Technical Note

Black Carbon Emissions from Light-duty Passenger Vehicles Using Ethanol Blended Gasoline Fuels

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ABSTRACT

Vehicular emissions of soot vary with the driving conditions and fuel properties. In 2017, China's central government released a policy to promote ethanol blended gasoline fuels, and this policy will be rolled out nationwide in 2020. It is necessary to characterize the emission differences between traditional vehicular fuels used in China and ethanol blended fuels. In this study, black carbon (BC) emissions from three gasoline light-duty passenger vehicles (LDPVs) were measured using the New European Driving Cycle (NEDC) and the Worldwide harmonized Light vehicles Test Cycle (WLTC). This study utilized three fuels, namely, two E10 fuels and a traditional gasoline (E0). The experimental results showed that the use of E10 blends (gasoline containing 10% ethanol) reduced BC emissions by 7–38%. Based on phase-separated analysis, BC emissions in the initial driving phase and the high-speed phase (e.g., the 1st ECE-15 phase in the NEDC and the extra-high speed phase in the WLTC) represented the majority (86–96%) of the total BC emissions, and the emission factors during the 1st ECE-15 phase (NEDC) and the low-speed phase (WLTC) were 0.36 mg km⁻¹ and 0.37 mg km⁻¹ lower, respectively, for the ethanol-blended fuels than the ethanol-free fuel. Furthermore, we found that using ethanol-blended fuels could reduce the mass concentration of the BC emitted during cold starts, which lasted 53–95 s for the tested vehicles, by 4.28 ± 4.19 mg km⁻¹ and 2.06 ± 0.17 mg km⁻¹ in the NEDC and the WLTC, respectively.

Keywords: Black carbon emissions; Light duty passenger vehicles; Ethanol blended fuels; Driving conditions; Cold start.

INTRODUCTION

With China's economic development in recent decades, rapid motorization has been observed in many regions since 2000 (Wu *et al.*, 2017). Consequently, on-road vehicles have become one of the major sources of urban atmospheric pollution (Wang and Hao, 2012). In China, light-duty passenger vehicles (LDPVs) comprise the majority of the total vehicles (Wu *et al.*, 2016), and the population of LDPVs reached 200 million for the first time in 2018 (MPS, 2018). Therefore, pollutant emissions from LDPVs and associated health impacts have created serious concerns to both governmental stakeholders and urban residents in China. To mitigate vehicle emissions, the China 6b emission standard for light-duty vehicles will be implemented in 2023, which will tighten the emission limit of particle mass (PM) from

4.5 mg km⁻¹ to 3 mg km⁻¹ (MEP, 2016). Thus, it is necessary to develop effective technologies and strategies for reducing the PM emissions from LDPVs.

One possible solution is increasing the oxygen content of gasoline, as previous studies have shown that increased oxygenates may reduce gaseous and PM emissions (Wang *et al.*, 2013; Zhang *et al.*, 2014a). In China, methyl tert-butyl ether (MTBE) is used as an additive to raise the oxygen content and octane number (Wu *et al.*, 2017). However, studies have reported that MTBE may be related to the induction of cell proliferation and the inhibition of cell apoptosis (Bogen *et al.*, 2015; Saeedi *et al.*, 2017). The United States began to phase out MTBE in 2004, and the Environmental Protection Agency (EPA) implemented the renewable fuel program, which mandates the blending of renewable fuels into transportation fuel by 2022 (U.S. EPA, 2005).

To replace MTBE, ethanol blended fuels have become the majority of oxygenated biofuels. Because of its high corn yields, the U.S. became the world's largest producer of ethanol fuel in 2005. In China, blended fuels also have

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huge potential for the replacement of MTBE, the reduction of vehicle emissions, the destocking of stale grain, and the adjustment of the energy structure (Hao *et al.*, 2018; Jiao *et al.*, 2018). Therefore, China's central government has released a policy to promote ethanol blended gasoline fuels (Li *et al.*, 2017). In October 2018, Tianjin (an urban metropolis with severe air pollution) replaced the traditional gasoline with E10 fuels (a blend of 90% gasoline and 10% ethanol), and similar measures will be rolled out nationwide in 2020.

