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Evaluating real-world CO_2 and NO_X emissions for public transit buses using a remote wireless on-board diagnostic (OBD) approach☆

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ABSTRACT

The challenge to mitigate real-world emissions from vehicles calls for powerful in-use compliance supervision. The remote on-board diagnostic (OBD) approach, with wireless data communications, is one of the promising next-generation monitoring methods. We collected second-by-second profiles of carbon dioxide (CO_2) and nitrogen oxides (NO_X) emissions, driving conditions and engine performance for three conventional diesel and three hybrid diesel buses participating in a remote OBD pilot program in Nanjing, China. Our results showed that the average CO_2 emissions for conventional diesel and hybrid diesel buses were 816 ± 83 g km^{-1} and 627 ± 54 g km^{-1}, respectively, under a typical driving pattern. An operating mode binning analysis indicated that CO_2 emissions reduction by series-parallel hybrid technology was largely because of the significant benefits of the technology under the modes of low speed and low power demand. However, significantly higher CO_2 emissions were observed for conventional diesel buses during rush hours, higher than 1200 g km^{-1}. The OBD data suggested no improvement in NO_X emission reduction for hybrid buses compared with conventional buses; both were approximately 12 g km^{-1} because of poor performance of the selective catalyst reduction (SCR) systems in the real world. Speed-dependent functions for real-world CO_2 and NO_X emissions were also constructed. The CO_2 emissions of hybrid buses were much less sensitive to the average speed than conventional buses. If the average speed decreased from 20 km h^{-1} to 10 km h^{-1}, the estimated CO_2 emission factor for conventional buses would be increased by 34%. Such a change in speed would increase NO_X emissions for conventional and hybrid buses by 38% and 56%, respectively. This paper demonstrates the useful features of the remote OBD system and can inform policy makers how to take advantage of these features in monitoring in-use vehicles.

1. Introduction

Recently, much attention has been paid to real-world vehicle emissions in real-world conditions by researchers and policy makers across many countries (Mock et al., 2013; Tietge et al., 2015; Zhang et al., 2014a; 2014b; Weiss et al., 2012; Lau et al., 2012; Zheng et al., 2015). For example, several studies in Europe and China have revealed significant discrepancies between real-world nitrogen oxides (NO_X) emissions and regulatory emission limits for both light-duty and heavy-duty diesel vehicles (HDDVs) (Yang et al., 2015; Wu et al., 2012a; Zhang et al., 2014c; Borken-Kleefeld and Chen, 2015; Carslaw et al., 2011; Muncrief, 2015). Additionally, more real-world evidence has been accumulated for the huge gap

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between real-world and type-approval carbon dioxide (CO_2) emissions for light-duty passenger vehicles (LDPVs), and the gap is generally becoming greater in both Europe and China as their CO_2 and fuel consumption limits become increasingly stringent (Mock et al., 2013; Tietge et al., 2015; Innovation Center for Energy and Transportation, 2015). Unsatisfactory real-world emission control can be attributed to the following factors. First, manufacturers tend to limit the controls of NO_X emissions as narrowly as possible to pass the type-approval test to reduce production costs and enhance fuel economy because of the trade-off between energy efficiency and NO_X emission control (Wu et al., 2012a; Krishnamurthy et al., 2007). Second, vehicles or engines that participated in the type-approval tests are commonly well optimized (Mock et al., 2013). Moreover, the type-approval test cycles currently adopted in Europe and China differ greatly from real-world conditions (Marotta et al., 2015; Wu et al., 2012a). For urban transit buses, the regulatory test cycles have a very low proportion of urban driving conditions, which would result in low exhaust temperatures and unsatisfactory performance for selective reduction catalyst (SCR) systems, the mainstream approach for controlling NO_X emissions for Euro IV to VI HDDVs (Wu et al., 2012a; Zhang et al., 2014c).

To address the issue of real-world emissions, policy-makers have proposed serval approaches. First, the modified cycles (e.g., the Worldwide Harmonized Light Vehicles Test Procedures (WLTP) for LDPVs and the World Harmonized Transient Cycle (WHTC) for HDDVs in Europe) have been proposed for regulatory test procedures and have included more real-world features and urban driving conditions (Marotta et al., 2015; Mock et al., 2014). Second, the portable emission measurement system (PEMS) (Kousoulidou et al., 2013) has played an increasingly important role in in-use testing for HDDVs since 2005 (U.S. EPA, 2005; European Commission, Joint Research Center, 2012; Franco et al., 2014). For example, the U.S. EPA released a final rule on a manufacturer-run in-use PEMS testing program in 2005 that aimed to assess gaseous emissions and particulate matter (PM) from heavy-duty trucks during real-world operation (U.S. EPA, 2005). In China, the PEMS measurement standard for HDDVs has been drafted and could be applicable to both type-approval and in-use compliance procedures (MEP, 2015). Note that in China most PEMS tests are typically performed with limited loading weight and durations (e.g., mostly within one or two hours). Therefore, a cost-effective approach covering a wide spectrum of completely real-world operating conditions is necessary to improve future in-use compliance programs.

On-board diagnostics (OBD) is an on-board system applying numerous vehicle sensors to monitor the status of some components, especially those designed for emission control, and alert the driver with an indicator light in case of any malfunctions that may lead to high emissions (U.S. EPA, 2015). OBD was first employed in gasoline LDPVs in the U.S. in 1980 and was introduced for heavy-duty vehicles (HDVs) in 2005 in Europe (Posada and Bandivadekar, 2015). So far, HDV OBD requirements have been adopted in the U.S., Europe, China, India and Brazil (Posada and Bandivadekar, 2015). Recently, the third generation of OBD (i.e., OBD-III) has been updated by adding a data sending and receiving module. Because of the remote wireless communications feature, the OBD-III system allows authorities to track real-time operating conditions, fuel consumption and emissions of targeted vehicles. In China, essential activities have been conducted to promote the adoption of this useful in-use monitoring technology. For example, Nanjing, the capital city of Jiangsu Province in China, has launched a pilot program equipping remote OBD monitoring systems for urban public buses since 2012. The real-time CO_2 and NO_X emissions and engine data monitored by the OBD system of 30 urban buses are recorded and sent back to the monitoring center. In November 2015, Beijing released a draft version of the Beijing VI emission standard that clearly standardizes the remote OBD as a mandatory system for future new HDDVs (Beijing EPB, 2015).

