission limits do not apply when the SCR temperature is lower than 250 °C (US Environmental Protection Agency, 2004). Thus, SCR has been widely used to meet the 2010 NO_x emission standard and achieve the in-use compliance.

However, a number of researchers have found that real-world NO_x emissions from SCR-equipped heavy-duty diesel vehicles can vary significantly, depending on the operating profile of a vehicle (Miller et al., 2013; Kotz et al., 2017). While SCR systems can generally provide good NO_x conversion efficiencies under highway driving conditions where engine load and SCR temperature are high, researchers have observed higher NO_x emissions under conditions where engine load and SCR temperature are relatively low such as during cold starts, long idling, and low speed driving (Misra et al., 2013; Thiruvengadam et al., 2015; Misra et al., 2016; Yoon et al., 2016; Carder et al., 2014). Remote sensing studies have also found SCR-equipped heavy-duty diesel trucks at weight scales and at ports to have high NO_x emissions when operating under these conditions (Bishop et al., 2012, 2013; Dallmann et al., 2011).

The operating conditions under which today's SCR-equipped heavy-duty diesel vehicles emit higher real-world NO_x emissions are associated with low SCR temperature (Misra et al., 2013). The frequency of these operating conditions, and thus the SCR temperature profile of a vehicle, could vary greatly by vocational use. For example, one would expect a drayage truck to have more idling time than a line haul truck. However, there is very little public data on in-use activity of heavy-duty diesel vehicles. Most of the data in literature do not differentiate vehicles by vocation (Boriboonsomsin et al., 2012). On the other hand, the data that do differentiate vehicles by vocation only contain vehicle activity data but have no engine activity data (Battelle, 1999; Jack Faucett Associates, 2002). In recent work, both vehicle and engine activity data were collected from 125 conventional diesel and diesel hybrid electric trucks in four vocations—beverage delivery, parcel delivery, linen delivery, and food distribution—but only a small fraction of these trucks were equipped with SCR (Thornton et al., 2015).

Therefore, it is important to collect new vehicle and engine activity data from today's SCR-equipped heavy-duty diesel vehicles in a variety of vocations, and then examine their real-world SCR temperature profiles to identify the fraction of vehicle operation with low SCR temperatures where SCR may not be as effective for NO_x control. This will lead to a better understanding of the potential impact of vocation-specific activity patterns on the effectiveness of current implementations of SCR in vehicles meeting the 2010 NO_x emission standard and on NO_x emission inventories of these vehicles. In this article, we describe the collection of real-world vehicle and engine activity data from a large number of heavy-duty diesel vehicles in California in a variety of vocations, and examine their SCR temperature profiles by vocation.

2. Material and methods

A large-scale data collection program was conducted in which vehicle and engine activity data were collected from 90 heavy-duty vehicles in California that make up 19 different groups defined by a combination of vocational use and geographic region. These include line haul, drayage, construction, food distribution, refuse, and utility repair, among others. Almost all of the vehicles have engine MY 2010 or newer and are equipped with SCR. The data were collected using advanced data loggers that recorded vehicle speed, position, and >170 engine parameters at the frequency of 1 Hz. The data collection effort spanned from November 2014 to September 2016, but was intermittent depending on when the participating fleets were successfully recruited and when the vehicles and data loggers were available. For each vehicle, the data were collected for a minimum period of one month with many vehicles having data collected for several months. Details of the data loggers and vehicles are described below.

2.1. Data loggers

Since the late 1990s, GPS data loggers have increasingly been used in vehicle activity studies as their cost has become lower and their accuracy continued to improve. In GPS-based vehicle activity studies, GPS data loggers are instrumented on vehicles to record the vehicles' position (latitude, longitude, and altitude), speed, and the associated timestamp. These data are recorded at high frequency, typically ranging from 0.5 to 10 Hz. Since a GPS data logger can be powered by the vehicle, either through the cigarette lighter or the on-board diagnostic (OBD) port, it can record vehicle activity data for a long period of time (several months). Recently, on-board engine control unit[1] (ECU) data loggers have emerged as a useful tool for vehicle and engine performance studies. Once connected to the vehicle's Controller Area Network (CAN) bus through the OBD port (for most light-duty vehicles) or the J1939 port (for most heavy-duty vehicles), an ECU data logger can record engine parameters such as wheel speed, engine speed, fuel rate, etc. at a high frequency.[2] Since the data logger is powered through

[1] Sometimes also known as electronic control unit.

[2] The frequency of the logged data for each parameter depends on the broadcasting rate of the respective parameter on the CAN bus. If the data logger requests data at a higher rate than broadcast on the CAN bus, the data will be interpolated to the logger-requested frequency.