Vehicle emission profiles using ethanol blended fuels have been discussed in many studies, and the emissions are related to the ethanol content (e.g., 5%, 10%, 15%, or 85%), driving cycle, ambient temperature, cold-start conditions, and engine technology (Chan *et al.*, 2014; Barrientos, 2016; Man *et al.*, 2018; Yamada *et al.*, 2018). However, most studies have focused on fuel economy, gaseous pollutants, PM, and particle number. Black carbon (BC), as an important product of the incomplete combustion of carbonaceous fuels (Bond *et al.*, 2013), can affect the climate by changing the radiation budget (Ramanathan and Carmichael, 2008; Bond *et al.*, 2013). Meanwhile, the relationship between BC and various human health issues, such as impaired lung function and increased cancer risks, has been proven (Suglia *et al.*, 2008; Silverman *et al.*, 2012). Unfortunately, studies on BC emissions from LDPVs utilizing ethanol blended fuels are rare.

To better characterize the relationship of BC emissions and ethanol blended fuels, three in-use gasoline LDPVs and three types of fuels (two E10 fuels and an ethanol-free gasoline) were selected for BC emissions measurements by a dynamometer. The New European Driving Cycle (NEDC) and Worldwide harmonized Light vehicles Test Cycle (WLTC) were employed to study the impacts of driving conditions and cold-start events based on second-by-second BC monitoring. Our results provide useful information for promoting ethanol blended fuels in the future in China.

METHODOLOGY

Test Vehicles, Driving Cycles, and Fuels

In this study, three LDPVs were tested using a chassis dynamometer to evaluate BC emissions under the NEDC and WLTC. The tested LDPVs were manufactured in 2003, 2007, and 2014 using port-fuel injection (PFI) technology. The detailed specifications of the test LDPVs are listed in

Table 1.

The vehicle driving cycles (i.e., the NEDC and WLTC) were selected to compare the effect of the BC emissions characteristics of various fuels. The entire NEDC includes four European urban driving cycle (ECE) segments repeated without interruption (marked as the 1st to 4th ECE-15 cycles in this study), followed by the extra-urban driving cycle (EUDC), which simulates high-speed modes at a maximum of 120 km h⁻¹ (Wu *et al.*, 2017). The WLTC replaced the NEDC in the European Union (EU) in 2017 because of the poor real-world representativeness of the NEDC (Zhang *et al.*, 2014b; Yang *et al.*, 2015; Tietge *et al.*, 2017), and the WLTC has a higher average speed (47 km h⁻¹ vs. 33 km h⁻¹) and more aggressive driving segments (see Fig. 1) than the NEDC. In China, an emission standard has been in place to limit the emissions of LDPVs for years (Zhang *et al.*, 2014c), and the latest China 6a emission standard regulation was released in 2016, declaring WLTC as a regulatory condition (MEP, 2016). The entire WLTC (class 3b) cycle lasts 1180 s and includes four segments, namely, low-speed (589 s), medium-speed (433 s), high-speed (455 s), and extra-high speed (323 s) phases in this study. The test temperature of the dynamometer climatic chamber was controlled at 25°C, and the regulatory configuration of the dynamometer road load was tested twice under each testing cycle for each vehicle. Meanwhile, to assess the impact of a cold start on vehicle emissions, each vehicle was rested for 6 h to ensure that the difference from the climatic chamber temperature was less than 1°C before testing, as per the requirement of the China 6 regulation (MEP, 2016).

Three fuels were employed in this study: an E0 fuel (China 5 standard) and two ethanol blended fuels (one with relatively low aromatic (ELA) content and one with relatively low olefin (ELO) content), which were provided by the Sinopec Research Institute of Petroleum Processing (RIPP). The ELA and ELO are E10 fuels (composed of approximately 10% ethanol), and the detailed fuel information is listed in Table 2. The largest difference between the E10 fuels and the E0 fuel is that MTBE is almost absent in the ethanol blended fuels (< 1%).

Experimental Section and Emission Calculation

Fig. 1 shows a schematic diagram of the experimental process that was used to analyze the BC concentrations of the exhaust in Beijing. A full-flow constant volume sampler

Table 1. Specifications of the tested vehicles.