In this study, we collected the remote OBD datasets of three conventional diesel buses and three hybrid diesel buses from the pilot program in Nanjing. A total of 87 h of second-by-second data on their instantaneous CO_2 and NO_X emissions and driving conditions were analyzed. We evaluated the real-world CO_2 and NO_X emissions of the buses based on the remote OBD data and explored the relationship between operating conditions and emissions. This paper aims to construct a method and to demonstrate an evidence-based case for the remote OBD-based monitoring of key vehicle fleets to better inform policy-makers of this advanced in-use inspection technology.

2. Methodology

2.1. Field study

Nanjing is the capital city of Jiangsu Province and an important economic city in the Yangtze River Delta region of Eastern China. By the end of 2015, the total vehicle population in Nanjing had reached 2.2 million (including gasoline motorcycles) and the total vehicle population density had climbed to 250 per 1000 people, significantly higher than the national average level for China (114) (NMSC, 2016). As the host city of the 2014 Summer Youth Olympic Games, over the past years, Nanjing has substantially developed public transit buses to satisfy huge traffic demand during rush hours and has promoted alternative fuel technologies to the public transit fleet such as hybrid electric vehicles (HEVs) (Wang et al., 2015). For example, 2530 new buses were introduced in 2014, and 85% of them are alternative fuel vehicles (NMTAB, 2014).

During the pilot program starting from 2012, remote OBD monitoring systems were installed on 30 urban public buses in Nanjing. Because the public transit bus fleet in China is mostly powered by diesel, it is considered to be one of the major fleets responsible for total NO_X emissions in urban areas because of its high vehicle-specific distances and congested driving conditions (Zhang et al., 2013; 2014d; Wang et al., 2010; Huo et al., 2011). In this study, we collected OBD data from three conventional diesel buses and three hybrid diesel buses (see Table 1) representing prevailing conventional and hybrid models in Nanjing. Three hybrid diesel buses were equipped with a 147 kW diesel internal combustion engine (ICE), a 90 kW electric motor (EM) and a series-parallel hybrid system. A 249.6 V battery pack with a capacity of 50 A h was installed in each hybrid bus. In a series hybrid system, the ICE is connected to the EM to propel the vehicle; therefore, the ICE can usually work at its highest efficiency for better energy economy (Rizoulis et al., 2001; Trindade et al., 2014). In a parallel system, the ICE and EM are connected to the transmission so that they can either work together or independently to propel the vehicle (Sabri et al., 2016). Researchers previously suggested that series HEVs might perform with better energy economy in urban driving conditions whereas parallel HEVs would be more suitable for highway driving (Rizoulis et al., 2001; Xiong et al., 2009; Park et al., 2007). The series-parallel hybrid system combines a series hybrid system and a parallel hybrid system to take advantage of both systems under complicated real-world conditions (Park et al., 2007; Xiong et al., 2009). SCR systems were installed in all tested buses to meet the NO_X emission limits of the China IV standard (i.e., Euro IV equivalent). The measurements were carried out during the duration of their real operations on regular bus routes for Bus 63 and Bus 33 (see Fig. S1), typically from 6 a.m. to 11 p.m. in March and November 2013. The air conditioning was turned off during all tests.

The remote OBD system used in the pilot program consisted of an OBD/Controller Area Network (CAN) interface, a Global Positioning System (GPS) receiver, a data storage system, and a General Packet Radio Service (GPRS) connected to the environmental monitoring center. The CO_2 emission rates were calculated by fuel consumption rates, exhaust temperatures, humidity and mass air flows reported by the OBD system. The NO_X emission rates were measured by NO_X electronic sensors originally installed on the vehicle. The engine speed, engine power and vehicle speed were read directly from the electronic control unit (ECU) by the OBD data logger at a frequency of 1 Hz. The sensors and OBD system complied with the national China IV emission standard and the environmental protection standard on technical specifications for OBD systems (MEP, 2008). After the data were preprocessed by removing a small proportion of invalid data, a total of 87 h of second-by-second data were available for the data processing procedure.

2.2. Data processing

In this study, an operating mode binning method was applied to analyze the relationships between instantaneous operating conditions real-time CO_2 and NO_X emissions (Zhang et al., 2014a; 2014c). We used the vehicle specific power (VSP) as one of the operating condition indicators; VSP is a proxy variable to describe real-world driving conditions. VSP is defined as the instantaneous power demand by the engine per unit mass of the vehicle. VSP was first introduced by Jimenez (Jimenez-Palacios, 1999) and has been widely used in emission models (U.S. EPA, 2009; Zhang et al., 2014d; Wang and Fu, 2010; Hu et al., 2014). In this study, VSP was calculated using the following equation (U.S. EPA, 2009), and the road load coefficients were specifically determined for urban buses in China (see Eq. (1)) (Wu et al., 2012a):

$$VSP = 0.0643 \cdot v + 0.000279 \cdot v^3 + a \cdot v + g \cdot v \cdot \sin\theta \tag{1}$$

where VSP is the estimated vehicle specific power (kW t^{-1}), v is the instantaneous vehicle speed (m s^{-1}), a is vehicle acceleration (m s^{-2}), and θ is the road grade (radians). A total of 22 operating modes, including a deceleration mode, an idling mode and 20 other modes, for three speed ranges was defined by instantaneous VSP and vehicle speed (v) (see Table 2) (Wu et al., 2012a).

We calculated the average time-specific emission rates ($\overline{ER}_{i,j,m}$, g s^{-1}) and average engine speed ($\overline{ES}_{i,j}$, rpm) for each pollutant m (CO_2 and NO_X), vehicle i and operating mode j. To eliminate the influence of different driving conditions among the various buses, the normalized emission factor (EF) ($EF_{i,m,0}$, g km^{-1}) of each vehicle was calculated based on the time distribution of each operating mode for a typical driving pattern (see Eq. (2)). The typical driving pattern with an average speed of 18 km h^{-1} (see Fig. S2) was previously established based on GPS trajectory data for urban transit buses in China (Wu et al., 2012a).

$$EF_{i,m,0} = \frac{3600 \sum_j \left(\overline{ER}_{i,j,m} \cdot P_j\right)}{\overline{v}} \tag{2}$$

Table 2
Definition of operating mode bins by v and VSP.

