Research on the real-world gaseous emission characteristics of a plug-in hybrid electric vehicle under different initial battery state-of-charge

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Abstract. Plug-in hybrid electric vehicles (PHEVs) have been greatly promoted due to their advantage in both vehicle performance and energy conversion efficiency. However, real-world emission measurements are rarely conducted for PHEV under different initial battery state-of-charge (SoC). In this study, a portable emission measurement system (PEMS) was employed to investigate the real-world emissions of carbon monoxide (CO), nitrogen oxides (NOx), and carbon dioxide (CO2) from a Euro V PHEV under fully and uncharged initial battery SoC. Compared to the emissions under the uncharged state, the average emission factors (EFs) of CO, NOx, and CO2 under the fully charged state are reduced by 72.2%, 27.8%, and 29.0%, respectively. And the reduction effect on the urban road is much more significantly prominent compared to that on the rural road and highway. In addition, obvious reduction effectiveness can be found for CO EFs in different average speed bins, especially those with speeds above 100 km/h. For NOx and CO2, however, the average speed-bin EFs are reduced only when the speed is below 70 km/h, while no obvious differences can be found when the speed is above 70 km/h. Furthermore, for the average vehicle specific power (VSP)-bin emission rates, obvious reduction effectiveness is observed for CO in different speed ranges, and for NOx and CO2 in the low- and medium-speed ranges except the high-speed range.

1. Introduction
With the rapid increase in vehicle population and activity, the vehicle has grown to be an enormous oil consumer and thus a vital factor that influencing air quality in urban areas[1, 2]. Compared with traditional internal combustion engine vehicles, new energy vehicles, such as pure electric cars, hybrid-electric cars, and so on, have been promoted because of their advantages in reducing energy consumption and pollutant emissions. Although pure electric vehicles possess stronger advantages in terms of vehicle performance and energy conversion efficiency relative to traditional vehicles, they are currently not widely used due to the disadvantages in cost, technological maturity, and slow construction of supporting facilities. However, Hybrid vehicles, especially plug-in hybrid electric vehicles (PHEVs), take into account the advantages of both traditional and pure electric vehicles, and thus have obvious advantages in terms of power performance and exhaust emission control[3, 4]. Especially with the continuous tightening of vehicle emission standards, the application demand for PHEVs will continue.
to increase. Therefore, conducting emission measurements on PHEVs, especially those under real-world driving conditions, will be beneficial to evaluate the emission level of PHEVs and formulate vehicle emission control management policies.

As to the emission characteristics of PHEVs, a large number of relevant studies have been done at home and abroad. Compared with traditional gasoline and diesel vehicles, hybrid electric/gasoline vehicles possess great benefits in reducing NOx and CO2 emissions[3]. In terms of energy saving, PHEVs exhibit considerable potential on normal driving conditions, while no advantages for severe driving conditions with high-speed/acceleration[5]. Besides, the CO2 emissions of PHEV generally exhibit a negative relationship with the initial battery state-of-charge (SoC), while NOx and particles are mainly related to the operating conditions of the internal combustion engine[6]. However, studies focused on real-world emissions for PHEV under different initial battery SoC are relatively limited. Therefore, this study addressed the impact of the initial battery SoC on emissions emitted by PHEV under real-world driving conditions.

To investigate the effect of different initial battery SoC on the exhaust emissions of PHEV, a Euro V PHEV was tested using a portable emission measurement system (PEMS) under real-world driving conditions. This study was mainly focused on carbon monoxide (CO), carbon dioxide (CO2), and nitrogen oxides (NOx) emissions. Emission measurements on the PHEV under fully charged and uncharged initial battery SoC were elaborately considered. Besides, the test route was categorized into 3 road types, such as urban road, rural road, and highway, so as to obtain the differences in emissions between different initial battery SoC under various road types. Furthermore, to fully analyze the impact of initial battery SoC on emissions under different driving conditions, the speed-bin emission factors (EFs) and vehicle specific power (VSP)-bin emission rates under different initial battery SoC were evaluated.

2. Materials and Methods

2.1. Test Vehicles and Routes

Real-world emission measurements on a Euro V PHEV were conducted in February 2019 in Tianjin city, China. During test periods, the ambient temperature and relative humidity were averaged as 6.0±2.5 °C and 65.0±8.6 %, respectively. Detailed information about the tested PHEV is demonstrated in Table 1. The E10 ethanol-blended gasoline used here was acquired directly from the local market. A typical route with a length of 74 km was chosen to conduct the PEMS test, which is mainly covered by urban, rural, and highway. To investigate the characteristics of real-world driving emissions emitted by the tested PHEV under various traffic situations in Tianjin as much as possible, a total of 6 trip tests were carried out during the test. Furthermore, to clarify the effect of the initial battery SoC on emissions, this study designed the real-world emission tests for the PHEV under two initial battery SoCs: (1) Fully charged state, namely the initial battery is charged to 100% before the vehicle is started; (2) Uncharged state, namely the battery is not charged before the vehicle is started, and the remaining battery power is less than 10%. Meanwhile, the trip emission tests for the PHEV under fully charged and uncharged states were both conducted 3 times. To avoid the differences in test results caused by the inconsistent driving habits of different drivers, one driver was arranged to drive the tested vehicle successively.