Tested vehicle information			
Manufacturer and model	Volkswagen Passat	Toyota Camry	Buick GL8
ID	V1	V2	V3
Model year	2003	2007	2014
Emission standard	China 2	China 3	China 5
Curb weight (kg)	1425	1490	1860
Fuel injection system	PFI	PFI	PFI
After-treatment device	TWC	TWC	TWC
Engine size (L)	1.8	2.4	2.4
Mileage traveled (km)	195,663	103,369	46,199

Fig. 1. The schematic diagrams of the test.

Table 2. Properties of the fuel used in this study.

Fuel ID	market fuel, E0	market fuel, E0	ELA, E10	ELO, E10
Reid vapor pressure (kPa)	51.7	57.4	56.8	44.7
Octane number	96.2	98.3	93.0	99.5
Ethanol (v/v %)	0	10.8	11.3	12.1
Aromatics (v/v %)	33.1	28.2	20.9	31.6
Olefins (v/v %)	9.8	6.2	23.7	7.0
MTBE (m/m %)	14.9	0.0	0.7	1.2
Carbon content (m/m %)	87.3	86.6	85.9	86.3

(CVS; Model 7400T; Horiba, Japan) was applied to dilute the vehicle exhaust. The flow rate of the CVS tunnel was $10.6 \text{ m}^3 \text{ min}^{-1}$. An Aethalometer (Model AE51; Magee, U.S.) was used to measure second-by-second BC exhaust concentrations (Aethlab, 2015).

For BC monitoring, previous studies have noted that the BC concentrations reported by Aethalometer are underestimated because the attenuation coefficient of the collected BC decreased as the soot deposited (Kirchstetter and Novakov, 2007). Meanwhile, the device noise also affects the uncertainties of the BC results (Ning *et al.*, 2013). Thus, we referred to Ning *et al.* (2013) for appropriate instrument parameter settings to lower the noise impact and applied a correction equation (Kirchstetter and Novakov, 2007) to correct the attenuation coefficient decrease, which is presented later.

The distance-specific emission factors of pollutants (in mg km^{-1}) are estimated for each vehicle using Eq. (1):

$$EF_{dis,i} = \frac{\sum_{j=1}^n BC_j \cdot V_{Gj}}{60 \cdot \sum_{j=1}^n v_j} \quad (1)$$

where $EF_{dis,i}$ is the distance-specific emission factors of pollutant i (BC), mg km^{-1} ; BC_j is the post-dilution concentration of BC measured by the AE51 at second j , mg m^{-3} ; V_G is the instantaneous exhaust flow rate recorded by the CVS, $\text{m}^3 \text{ min}^{-1}$; and v_j represents the instantaneous vehicle speed at second j , km s^{-1} . The exhaust flow rates (V_{Gj}) in the calculation are normalized to standard temperature (298 K) and pressure (1 atm) conditions.

The BC concentrations directly from the AE51 are corrected by Eqs. (2) and (3):

$$P_{BCj} = \frac{P_{BC0,j}}{(0.88Tr + 0.12)} \quad (2)$$

$$Tr = \exp\left(\frac{-ATN}{100}\right) \quad (3)$$

where $P_{BC0,j}$ and P_{BCj} are the raw and adjusted BC concentrations at second j , respectively, mg m^{-3} ; Tr is the filter transmission; and ATN is the absorbance parameter, which is directly obtained from the Aethalometer second by second. Previous study suggested that the ATN should be lower than 100 in the test (Kirchstetter *et al.*, 2007).

Kirchstetter *et al.* (2007) demonstrated that corrected BC concentrations exhibit good correlations with the results measured by thermal-optical analysis (TOA) methods. This correction has been commonly applied in other vehicular emissions measurement studies (Zheng *et al.*, 2015, 2016).

