Applied Energy 161 (2016) 101–111

Contents lists available at ScienceDirect

Applied Energy

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

Improving urban bus emission and fuel consumption modeling by incorporating passenger load factor for real world driving

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HIGHLIGHTS

- We proposed a method to quantify influence of passenger load on bus emissions and fuel consumption.
- Influence of passenger load on emission and fuel consumption rate were related to speed and acceleration.
- Per-passenger emission and fuel consumption factors decreased as the passenger load increased.
- We compared the emission (or fuel consumption)–VSP correlations with and without passenger load included.

ARTICLE INFO

Article history:
Received 25 January 2015
Received in revised form 26 September 2015
Accepted 29 September 2015
Available online 22 October 2015

Keywords:
Urban diesel bus
Emission
Fuel consumption
Passenger load
VSP
PEMS

ABSTRACT

Vehicle Specific Power (VSP) has been increasingly used as a good indicator for the instantaneous power demand on engines for real world driving in the field of vehicle emission and fuel consumption modeling. A fixed vehicle mass is normally used in VSP calculations. However, the influence of passenger load was always been neglected. The major objective of this paper is to quantify the influence of passenger load on diesel bus emissions and fuel consumption based on the real-world on-road emission data measured by the Portable Emission Measurement System (PEMS) on urban diesel buses in Nanjing, China. Meanwhile, analyses are conducted to investigate whether passenger load affected the accuracy of emission and fuel consumption estimations based on VSP. The results show that the influence of passenger load on emission and fuel consumption rates were related to vehicle's speed and acceleration. As for the distance-based factors, the influence of passenger load was not obvious when the buses were driving at a relative high speed. However the effects of passenger load were significant when the per-passenger factor was used. Per-passenger emission and fuel consumption factors decreased as the passenger load increased. It was also found that the influence of passenger load can be omitted in the emission and fuel consumption rate models at low and medium speed bins but has to be considered in the models for high speed and VSP bins. Otherwise it could lead to an error of up to 49%. The results from this research will improve the accuracy of urban bus emission and fuel consumption modeling and can be used to improve planning and management of city buses and thus achieve energy saving and emission reduction.

1. Introduction

Vehicle Specific Power (VSP) is defined as the instantaneous power demand to an engine per unit mass of a vehicle. The VSP-based modeling approach is becoming more and more popular in the estimation of the vehicular emissions and fuel consumption (FC) [1–3] especially for real world driving. VSP that contains the information of vehicle speed, acceleration, vehicle mass, and road grade is identified as an explanatory variable which is highly correlated with emissions and FC. Many models have adopted VSP as the primary parameter, because of its direct physical interpretation and strong statistical correlation with emissions and FC [4].

Frey et al. [5,6] and Zhai et al. [7] had assessed the relationship between the VSP and emission. Then they developed a VSP-based approach for emissions and FC estimation. The modal approach was used to standardize the comparisons of emission and FC rates for different vehicles and routes [8]. They also use this method to compare modal average emission and FC rates for E85 versus gasoline [9]. A VSP-based FC model was also developed for passenger cars in China [10]. Song and Yu [4] proposed a mathematical model of VSP distribution for the FC estimation. Then, based on the model,

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http://dx.doi.org/10.1016/j.apenergy.2015.09.096
0306-2619/

Wu et al. designed an approach for estimating FC by integrating VSP and controller area network bus technology [11]. However, these models used a fixed mass of the vehicle (often vehicle curb weight, i.e. unloaded vehicles) in their VSP calculations. The influence of passenger load variation on emission and FC estimations was neglected.

The formulas to calculate the VSP value for each type of vehicle are different. For transit diesel buses, unlike the private car, the passenger load should not be ignored for bus emissions and FC estimation because the load changes during the trip. Frey et al. [5] found that the passenger load had a significant effect on FC, particularly at the middle and high-speed ranges. The increased passenger load could increase the modal average emission and FC rates. In another study, eight buses were tested with 1.0 and 2.5 t load mass respectively for comparison. The average FC was increased by 4.6 ± 3.6% with 2.5 t load mass compared to 1.0 t load mass [12]. Alam and Hatzopoulou [13] used the MOVES model to estimate the bus emissions and found that the increasing passenger load on the bus would increase tailpipe total emissions. However, for the per-passenger based emissions, the passenger load or the bus occupancy will be inversely proportional to emissions. It was also found that the influence of passenger load on emissions is also related to road grade. The steeper the road, the stronger the influence of passenger load on emissions. Nanjing is situated in a relatively flat area and thus the influence of road grade on emissions and FC is negligible in this paper. The main parameters affecting the impact of passenger load on emissions and FC are vehicle speed and acceleration. Li et al. [14] reported that passenger loads of the buses could influence buses' emissions and it is possible to obtain real-time passenger count on bus with the advanced passenger count system. So the transient bus weight could be incorporated in the emission and FC assessments. However, there is a gap in this area and there are no modal emission rates available in the literatures that take the transient bus weight into account. A constant value for bus weight was used.

