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Estimation of bus emission models for different fuel types of buses under real conditions

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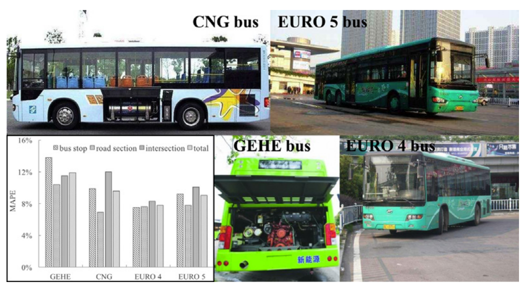
HIGHLIGHTS

- Different fuel types of buses had no or small impacts on the bus operation (speed and acceleration).
- Differences in emissions between different locations and fuel types were statistically significant.
- CNG buses tended to have lower CO and NO_X emissions, but CO_2 and HC emissions were higher.
- By contrast, CO and NO_X levels were quite high in both EURO 4 and EURO 5 buses.
- GEHE buses performed best, with lowest emission values for CO_2, CO, and NO_X.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban buses are heavy vehicles that move frequently throughout the day, and most of them are propelled by heavy-duty diesel engines. For these reasons, they have energy and environmental impacts that should not be ignored. Consequently, the primary objectives of this study were to compare the changes in bus speed, acceleration, and emissions between bus stops, intersections, and road sections by applying statistical methods; and to develop a vehicle specific power (VSP)-based artificial neural network (ANN) model to estimate emissions of CO, HC, NO_X, and CO_2 for four different fuel types of buses including gas-electric hybrid electric buses (GEHE bus), compressed natural gas buses (CNG bus), EURO 4 heavy-duty diesel engine buses (EURO 4 bus), and EURO 5 heavy-duty diesel engine buses (EURO 5 bus). The results of *t*-tests (with *p*-values varying between <0.001 and 0.026, which were not >0.050) showed that the differences in emissions between different locations and between different fuel types of buses were all statistically significant. In addition, to evaluate the performance of the proposed method, a polynomial regression model using linear, quadratic, and cubic terms of transient speed and acceleration was utilized for comparison. According to the results, the proposed method had more accurate and reliable estimation, which increased the lower 10% of absolute percentage error (Lower-10% APE) by 65.2%; reduced mean absolute percentage error (MAPE) by 41.4%, root mean squared error (RMSE) by 44.9%, and mean absolute error (MAE) by 43.5%; and increased R-squared from 0.659 to 0.781.

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1. Introduction

Environmental awareness and sustainable development are growing concerns in both developed and developing countries (Abuzo and Muromachi, 2014; Lumbreras et al., 2008; Vallamsundar et al., 2016; Gao et al., 2015). Many previous research studies have explored air quality deterioration from traffic sources (Alam et al., 2014; Vedrenne et al., 2016; Jiao and Frey, 2014; Lang et al., 2016). For instance, Wang et al. (2016) found that road transportation was a major source of air pollutant emissions, such as NO_X, CO, HC, and CO_2 as a greenhouse gas. Congested traffic corridors in dense urban areas are key contributors to the degradation of urban air quality (Moore et al., 2012; Zhang et al., 2011). In light of this, more and more countries have developed public transportation to reduce congestion and improve the environment.

However, we cannot ignore the energy and environmental problems caused by transit buses. Most of these buses are propelled by heavy-duty diesel engines, which are major contributors to urban environment pollution, because they are the only diesel vehicles which move frequently throughout the day (Yu and Li, 2014; Song et al., 2015; Fu et al., 2013). Buses add to pollution levels through the direct emission of the pollutants from the vehicles and by the resulting chemical reactions of the emitted pollutants with each other or with the existing materials in the atmosphere (Bartin et al., 2007; Ahn and Rakha, 2008; Tadano et al., 2014). In particular, bus stops and intersections can create congestion, which leads to increased fuel consumption and emission rates as a result of speed reduction and frequent stop-and-go operations (Li et al., 2012; Moore et al., 2012; Lv and Zhang, 2012). According to one relevant reference (Yu and Li, 2014), about 50% of bus trip emissions were generated near stops and intersections. Thus, measuring and modeling emission effects for urban buses, and exploring the difference in bus emissions between bus stops, intersections, and road sections, are the emphasis of this study.