RESULTS AND DISCUSSION

The Impact of Alternative Fuel on BC Emissions

The BC emissions for three vehicles over the NEDC and WLTC are shown in Fig. 2. The detailed emission results of each trip are presented in detail in Tables S1 and S2. In general, the ethanol blended fuels showed lower average BC emissions for the tested vehicles. For E0, the average emission factors of V1, V2, and V3 are $0.49 \pm 0.43 \text{ mg km}^{-1}$, $0.46 \pm 0.09 \text{ mg km}^{-1}$, and $0.44 \pm 0.38 \text{ mg km}^{-1}$, respectively. For ELA, the average emission factors are $0.31 \pm 0.13 \text{ mg km}^{-1}$, $0.50 \pm 0.36 \text{ mg km}^{-1}$, and $0.35 \pm 0.13 \text{ mg km}^{-1}$. For ELO, the average emission factors are $0.26 \pm 0.10 \text{ mg km}^{-1}$, $0.38 \pm 0.32 \text{ mg km}^{-1}$, and $0.20 \pm 0.09 \text{ mg km}^{-1}$, respectively. Compared with E0 fuel, the BC emissions from all vehicles using E10 fuels are lower, except for V2 utilizing ELA. One possible reason for the phenomenon for V2 is that the aging of V2 causes the vehicle to burn engine oil. The BC emissions from engine oil combustion covered part of the discrepancy between using E0 and ethanol blended fuels. For example, the BC emission from V2 utilizing ELO is 0.15 mg km^{-1} under WLTC which is similar with utilizing E0 ($0.15 \pm 0.04 \text{ mg km}^{-1}$). Although the BC values were measured by different methods (e.g., TOA and light absorption) and the ethanol content varied, the BC reduction rates in our results are in the range of those in previous studies (Maricq *et al.*, 2012; Karavalakis *et al.*, 2014; Short *et al.*, 2015). For example, Short *et al.* (2015) tested BC emissions from three PFI vehicles using E10 and E20 fuels. In their study, the BC concentrations from two of the vehicles decreased by more than 50% when the fuel was switched from E10 fuel to E20 fuel at 70 mile h^{-1} , and the BC concentrations of the third vehicle

were roughly flat. In a study by Maricq *et al.* (2012), a gasoline direct injection (GDI) vehicle exhibited a moderate ($\sim 20\%$) PM improvement using E10 fuel relative to using E45 fuel under the Federal Test Procedure (FTP) cycle. The improvement in soot (e.g., BC and PM) has been widely attributed to the presence of oxygen content in the fuel, which results in the lean air-fuel ratio and promotes oxidation during combustion and over the catalyst. For instance, Karavalakis *et al.* (2014) also reported that BC reductions with increasing alcohol concentration were found for three LDPVs over the FTP cycle because the higher oxygen content reduced the tendency to form soot.

Furthermore, the ELO fuel also appeared to be associated with greater reductions in BC emissions. The BC emissions associated with using ELO were 20–42% lower than those associated with using ELA. In previous studies, the impact of fuel content varied, and our results are partially consistent with previous results. For example, in the results obtained by Khalek *et al.* (2010), soot emissions decreased by more than 75% when the olefin content was reduced from 6.9% to 0.1% (wgt) and the aromatic content increased from 32% to 42% (wgt) under the US06 cycle. However, Wang *et al.* (2016) showed different results, in which PM increased by 23.7% when the olefin content of the tested fuel increased by 14.7% (v/v) under 2000 r min^{-1} , 50% of full load (Wang *et al.*, 2016). Wang *et al.* explained that a higher olefin content increased the particulate emission because of the higher double bond equivalent. Moreover, in the study of Wang *et al.* (2016), PM emissions increased by 11.5% when the aromatic content was increased by 8.2% (v/v), mainly because aromatics have a more compact structure, lower H/C ratio are harder to evaporate and relatively slower decomposition than other hydrocarbon compounds (e.g., olefin), as Wang *et al.* (2016) explained. Meanwhile, Yang *et al.* (2019a) also showed the complex impact of aromatic and ethanol levels on the PM and BC emissions. In their study, the higher aromatic content fuels showed increases in PM and BC emissions that were statistically significant compared to the lower aromatic

Fig. 2. Average BC emissions for tested vehicles during the entire test cycles.

content fuels. But the trend of PM mass emissions increased with increases in ethanol content and likely due to ethanol's evaporative charge cooling effect as the authors explained. This result was significantly different from other studies by the same group of authors when they reported reductions in PM and BC with higher ethanol fuel blends (Yang *et al.*, 2018, 2019b). They explained that the combined effects of aromatic displacement and soot oxidation mechanisms are more dominant for PM formation compared to the evaporative charge cooling effect at these higher ethanol levels (Yang *et al.*, 2018). Thus, we believe that we cannot directly apply the variation in olefin and aromatic content to explain the BC reduction. To maintain the balance of Reid vapor pressure (RVP) and research octane number (RON), changes in olefin and aromatic content may also result in variations in the C/H ratio and the H₂O content, leading to differences in combustion completeness (Hochhauser *et al.*, 1991). We suggest that more experiments should be conducted to determine the cause of BC reduction by ELO in the future.