VSP (kW t^{-1})	Vehicle speed (km h^{-1})				
		$v < 1.6$	$1.6 \le v < 40$	$40 \le v < 80$	$v \ge 80$[a]
$VSP < -4$			Bin 11	Bin 21	
$-4 \le VSP < -2$			Bin 12	Bin 22	
$-2 \le VSP < 0$			Bin 13	Bin 23	Bin 35
$0 \le VSP < 2$	Bin 0	Bin1	Bin 14	Bin 24	
$2 \le VSP < 4$	Braking	Idling	Bin 15	Bin 25	
$4 \le VSP < 6$			Bin 16	Bin 26	Bin 36
$6 \le VSP < 8$			Bin 17	Bin 27	Bin 37
$VSP \ge 8$			Bin 18	Bin 28	Bin 38

Note.
[a] We collected no data in the high-speed operating modes (Bins 35 to 38) for tested buses.

where $EF_{i,m,0}$ is the normalized distance-specific EF of pollutant m for vehicle i (g km^{-1}), P_j is the time distribution of the operating mode bin j in a given driving cycle and $\overline{v}$ is the average speed (km h^{-1}) of the given driving cycle.

The application of operating mode-based models is often constrained by the availability of data for second-by-second traffic conditions, in particular the collection of real-time instantaneous speed data. Therefore, Liu et al. (2011) linked two aggregated traffic parameters (road type and hourly volume) to the time distribution of operating modes. Similarly, based on modal emission rates Zhang et al. (2014a) found that average speed affected CO_2 emissions for public buses in Beijing more than other traffic parameters (e.g., road type). Average traffic speed is more easily determined from intelligent transportation systems data (e.g., floating car and navigation data); therefore, we also applied a micro trip method for the urban public buses to observe the impact of average speed based on the remote data (Zhang et al., 2014a; 2014c). By using the micro-trip method, the entire OBD dataset for each vehicle was divided into hundreds of micro-trips that lasted for 250–350 s and could represent real-world conditions and performance on a road segment (i.e., at the link-level) (Zhang et al., 2014b). In this study, 1040 micro trips were generated with average speeds that ranged from approximately 5 to 40 km h^{-1}. In addition to driving conditions, on-road CO_2 and NO_X emissions are influenced by vehicle weight and the number of passengers loaded (Zhang et al., 2014a; 2014c). To eliminate these parameters and only study the impact from average speed, two non-dimensional variables, the relative CO_2 EF and relative NO_X EF, were developed according to Eq. (3).

$$REF_{i,k,m} = \frac{EF_{i,k,m}}{EF_{i,m,0}} \tag{3}$$

where $REF_{i,k,m}$ is the relative EF of pollutant m in micro-trip k for a vehicle i, $EF_{i,k,m}$ is the distance-specific EF (g km^{-1}) of a pollutant m in a micro-trip k for a vehicle i and $EF_{i,m,0}$ is the normalized distance-specific EF of a pollutant m for a vehicle i under a typical driving cycle calculated in Eq. (2).

Table 1
Summary of on-road OBD tested samples.

Vehicle type	Manufacturer	Emission standard	Rated engine power (kW)	Max torque (N m)	Sample numbers
Hybrid diesel	Sunwin	China IV	147[a]	730	3
Conventional diesel	King Long	China IV	176	1000	3

Note.
[a] The hybrid diesel buses are equipped with a 147 kW diesel internal combustion engine plus a 90 kW electric motor and series-parallel hybrid system.

3. Results and discussion

3.1. Overall CO_2 and NO_X emissions

The overall distance-specific CO_2 and NO_X EFs (g km^{-1}) for each individual bus were normalized to a typical driving pattern, as Fig. 1 illustrates. For more information, the actual CO_2, NO_X EFs and average speed for each bus are summarized in Table S1. For conventional and hybrid diesel buses, the average CO_2 EFs (mean ± standard deviation) were 816 ± 83 g km^{-1} and 627 ± 54 g km^{-1}, respectively. The results were close (average discrepancies within 7%) to our real-world results for conventional and hybrid diesel buses in China obtained by using the PEMS method (871 ± 198 g km^{-1}, 62 samples and 646 g km^{-1}, 2 samples) (Zhang et al., 2014a). The average CO_2 EF for the three hybrid diesel buses indicated an overall reduction of 23% relative to their conventional counterparts. This could further add new on-road evidence for the CO_2 emission reduction benefits from hybrid technologies based on the remote OBD system (Fontaras et al., 2008; Wu et al., 2012b; Muncrief et al., 2012; Zhang et al., 2014a; Sabri et al., 2016).

One important finding from this study is that no significant reductions could be observed in the NO_X emissions of hybrid diesel vehicles compared with their conventional counterparts. The average NO_X EFs were 11.7 ± 0.3 g km^{-1} for China IV conventional diesel buses and 12.3 ± 0.8 g km^{-1} for hybrid buses. For China IV conventional diesel buses, the remote OBD reported results were very close to previous PEMS data (11.8 ± 4.8 g km^{-1} for 25 samples, see Wu et al., 2012a). High NO_X emissions for SCR-equipped China IV diesel buses are because of stop-and-go and congested traffic conditions, which would result in low exhaust temperatures and not favor the activation of SCR systems. However, unlike our previous PEMS study (Zhang et al., 2014c) that revealed a reduction of approximately 63% in NO_X emissions from China IV parallel hybrid buses, this study indicates that uncertainty remains in the NO_X control benefit from hybrid bus technologies. Several studies from other groups (e.g., Guo et al., 2015; Hallmark et al., 2013a) have also indicated that hybrid diesel buses may have higher NO_X emissions than conventional diesel engines (see Table 3). For example, Hallmark et al. (2013a) tested three hybrid buses and two conventional buses and observed that the NO_X emissions rates from hybrids were 3–9 times as high as conventional buses in all driving conditions. Detailed discussions on NO_X emissions rates in different operating modes and possible reasons for this will be presented in the next section.