As more and more researchers focus on vehicle emission estimation, two categories of methods have been reported in mainstream references (Tong et al., 2000). The first category is conducted by driving the vehicle through standard driving cycles in a laboratory (St. Denis et al., 1994). For instance, Wang et al. (2010) studied the emissions from traffic interrupted transport microenvironments. They developed the composite line source emission (CLSE) model to evaluate the particle number concentrations along the platform by constructing one representative line source. However, in the study of Wang et al. (2010), the emission rate from a dynamometer test was used to estimate emissions in a driving mode regardless of different speeds or acceleration in this state. Thus, the test conditions are restrictive in that they may not represent real-world conditions (Joumard et al., 1995; Rapone et al., 1995; St. Denis et al., 1994). In the second category, emissions are measured directly from testing vehicles under actual on-road driving conditions (Zhang et al., 2018), which is the method selected for this study. Li et al. (2012) used second-by-second GPS data (including latitude, longitude, time, and speed) to estimate vehicle specific power (VSP) and bus emissions near bus stops. Unal et al. (2003) put forward an idea that a study can be designed and executed to collect, analyze, and interpret real-world on-road emissions data, using a comparison associated with a change in the traffic control. They found the total emissions of NO, CO, and HC were higher in the congested situation compared to the uncongested situation. Frey et al. (2007) and Zhai et al. (2008) assessed the relationship between VSP and fuel consumption or emissions and found that VSP, as an explanatory variable, is highly correlated with emissions. In recent years, the Portable Emission Measurement System (PEMS) has become an important method for vehicle real-world emission research because it can obtain real-time emission characteristics directly from the tailpipe for real-world driving (Yu et al., 2016). The on-board vehicle emission measurements with PEMS have been applied to measure gaseous pollutants from urban buses (Wang et al., 2011; Liu et al., 2011). For instance, Wyatt et al. (2014) investigated the impact of road grade on carbon dioxide (CO_2) emissions of passenger cars with PEMS.

Even though previous studies have, to some extent, been conducted to explore the emissions from urban buses, they do suffer from several limitations. Literature review results indicate that the following two issues have not been addressed in previous studies: 1) previous studies seldom analyze the differences in bus emissions for different locations including bus stops, intersections, and road sections; and 2) the existing research studies merely consider one type of buses for their on-road testing (typically diesel buses), and rarely contribute a useful comparison of results on different fuel types of urban buses. Under current engineering practice in China, there are four fuel types of buses: 1) gas-electric hybrid electric buses (GEHE bus); 2) compressed natural gas buses (CNG bus); 3) EURO 4 heavy-duty diesel engine buses (EURO 4 bus); and 4) EURO 5 heavy-duty diesel engine buses (EURO 5 bus). EURO 4 bus and EURO 5 bus denote the buses using EURO 4 and EURO 5 emissions regulations for heavy-duty engines, respectively. EURO 4 heavy duty emissions regulations have applied to new vehicles registered since 2006 and were replaced by EURO 5 regulations which have applied to new vehicles registered since 2009. The major difference between the EURO 4 and EURO 5 is the reduction in the emission limits for each pollutant (RSA, 2016).

In light of these considerations, this study aims to achieve two primary objectives. The first objective is to compare the changes in emissions of CO, CO_2, HC, and NO_X between bus stops, intersections, and road sections for four types of buses by applying *t*-tests and descriptive statistics. The second objective is to develop a bus emission estimation method that takes into account the statistical test for different locations (bus stops, intersections, and road sections) and analytical model for different types of buses (GEHE bus, CNG bus, EURO 4 bus, and EURO 5 bus). An artificial neural network (ANN) is particularly suitable for modeling multifactor, uncertainty and nonlinearity (Kukkonen et al., 2003). Unlike the stochastic approach, it makes no prior assumptions about the data distribution (Cai et al., 2009). Therefore, ANN has been increasingly applied and evaluated for the regression analysis and forecasting of air pollutant emissions (Antanasijević et al., 2018). Stamenković et al. (2017) described the development of a model for NO_X emission prediction based on ANN and on available sustainability, industrial, and economic parameters as input variables. Antanasijević et al. (2014) developed a model for greenhouse gas (GHG) emissions forecasting for European countries using an ANN approach. The results showed that the developed ANN models performed better than the multiple linear regression (MLR) model. In addition, an attempt had been made to develop an ANN for real-world emission of CO, HC, and NO_X using on-board emissions measurement. It showed that the ANN model could be used to predict the traffic emissions under real-world conditions (Jaikumar et al., 2017). As mentioned above, no significant use of ANN in urban bus emissions (especially for different fuel types of buses) is recorded in the literature. Thus, the VSP-based ANN model is chosen for this study.

According to a relevant reference (Zhang et al., 2013), the main sources of $PM_{2.5}$ in urban areas are soil dust, coal combustion, biomass burning, industrial pollution, and secondary inorganic aerosol, with contributions of 16%, 14%, 13%, 28%, and 26%, respectively. The $PM_{2.5}$ from traffic and waste incineration emission accounts for merely 3%. Thus, $PM_{2.5}$ is not included in this study.

2. Methods

In order to compare the changes in emissions of CO, CO_2, HC, and NO_X at different locations (bus stops, intersections, and road sections) and estimate these four emissions for different types of buses (GEHE, CNG, EURO 4, and EURO 5), the research team utilized the following methods in this study: 1) testing differences in emissions of CO, CO_2, HC, and NO_X. On the basis of the collected emission data, statistical analysis is conducted to test the differences between bus stops,