The Impact of Driving Conditions on BC Emissions

To address the differences in vehicular emissions associated with the use of various fuels under regulated conditions, we compare the BC emissions from all LDPVs on the NEDC and WLTC. As Fig. 2 indicates, the BC mass results ranged from 0.14 to 0.33 mg km⁻¹ for the NEDC and 0.26 to 0.75 mg km⁻¹ for the WLTC, averaging 0.24 and 0.47 mg km⁻¹ for V1, 0.19 and 0.70 mg km⁻¹ for V2, and 0.24 and 0.42 mg km⁻¹ for V3 with the NEDC and WLTC, respectively. In addition, the average differences between the NEDC and WLTC results for V1, V2, and V3 using the E0 fuel are 116%, 367%, and 67%. When switching to E10 fuels, the differences are 45%, 67%, and 41% for ELA and 44%, 75%, and 48% for ELO for V1, V2, and V3, respectively. In addition, other studies have also noted higher BC emissions under the WLTC than under the NEDC. For example, He *et al.* (2018) reported that the average BC emission factors of two PFI vehicles under the WLTC (e.g., 0.53 and 2.38 mg km⁻¹) were significantly higher than those under the NEDC (e.g., 0.28–2.16 mg km⁻¹). The BC increases under the WLTC are mainly related to the increased aggressive driving activities, which include more acceleration and deceleration modes and less idling.

Based on phase-separated analysis (Fig. 3), we find that the BC emissions in the initial driving phase (including the cold start) and high-speed phase (i.e., 1st ECE-15 and EUDC in the NEDC and the low-speed and extra-high speed phases in WLTC) are much higher than those in the hot-running stage (i.e., 196–780 s in the NEDC and 490–1478 s in the WLTC). The average proportion of BC emissions from the 1st ECE-15 cycle and EUDC accounted for 95 ± 5% of the total BC mass in the NEDC for E0, 96 ± 5% for ELA, and 96 ± 5% for ELO. For the WLTC, the average proportion of BC emissions during the low-speed and extra-high speed phases were 86 ± 7%, 90 ± 6%, and 90 ± 3% for E0, ELA, and ELO, respectively, which were lower than the NEDC values. Furthermore, taking the

instantaneous emissions of V3 as an example (Fig. 4; the other vehicles are illustrated in Fig. S1 and S2), the high BC values were related to cold-start and high-speed (approximately 100 km h⁻¹) driving emissions. The cold-start emissions are discussed in detail in the next section. For high-speed driving, we selected the part with a speed higher than 100 km h⁻¹ from the entire cycle and found that this part, for the fuels E0, ELA, and ELO, accounted for, on average, 26 ± 25%, 36 ± 33%, and 38 ± 28% of the total BC emissions in the NEDC and 45 ± 31%, 45 ± 18%, and 49 ± 23% of the total BC emissions in WLTC, respectively.

In addition, Fig. 3 shows that the ethanol blended fuels could effectively reduce the BC emissions in all phases except V2 in the 1st ECE-15. For example, in the WLTC, the average BC emission factors of the E10 fuels (ELA and ELO) are lower than those of the E0 fuel by 54% for V1, 19% for V2, and 41% for V3 in the extra-high speed phase and by 30% for V1, 24% for V2, and 23% for V3 in the low-speed phase. In the NEDC, although the BC emissions in some phases were slightly higher (e.g., EUDC for V1), the BC emissions were markedly lower in the other phase (e.g., 1st ECE-15 phase), resulting in a general decline in the BC emissions.