3.2. Instantaneous CO_2 and NO_X emission rates by operating mode

Average CO_2 and NO_X emission rates as well as engine speeds by operating mode are presented in Fig. 2. For both conventional and hybrid buses, their average CO_2 and NO_X emission rates generally increased with VSP, which is consistent with previous studies (Wu et al., 2012a; Zhang et al., 2014c; Guo et al., 2015). For braking (Bin 0), idling (Bin 1), and operating modes in low-speed zones with VSP lower than 4 kW t^{-1} (Bins 11 to 15), the average CO_2 emission rates of hybrid buses were lower than for conventional buses, corresponding to fuel reductions of 6%–72% (see Fig. 2a). For urban buses in China, these seven operating modes dominate total real-world driving conditions (e.g., 88% of total time for the typical driving pattern; see Fig. S2). The significant CO_2 savings for braking, low-speed and especially idling modes are primarily attributed to the control strategy of hybrid systems. First, the start-stop system adopted by hybrid vehicles could enable the ICE to be shut down temporarily during standstill phases. Second, the hybrid bus can be braked by the generator braking torque of the electric drive (i.e., regenerative braking) rather than the service brake's friction torque. Therefore, the electric drive converts kinetic energy into electrical energy in the battery (Robert Bosch GmbH, 2011), which would occur when VSP is negative during deceleration. For low-speed modes, the series-parallel hybrid system typically performs as a series system and offers the advantage of reducing fuel consumption because of the ability to freely select the engine's operating point (Robert Bosch GmbH, 2011). Therefore, the engine speed of hybrid buses remains consistent with a small standard deviation (see Fig. 2c). However, when VSP is increased to over 4 kW t^{-1} within the low-speed zones (i.e., Bins 16 to 18), more electricity is needed to provide power to the motor, and the losses from double energy conversion (i.e., from ICE power to electric battery charge, and from battery charge to electric motor power) are higher than those of a conventional ICE. As a result, for Bins 16

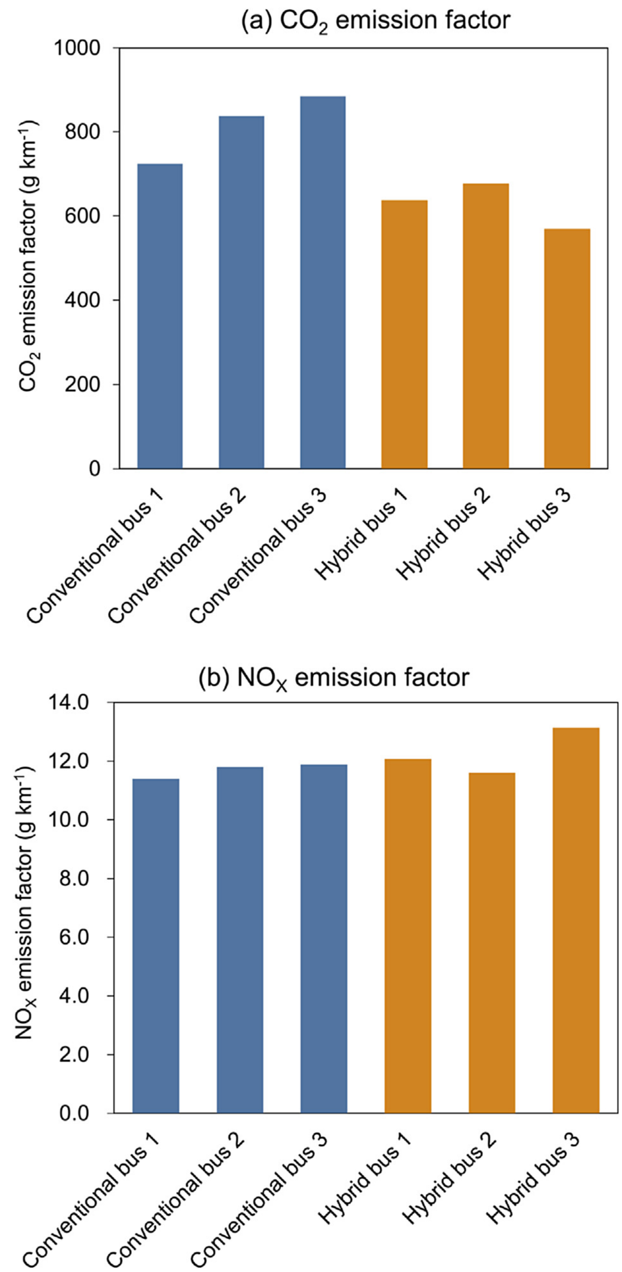

Fig. 1. Normalized (a) CO_2 and (b) NO_X emission factors for conventional and hybrid diesel buses under a typical driving cycle for public buses.

to 18, average CO_2 emission rates for hybrid buses are 4–25% higher than for conventional buses. For medium-speed zones (bin 21-28), average CO_2 emission rates of hybrid buses were higher than those of conventional buses by 28%–72%. In medium-speed zones, because the maximum engine torque of conventional buses is larger than that of hybrid buses, the engine speed of hybrid buses would be higher than conventional buses (see in Fig. 2c; similar trends are described in Muncrief et al., 2012) to achieve the same engine power. Therefore, the ICE of hybrid buses runs at a less optimal point (i.e., the top right corner) in the engine map, which may lead to higher fuel consumption for hybrids at medium speeds. No significantly higher engine speeds for hybrid buses are observed in low-speed zones because engine power demand is relatively small at low speeds and the ICE can run at its relatively optimal point. For the hybrid buses, although their average CO_2 emission rates in medium-speed modes were higher than conventional buses, such an impact on overall fuel consumption was not significant because the medium-speed modes account for only 10% of the total time for the typical urban driving pattern in congested Chinese cities.