| Parameters                  | PHEV                  |
|-----------------------------|-----------------------|
| Vehicle model               | GEELY Borui GE        |
| Fuel type                   | E10                   |
| Gross/Curb weight (t)       | 1.79/2.16             |
| Engine type                 | Turbocharged + direct injection +DOHC |
| Max. combustion engine power (kW/Nm) | 192/425              |
| Max. electric engine power (kW/Nm) | 60/160              |
The driving parameters of the tested PHEV under different road types are demonstrated in Table 2. The road types here are mainly classified based on the speed referring to the Real Driving Emissions (RDE) legislation[7]. It is clear that with the average speed increase from urban, rural to highway, the cruise fraction also exhibits an increasing trend, while the relative positive acceleration (RPA)[8], acceleration fraction, and deceleration fraction present decreasing trends. Consequently, compared to the complex traffic conditions on the urban road, the traffic behaviors on the rural road, especially on the highway, are relatively more stable due to the lower frequency and strength of acceleration and deceleration.

Table 2 The real-world driving parameter of the tested buses

| Parameters          | Urban     | Rural     | Highway   | Whole trip |
|---------------------|-----------|-----------|-----------|------------|
| Trip distance (km)  | 24.1±1.8  | 29±2.6    | 21.3±2.5  | 74.4±0.1   |
| Avg. speed (km/h)   | 27.1±3.5  | 74.7±0.9  | 107.0±1.6 | 50.2±5.0   |
| RPA (m/s²)          | 0.19±0.015| 0.102±0.014| 0.053±0.006| 0.117±0.009|
| Acceleration fraction (%) | 28.7±1.8 | 24.3±1.9 | 14.5±1.8  | 25.5±0.7   |
| Cruise fraction (%)  | 20.7±1.8  | 53.3±4.8  | 74.5±3.0  | 36.5±2.9   |
| Deceleration fraction (%) | 30.2±2.5 | 22.4±2.9 | 11.0±1.5  | 25.5±1.2   |
| Idle fraction (%)    | 20.4±5.6  | 0         | 0         | 12.5±3.9   |

2.2. Measurement system

In this study, the real-world instantaneous and cumulative emissions of CO, NOx, and CO2 were collected by a SEMTECH-DS PEMS. The SEMTECH-DS, developed by Sensors Inc., adopts a non-dispersive infrared sensor (NDIR) to measure CO and CO2 concentration and a non-dispersive ultraviolet sensor (NDUV) to acquire concentrations of NOx. Besides, several other units fixed around the vehicle body were also included, such as a SEMTECH High-Speed Exhaust Flow Meter (SEMTECH EFM-HS) to continuous and direct monitor the vehicle exhaust flow, a temperature probe to monitor the exhaust temperature near the exit of the tailpipe, a GPS to acquire vehicle speed and location information (i.e., altitude, latitude, and longitude), and a weather probe for the ambient temperature and relative humidity. To prevent the generation of condensates and high molecular weight hydrocarbons during the test periods, the sampling tube between the EFM and SEMTECH-DS analyzer was heated and maintained at 190 °C.

The lithium battery was employed to power the PEMS instrument to make sure that the vehicle engine operation will not be affected by the power demand of the device. All data acquired in this study were recorded at a frequency of 1 Hertz. The whole PEMS together with the co-driver, with a total weight being around 120 kg, resulted in 5.6% of the curb weight of the tested PHEV. Routine calibrations for the gaseous analyzers were conducted by controlling for the zero and span drift to ensure the error was not above 2%[9]. Meanwhile, purging and zero flow verifying were also conducted for the EFM before and after each test. Besides, a laptop computer, connected to the instrument by the local area network, was employed to monitor the real-time operational status of the device.

2.3. Analysis method

To investigate the effect of initial battery SoC on gaseous emissions in different speed intervals for the tested PHEV, the calculation method of EFs for each speed range in the COPERT model was drawn in this study[10]. The average speed-bin gaseous EFs herein were obtained firstly by integrating exhaust
gaseous emissions from on-road tests over micro-trips with 1 km distance to obtain the EFs for these trips\cite{11}, and then by averaging the EFs over different speed ranges of 10 km/h split by the average micro-trip speeds\cite{12}.