Emission Characteristics of Cold-starts for Different Fuels

Forestieri *et al.* (2013) noted that BC emissions are especially high during the cold start because the emissions are sensitive to the fuel/air ratio in an engine cylinder using E0 fuel. In this study, Fig. 3 shows that the average BC emission factors of the tested vehicles from the 1st ECE-15 are 1.49 ± 1.17 mg km⁻¹ for E0, 1.49 ± 0.91 mg km⁻¹ for ELA, and 0.77 ± 0.69 mg km⁻¹ for ELO in the NEDC. In the WLTC, the average BC emission factors are 1.37 ± 0.81 mg km⁻¹ for E0, 1.15 ± 0.78 mg km⁻¹ for ELA, and 0.84 ± 0.33 mg km⁻¹ for ELO in the low-speed phase. Therefore, using ethanol blended fuel can effectively mitigate the BC emissions during cold starts. Compared with ethanol-free gasoline, the average emission factor under the 1st ECE-15 was reduced by 0.36 mg km⁻¹ for ethanol blended fuels (ELA and ELO) in the NEDC and by 0.37 mg km⁻¹ in the low-speed phase in the WLTC. Iodice *et al.* (2018) detected that the air/fuel ratio (A/F) of E0 during cold start was much lower than E30 (Fig. S3). Thus, the enrichment of the air/fuel mixture was reduced using the ethanol blended fuel and mitigated the BC emissions.

Based on Fig. 4, we find that BC emissions are highly concentrated during the cold-start phase. Following Zheng *et al.* (2017), we assume that the cold-start process continues until the BC level drops to a certain level corresponding to the average BC concentration of the 2nd to 4th ECE-15 cycles in the NEDC or the medium- and high-speed cycles in the WLTC (see Fig. 4). The results indicate that the average duration of the cold-start phase in all tested vehicles using E0 is 69 s (ranging from 58 to 92 s) under the NEDC and 55 s (ranging from 47 to 62 s) under the WLTC. For ELA, the results are 81 s (ranging from 58 to 95 s) under the NEDC and 57 s (ranging from 49 to 63 s) under the

Fig. 3. Average BC emissions for tested vehicles during each phase in NEDC and WLTC. Note: the BC emissions factors of V1, V2, and V3 during the 2nd to 4th ECE-15 and EUDC in NEDC are represented as right Y-axis in (a), (c) and (e).

WLTC. For ELO, the results are 77 s (ranging from 58 to 92 s) under the NEDC and 56 s (ranging from 53 to 60 s) under the WLTC. The first approximately 100 s at the beginning of the driving cycle are associated with especially high BC emissions. The proportions of cold-start BC emissions for E0, ELA, and ELO with respect to the entire NEDC are $44 \pm 26\%$, $57 \pm 26\%$, and $48 \pm 32\%$, respectively. In the WLTC, the proportions are $24 \pm 11\%$, $29 \pm 19\%$, and $32 \pm 17\%$, respectively. In China, the cold-start emissions have been included in China 3 emission standard in 2007. With the development of engine control technology, BC emission can be reduced by higher cold-start idle speed (~2000 rpm) to rapid warming up the engine to reduce the cold wall quenching over the cold start (Jiang *et al.*, 2017). Meanwhile, calibrations of variable valve timing

and fuel injection timing can also optimize the particulate (or BC) emissions. However, these strategies have been accepted in the current engine control technology. The calibrations of the engine have finished before the type approval and there might be little space for optimizing (Jiang *et al.*, 2017). Thus, installment for gasoline particulate filter (GPF) might be an effective strategy to reduce the cold-start BC emissions.

In addition, Drozd *et al.* (2016) suggested that employing the ratio of total cold-start emissions to the hot-running emissions per km, defined as γ , could provide the distance that a vehicle would need to travel between cold starts before hot-running emissions would exceed cold-start emissions. As Fig. 5 illustrates, the average estimated γ values using E0, ELA, and ELO are 14 km, 24 km, and

Fig. 4. Real-time BC concentrations and vehicle speed profiles (one NEDC trip and one WLTC trip) for V3 using the three fuels.

Fig. 5. The ratio of total cold-start emissions factors to the hot-running emission factors.