Average NO_X emission rates of hybrid buses in medium-speed zones (Bin 21-28) were observed to be significantly (i.e., 41%–97%) higher than those of conventional buses (see Fig. 2b). For braking (Bin 0), idling (Bin 1), and all low-speed operating modes (Bins 11 to 18), no significant differences between hybrid and conventional groups were observed. Because such low-speed driving patterns dominate real-world driving conditions for urban buses in China, the overall NO_X EF of hybrid buses was in line with conventional buses, as illustrated in Fig. 1b. As SCR systems are installed on these buses, NO_X emissions are influenced by several things such as engine out NOx, urea injection strategy, efficiency of the catalyst, catalyst temperature, and exhaust flow rate. However, such valuable data for diagnosing real-world SCR performance can probably only be collected with dedicated OBD decoders provided by manufacturers. Therefore, we used a relative empirical and aggregated method to calculate the NO_X to CO_2 ratio (g NO_X per g CO_2) by operating modes for both technology groups (see Fig. 2d). The NO_X to CO_2 ratio is a widely accepted indicator of real-world NO_X emissions that allows the comparison of different HDDV engine sizes (Vermeulen et al., 2014). Unlike in previous PEMS studies on SCR-equipped HDDVs (Zhang et al., 2014c; Vermeulen et al., 2014; Verbeek et al., 2010; Velders et al., 2011; Guo et al., 2015), we observed no significant decrease in the NO_X to CO_2 ratios as vehicle speed and VSP increased for both conventional and diesel buses. Because SCR systems tend to perform better under high speed and high load driving conditions because of higher exhaust temperatures (Verbeek et al., 2010; Velders et al., 2011; Zhang et al., 2014c), we infer that the SCR systems did not perform effectively for the tested buses.

HEVs are designed to reduce tailpipe pollutants and fuel consumption (Chau and Wong, 2002). However, it is challenging to minimize CO_2 and NO_X emissions at the same time because of the trade-off between energy efficiency and low NO_X emissions (Sabri et al., 2016; Johnson et al., 2000). For example, in an HEV control strategy that was targeted to optimize fuel consumption and emissions, NO_X and PM were reduced by 17% and 10% at the sacrifice of an increase of 3.4% in fuel consumption compared with the baseline performance (Johnson et al., 2000). When SCR systems are introduced to hybrid diesel buses, their real-world NO_X emissions would become more complicated and uncertain based on previous measurements. Zhang et al. (2014c) tested 2 China IV hybrid diesel buses equipped with SCR systems by PEMS and observed no significant differences in exhaust temperatures between conventional and diesel buses; this specific HEV model could reduce NO_X EF by 63% compared with conventional buses. However, Guo et al. (2015) tested 2 hybrid buses which could operate in either hybrid mode or diesel mode by simply pressing a button and found that the exhaust temperatures in hybrid mode were 20 °C to 60 °C lower than in diesel mode. Therefore, the urea injection ratios were between 20% and 50% in hybrid mode under all operating modes, whereas the values were over 80% for conventional diesel buses. This led to 36% higher NO_X EFs in hybrid modes. Li et al. (2011) also found that the exhaust temperature of an SCR-equipped hybrid bus was approximately 20 °C lower than that of conventional buses, whereas the NO_X EF of the hybrid bus remained 19% lower than conventional buses. These studies indicate that in those particular SCR systems the exhaust temperature would be an important factor that affects the NO_X reduction efficiency of hybrid buses, and different energy

Table 3
Comparison of CO_2 emissions and NO_X emissions between hybrid buses and conventional buses by previous studies.

Study source	Location	Method	Conventional diesel buses		Hybrid diesel buses			Hybrid vs. Conventional	
			Sample size	Emission standard or model year	Sample size	Emission standard or model year	Powertrain type	CO_2 emissions	NO_X emissions
This study	Nanjing	Remote OBD	3	China IV, SCR	3	China IV, SCR	Series-parallel hybrid	77%	105%
Wu et al., 2012a; Zhang et al., 2014a and 2014c [a]	Beijing	PEMS	29	China IV, SCR	2	China IV, SCR	Parallel-hybrid	71%	37%
Guo et al., 2015	Beijing	PEMS	2	China IV, SCR	2	China IV, SCR	Parallel-hybrid	73%	136%
Li et al., 2011	Beijing	PEMS	1	China IV, SCR	1	China IV, SCR	Series-parallel hybrid	NA [b]	81%
Hallmark et al., 2013a	Ames, Iowa	PEMS	2	2010	3	2010	Parallel-hybrid	60-76%	300% –900% [d]
Hallmark et al., 2013b	Ames, Iowa	In-use fuel consumption report	7	2008/2010	12	2010	Parallel-hybrid	89% [c]	NA
Shorter et al., 2005	New York	Chasing	132	~2000	3	~2000	NA	NA	50%
Chandler et al., 2002	New York	In-use fuel consumption report	14	1998	10	1998,1999	Series-hybrid	87% [c]	NA

Note.
[a] We combined our PEMS results for China IV diesel buses and hybrid buses in Beijing together for comparison in this table.
[b] Not available.
[c] We estimated CO_2 emissions from in-use fuel consumption data.
[d] Emission rates.