In recent years, 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. The USEPA has put considerable emphasis on the development of PEMS for the development of emissions database for its vehicle emission model MOVES [15]. The on-board vehicle emission measurements with PEMS in China have been used to measure gaseous pollutants from buses in recent years [16,17]. Lai et al. [18] used PEMS to obtain bus emission characteristics at intersection. Zhang et al. [19] used PEMS to analyze whether alternative fuel technologies can mitigate NO_X emissions for buses. Wyatt et al. [20] investigated the impact of road grade on carbon dioxide (CO_2) emission of a passenger car with PEMS. There is a clear need to investigate the impact of passenger load on real world driving emission and FC for city buses using PEMS and modeling methods. This forms the objective of this paper.

In this study, the correlations between emissions, FC and passenger load, vehicle speed, acceleration and VSP under real world driving conditions were evaluated using the data measured by a PEMS. The transient emissions and FC were divided into 31 bins based on vehicle speed and the VSP. A comparison was made for the emission (or FC)–VSP correlations between the VSP with and without passenger load included. The results demonstrate that the emissions and FC could be significantly underestimated when the passenger load was ignored in the VSP calculation for the prediction of emissions and FC.

2. Data and methods

2.1. Experiments using PEMS

SEMTECH-DS and SEMTECH-EFM3, manufactured by Sensors Inc., were used for this study. This PEMS uses a non-dispersive infrared (NDIR) sensor for CO and CO_2 measurement, a non-dispersive ultra-violet (NDUV) analyzer to measure NO and NO_2 separately and simultaneously, a heated flame ionization detector (FID) to analyze total hydrocarbons (THC), and an electrochemical sensor to measure O_2. A Garmin International Inc. global positioning system receiver model GPS 16-HVS was used to track the route, elevation, and ground speed of the bus under test. The vehicle activity, exhaust concentration, and emission rate data were logged on a second-by-second basis. Standard calibration gases were used to verify the accuracy of the system before each individual test, and set the target pollutants to zero [21].

The field data collection was conducted on five buses in Nanjing of China. Nanjing is a large metropolitan city with an urban population of 6.5 million and located in the east of China. The city has 5646 buses running on 369 bus routes (lines) daily in its public transport system in 2012. Majority of buses are EURO III emission compliant [22]. To represent the majority of bus fleet, five EURO III buses were selected for the field test. The typical diesel fuel used daily by the fleet with a sulfur content of 350 ppm and a specific gravity of 0.85 was employed for the test. Other detailed information of these buses is listed in Table 1. The buses were operated at normal service mode. The passengers could get on and off the bus at stops as usual.

The routes traveled by the buses were showed in Fig. 1. The data collection was carried out at the peak hour and off-peak hour on five working days. The weather was similar during the tests. The measurements were carried out with the bus' air conditioning system switched off.

2.2. Data processing

The number of passengers getting on and off the bus at every stop has been recorded so that the real-time ridership data were obtained. The passengers were divided into six groups according to the age and gender. Fifty kilogram was taken as one basic unit of passenger load. Various coefficients were applied for six groups' passenger load calculation as shown in Table 2 [23].

2.3. Calculation formula of VSP for urban transit buses in Nanjing

Fig. 2 shows the force analysis of a testing bus. According to the definition of VSP, the calculation formula can be derived as Eq. (1):

Table 1
Buses selected for field data collection.

Number	Bus line	Vehicle model	Engine model	Displacement (L)	Curb vehicle mass (kg)	Vehicle mileage traveled (*1000 km)
#1	#30	NJC6104HD3	CA6DF3-24E3	6.74	9450	141
#2	#163	NJC6104HD3	CA6DF3-24E3	6.74	9450	118
#3	#100	SWB6116MG	SC8DK250Q3	8.27	10,450	49
#4	#60	SWB6116MG	SC8DK250Q3	8.27	10,450	91
#5	#44	XMQ6116G3	CA6DL1-26E3	7.7	11,000	134