19 km under the NEDC and 8 km, 11 km, and 14 km under the WLTC, respectively. In general, the γ values under the NEDC are higher than those under the WLTC. This result can be explained by the fact that the 2nd to 4th ECE-15 phases are much smoother than the hot-running phase in the WLTC, which results in lower baseline BC emission factors and higher γ values. Moreover, the γ values from ethanol blended fuels are higher than from E0. This observation should be primarily attributed to lower emission factors for ELA and ELO than for E0 in the hot-running phase.

Furthermore, GDI technology has become increasingly mainstream in China's gasoline car market. However, Zimmerman *et al.* (2019) reported that the toxic pollutant emission factors during cold starts can be 10 $\times$ higher than those for highway cruising for a GDI engine. He *et al.* (2018) reported that BC emissions in the low-speed phase from GDI vehicles are approximately 6 $\times$ higher than those from PFI vehicles in the WLTC (11.6 mg km⁻¹ vs. 1.9 mg km⁻¹, averaged over three samples). However, Zimmerman *et al.* (2016) evaluated the climatic impact of GDI vehicles using global warming potential and global temperature potential and concluded that installing a GPF with an 80% BC removal efficiency and < 1% fuel penalty is climatically beneficial. Thus, the BC emission characterization of GDI vehicles using ethanol blended fuel, especially with a GPF, should be conducted in the future.

CONCLUSIONS

In this study, we measured the BC emissions from three LDPVs powered by an ethanol-free fuel, E0, and two ethanol-blended E10 fuels, ELA and ELO, with a classic dynamometer and an Aethalometer. The distance-based BC emission factors for all of the tested LDPVs were calculated based on second-by-second monitoring. Furthermore, we analyzed the effects of using ethanol blended fuels and of the driving conditions on these emissions, with a special emphasis on the characteristics of cold-start emissions.

The results showed that, for the same vehicles, the BC emissions were 7–38% lower when using the E10 fuels than the E0 fuel; this decrease was mainly attributable to the higher oxygen content of the blended fuels, which reduced soot formation in the cylinder. Of the two blended fuels, the lower olefin content of the ELO potentially resulted in the largest reduction of BC, but more experiments should be conducted to confirm this hypothesis. Also, the ELO's higher octane number may have mitigated BC emission. The vehicular emissions were approximately 40–370% higher during the WLTC than the NEDC, and the increase in BC emissions from the ethanol blended fuels was consistent with that of the ethanol-free fuel.

The BC generated during the initial driving and aggressive high-speed phases (the 1st ECE-15 and EUDC in the NEDC and the low-speed and extra-high-speed phases in the WLTC) formed the vast majority (86–96%) of the total BC emissions. Based on the instantaneous emission profiles, the BC emissions were markedly higher during the cold-start and high-speed (above ~ 100 km h⁻¹) phases, the latter

of which contributed $26 \pm 25\%$, $36 \pm 33\%$, and $38 \pm 28\%$ of the total BC in the NEDC and $45 \pm 31\%$, $45 \pm 18\%$, and $49 \pm 23\%$ of the total BC in the WLTC while using E0, ELA, and ELO, respectively.

The impact of the cold start was discussed in detail in this study. Compared with those of the ethanol-free gasoline, the emission factors of the blended fuels during the 1st ECE-15 (NEDC) and the low-speed phase (WLTC) were reduced by 0.36 mg km⁻¹ and 0.37 mg km⁻¹, respectively. Additionally, we observed that cold starts lasted 53–95 s with the three tested fuels and contributed a significant percentage of the total BC emissions (44–57% and 24–32% during the NEDC and the WLTC, respectively). The BC mass concentration also decreased by 4.28 ± 4.19 mg km⁻¹ and 2.06 ± 0.17 mg km⁻¹ during the NEDC and the WLTC, respectively, when using the ethanol blended fuels. As ethanol blended fuel will soon be rolled out nationwide, we suggest investigating more testing conditions (e.g., various environmental temperatures) and fuel properties (e.g., detailed fuel compositions). Finally, although the European Real Driving Emissions (RDE) regulatory standard incorporated cold-start emissions in 2017, the China 6 standard has not specified any limit for these emissions. Thus, China's RDE regulations should follow suit in limiting cold-start emissions as soon as possible.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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