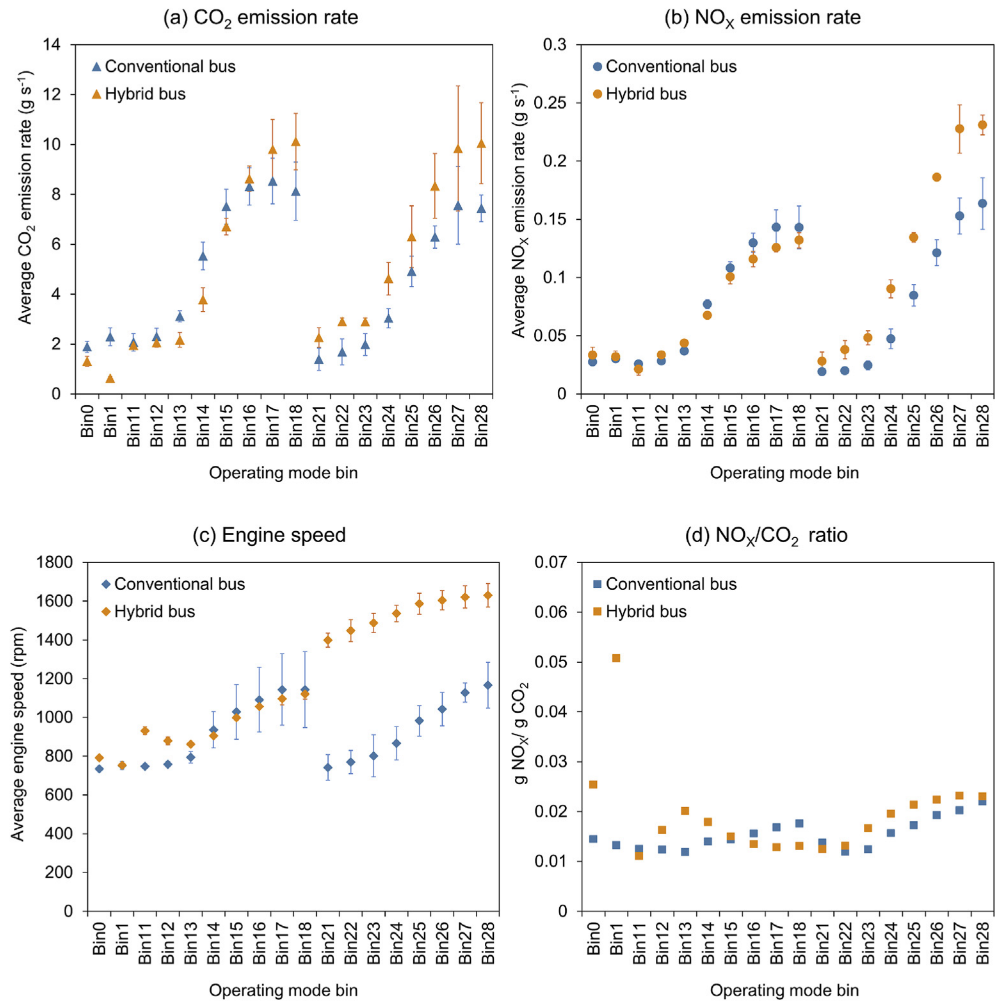

Fig. 2. Average (a) CO_2 emission rates, (b) NO_X emission rates, (c) engine speed and (d) NO_X/CO_2 ratio for conventional and hybrid diesel buses by operating mode (error bars indicate standard deviation).

control strategies employed by different hybrid models have resulted in dramatically different NO_X reduction performance. Therefore, manufacturers should propose specific and effective solutions, e.g., electrically heated catalysts (Johnson, 2011), to enhance the SCR working performance of hybrid buses by simultaneously optimizing the energy and environmental targets. On the other hand, parameters indicating the effectiveness of SCR systems are not covered by the current communications requirements of the OBD-III system. Considering that the SCR system is the prevailing after-treatment approach for controlling NO_X emissions for urban diesel bus fleets in China, we propose that the next generation of OBD-III system should report parameters such as exhaust temperature, urea injection ratios and urea consumption to allow the authorities to monitor the performance of SCR systems and take effective measures to control the on-road NO_X emissions from heavy-duty vehicles.

3.3. Impacts of driving conditions on real-world CO_2 and NO_X emissions

Fig. 3 presents daily variations in hourly CO_2 EFs, NO_X EFs and average speeds that have not yet been assessed on roads by other measurement methods (e.g., PEMS). On weekdays, two peaks in hourly NO_X EFs can be observed for conventional buses in accordance with rush hours (7–8 a.m. and 5–6 p.m.), whereas several peaks occur at 7 a.m. and 2, 6, and 8 p.m. for hybrid buses. Similarly, two peaks in CO_2 EF for conventional buses during weekdays were observed that were higher than 1200 g km^{-1}. In contrast, hourly CO_2 EFs for hybrid buses did not fluctuate as significantly as their conventional counterparts and were significantly lower than conventional buses for all diurnal hours. On weekends, heavy traffic generally occurred in the afternoon (e.g., 2–4 p.m.), which significantly increased hourly CO_2 EFs for conventional buses as well as hourly NO_X EFs for both conventional and hybrid buses. Two aspects of impacts would result in these daily fluctuations. First, the average speeds during rush hours were approximately 10–12 km h^{-1}, which were lower than those in non-rush hours (e.g., up to 15 km h^{-1}) by at least 20%. Second, the number of passengers loaded during rush hours was typically higher than that in non-rush hours, which would further increase the power demand of the buses. Nonetheless, the CO_2 EF of hybrid buses indicated less sensitivity to the change of hourly speed; this will be quantitatively assessed in the next paragraph. Our long-period observations enabled by the remote OBD technology indicate that hourly trends in CO_2 and NO_X emissions for conventional buses are strongly correlated (i.e., R^2 = 0.92 on weekdays, and R^2 = 0.91 on weekends) and also indicate that the SCR systems for those conventional buses hardly functioned effectively. Moreover, considering that the fuel consumption limit for public buses is set at 37.5 L 100 km^{-1} (gross vehicle weight of 18 t, equivalent to 1010 g km^{-1} for CO_2 EF) by a national standard in China (MIIT, 2014), our OBD-monitored data indicate that real-world CO_2 EFs for the tested conventional buses exceeded the limit most of the time.

The correlations between average speed and relative CO_2 and NO_X EFs for micro-trips for conventional and hybrid buses are separately presented in Figs. 4 and 5. The power functions were applied to estimate the best fit for relative CO_2 and NO_X EFs (except for relative CO_2 EF for hybrid buses). For relative CO_2 EF, conventional diesel buses have a correlation coefficient of 0.46, whereas the CO_2 EFs of hybrids did not correlate significantly with average speed ($R^2 = 0.07$). For hybrid buses, this study provided more comprehensive samples of 592 micro trips than our previous PEMS study (Zhang et al., 2014a) because of the long-duration sampling feature of the remote OBD system. Recently, Wu et al. (2015) tested two light-duty hybrid gasoline cars in China using the PEMS method and also found that the CO_2 emissions of hybrid cars were almost insensitive to changes in driving conditions. These results indicate again that hybrid technology could bring benefits to CO_2 emissions reduction under urban congested driving conditions. For NO_X emissions, conventional and hybrid buses resembled each other in their speed-dependent patterns; both presented strong correlations between average speeds and relative NO_X EFs (i.e., $R^2 = 0.54$ for conventional buses, and $R^2 = 0.62$ for hybrid buses). As we previously discussed, elevated NO_X emissions under low-speed traffic conditions were associated with exhaust temperatures not sufficiently high to activate the SCR system. A sensitivity analysis was performed to quantify the impacts from changes in average speed using the fitting functions. When average speed decreased from 20 km h^{-1} to 10 km h^{-1}, indicating a switch from non-rush hour traffic to extremely congested traffic, estimated CO_2 EFs increased by 34% for conventional buses. Additionally, NO_X emission factors increased by 38% and 56% for conventional and hybrid buses, respectively. This suggests that although hybrid buses have the advantage in reducing CO_2 emissions under congested driving conditions, substantial attention should be paid to controlling their real-world NO_X emissions under unfavorable conditions. Moreover, the distributions of micro-trip NO_X emissions (as well as CO_2 emissions for conventional buses) present belt patterns that indicate uncertainties in complex real-world traffic conditions in addition to average speed. Therefore, we suggest that second-by-second traffic data be collected so that emissions can be estimated by using modal emission rates when focusing on specific micro-level environments (e.g., road intersections).

Heavy traffic congestion occurs very frequently in Nanjing because of the impressive increase in the number of vehicles. Because the Second Youth Olympic Game was held in Nanjing in 2014, several traffic control measures were implemented to improve traffic congestion. For urban buses, 50 km of dedicated bus lanes (DBL) were constructed by 2014, and 30 km more were scheduled to be added in 2015 (Nanjing Municipal Government, 2015). Moreover, Nanjing has adopted the Bus Priority Signaling System since 2014, which gives public buses priority when passing crossroads. Upon the application of this system, the average speed of public buses increased by 15%, and the average stop frequency decreased by 30% (NMCDR, 2014). On the bases of our remote OBD data and findings, we estimate that this change in average speed (from 14.6 km h^{-1} to 16.7 km h^{-1}) could reduce CO_2 emissions by 6% for conventional buses and reduce NO_X emissions by 6% for conventional buses and 9% for hybrid buses. Recently, some cities are also considering building a Bus Rapid Transit (BRT) system, a flexible supplemental mode for the

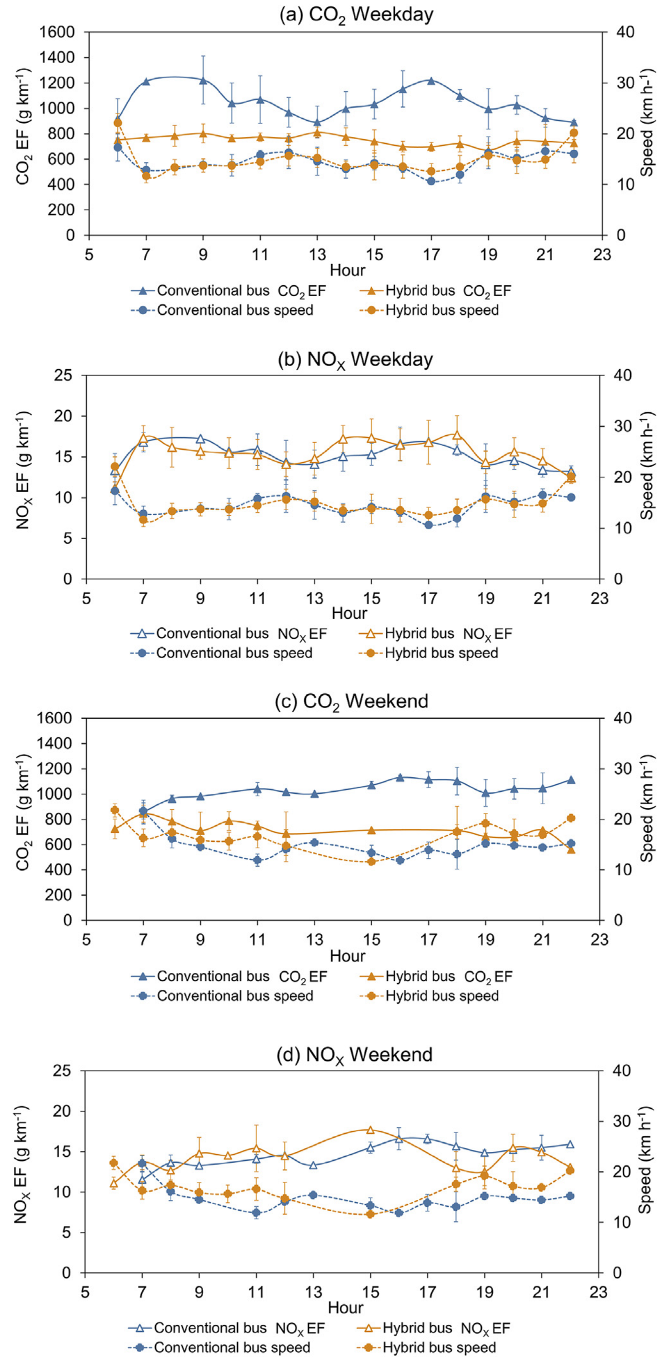

Fig. 3. Average diurnal patterns of hourly CO_2 EFs, NO_X EFs and average speed for conventional and hybrid diesel buses on weekday and weekend (error bars indicate standard deviation).

massive and capital-intensive public transit system, to improve traffic efficiency. According to the China BRT database (ITDP, 2015), 21 cities in China have already constructed BRT systems that add up to a total length of 790 km. Taking Changzhou (a medium-sized city also located in Jiangsu province) as a representative example, the average speed of its BRT routes during rush hours is 19.5 km h^{-1}. Therefore, the BRT system may have potential benefits in reducing CO_2 emissions by 24% for conventional buses in rush hours and in reducing NO_X emissions by 27% for conventional buses and 39% for hybrid buses.

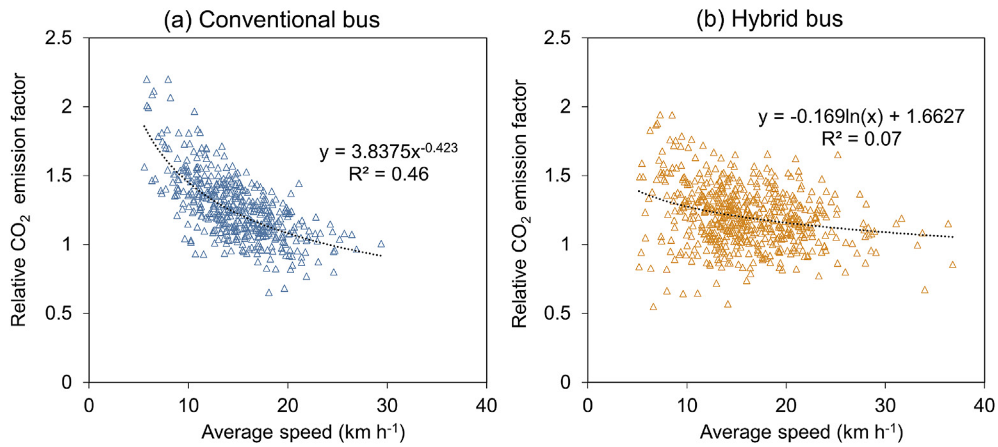

Fig. 4. Correlations between average speeds and relative CO_2 EFs of generated micro-trips for (a) conventional and (b) hybrid diesel buses.

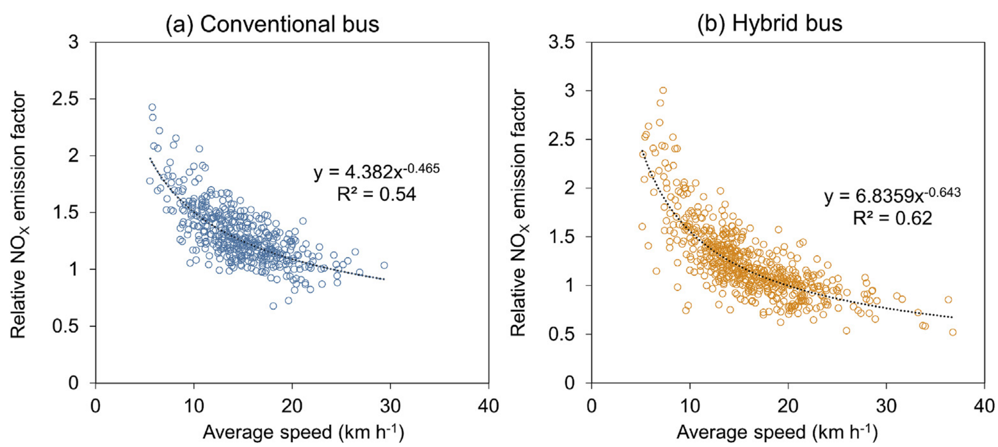

Fig. 5. Correlations between average speeds and relative NO_X EFs of generated micro-trips for (a) conventional and (b) hybrid diesel buses.

4. Conclusions

The remote OBD system (i.e., OBD-III) is considered to be an important future method for monitoring in-use vehicle emission compliance. Since 2012, a pilot program was launched in Nanjing to employ remote OBD technology to report real-time data for CO_2 and NO_X emissions and operating conditions for the urban buses that participated. This study evaluated in detail the reliability and practicability of this next-generation in-use monitoring method based on three China IV conventional diesel buses and three China series-parallel hybrid diesel buses.

The remote OBD has the unique feature of collecting large volumes of second-by-second data reflecting the on-road profiles for the tested buses. Our results showed that the average CO_2 EFs for conventional and hybrid diesel buses were 816 ± 83 g km^{-1} and 627 ± 54 g km^{-1}, respectively, for a typical driving pattern. However, significantly higher CO_2 EF was observed for conventional buses during rush hours, higher than 1200 g km^{-1}. Using an operating mode binning method, our analysis indicates that a considerable part of the CO_2 emissions reduced by the series-parallel hybrid technology (~23% relative to conventional buses) can be attributed to its significant benefits under low-speed and low-load conditions. For NO_X emissions, the remote OBD data suggest that there was no improvement in emission reduction for hybrid buses (12.3 ± 0.8 g km^{-1}) compared with conventional buses (11.7 ± 0.3 g km^{-1}), although both bus models were equipped with SCR systems. Considering the substantial uncertainty in real-world NO_X emissions from various measurements for hybrid buses, manufacturers should jointly optimize the control of NO_X and CO_2 emissions and, in particular, should find a solution to enhance the SCR efficiency when the exhaust temperature is low.

Speed-dependent functions for real-world CO_2 and NO_X emissions were further constructed based on a micro-trip method. For CO_2 emissions, hybrid buses are much less sensitive to average speed than conventional buses. For example, if the average speed decreased from 20 km h^{-1} to 10 km h^{-1}, estimated CO_2 emissions of conventional buses would be increased by 34%. However, for NO_X emissions, the changes in the average speed significantly affect both conventional and hybrid buses; their NO_X emissions were estimated to increase by 38% and 56%, respectively. Therefore, effective traffic measures (e.g., DBL and BRT) could bring benefits in CO_2 and NO_X emission control by improving traffic conditions.

With respect to the future of policing, the remote OBD system is likely to be mandatory for new HDDVs in Beijing from December 2017. This paper can vividly inform policy makers of the methodology of remote OBD technology for monitoring in-use vehicle emissions. In addition to urban transit buses, other HDDV fleets such as long-distance freight trucks are also major targets of in-use emission supervision in China. High emissions of black carbon for freight trucks registered in many places have been detected, probably because these HDDVs are equipped with improper engines (e.g., mechanical pump fuel injection engines) (Zheng et al., 2015); therefore, robust sensors for measuring particles (e.g., particle mass, particle number) and black carbon will be of great importance to the remote OBD-based monitoring system. More efforts are required to develop advanced particulate sensors with high time resolution, high accuracy, lasting durability and satisfactory reliability under transit and complicated conditions, which present technical challenges not only to the OBD-based monitoring system but also to the PEMS-based in-use regulations. Additionally, we suggest that more parallel measurements of air pollutants between PEMS and remote OBD systems should be conducted to further validate the real-world accuracy of remote OBD systems.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2016.07.025.

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