Vehicle Specific Power (VSP), defined as the instantaneous engine power output per vehicle unit mass (kW/ton), is also used herein to further reflect the gaseous emission characteristics and the differences in emissions between different initial power states under various operating modes. The operating modes are assigned based on VSP as shown in Table 2. According to the MOVES\cite{12}, based on instantaneous vehicle speed, acceleration, vehicle mass, and road load coefficients, VSP can be calculated as the following equation:

$$VSP = \frac{A}{M} \cdot v + \frac{B}{M} \cdot v^2 + \frac{C}{M} \cdot v^3 + a \cdot v + g \cdot v \cdot \sin \theta$$ \hspace{1cm} (1)

Where $M$ is the gross mass of individual test vehicle (tons), $v$ is the vehicle speed (m/s), $a$ is the vehicle acceleration (m/s$^2$), $g$ is the gravitational acceleration (9.81 m/s$^2$), and $\theta$ is the road grade (radians). The road load coefficients of $A$ (kW s/m), $B$ (kW s$^2$/m$^2$), and $C$ (kW s$^3$/m$^3$) represent the coefficients of the rolling resistance, rotational resistance, and aerodynamic drag, respectively. Obtained from the MOVES model, the values of $A$, $B$, and $C$ coefficients are 0.13810, 0.00177, and 0.00043 for the light-duty tested vehicle herein. The road grade can be regarded as 0 due to the relatively flat area for the test route with elevation gain less than 15 m over 20 km\cite{13}.

Table 3 Definition of instantaneous operating mode bins based on vehicle speed and VSP

| VSP (kW/t) | Bin0 (Braking: $a$<0.894 m/s$^2$ or consecutive 3 seconds $a$<0.447 m/s$^2$) | Bin1 (Idling) | Vehicle speed (km/h) |
|-----------|-------------------------------------------------|---------------|----------------------|
| VSP<0     | Bin0                                            |               | $v$$<1.6$            |
| 0≤VSP<3   | Bin1                                            |               | 1.6≤$v$$<40$        |
| 3≤VSP<6   | Bin2                                            |               | 40≤$v$$<80$         |
| VSP<6     | Bin3                                            |               | $v$$≥80$            |
| 6≤VSP<9   | Bin4                                            |               | Bin11                |
| 6≤VSP<12  | Bin5                                            |               | Bin12                |
| 9≤VSP<12  | Bin6                                            |               | Bin13                |
| VSP≥12    | Bin7                                            |               | Bin14                |
| 12≤VSP<18 | Bin8                                            |               | Bin15                |
| 18≤VSP<24 | Bin9                                            |               | Bin16                |
| 24≤VSP<30 | Bin10                                           |               | Bin17                |
| VSP≥30    | Bin11                                           |               | Bin27                |
|           | Bin12                                           |               | Bin28                |
|           | Bin13                                           |               | Bin29                |
|           | Bin14                                           |               | Bin30                |
|           | Bin15                                           |               | Bin31                |
|           | Bin16                                           |               | Bin32                |
|           | Bin17                                           |               | Bin33                |
|           | Bin18                                           |               | Bin34                |
|           | Bin19                                           |               | Bin35                |
|           | Bin20                                           |               | Bin36                |
|           | Bin21                                           |               | Bin37                |
|           | Bin22                                           |               | Bin38                |
|           | Bin23                                           |               | Bin39                |
|           | Bin24                                           |               | Bin40                |
|           | Bin25                                           |               |                     |
|           | Bin26                                           |               |                     |
|           | Bin27                                           |               |                     |
|           | Bin28                                           |               |                     |
|           | Bin29                                           |               |                     |
|           | Bin30                                           |               |                     |
|           | Bin31                                           |               |                     |
|           | Bin32                                           |               |                     |
|           | Bin33                                           |               |                     |
|           | Bin34                                           |               |                     |
|           | Bin35                                           |               |                     |
|           | Bin36                                           |               |                     |
|           | Bin37                                           |               |                     |
|           | Bin38                                           |               |                     |
|           | Bin39                                           |               |                     |
|           | Bin40                                           |               |                     |

3. Results & Discussion

3.1. On-road driving based emissions

The real-world average CO, NO$_x$, and CO$_2$ EFs for the tested PHEV are demonstrated in Table 4. The gaseous EFs on the highway are significantly greater than those on the rural and urban roads. This may be because the electric motor assists in more work in other road types relative to the highway, thus contributing more beneficial to reduce emissions. Compared with the gaseous EFs under uncharged state, the average EFs of CO, NO$_x$, and CO$_2$ under fully charged state are reduced by 72.2%, 27.8%, and 29.0%, respectively. It is obvious that the difference in CO between different initial battery SoC is greatly larger than that in other gaseous emissions. This is probably due to that the electric motor can assist the engine work during the acceleration process with incomplete combustion conditions that contribute easily to the production of CO relative to NO$_x$ and CO$_2$ for gasoline engines, which thus leads to larger reductions in CO compared to other gaseous emissions.
Since CO₂ emissions are generally related to fuel consumption, the difference of auxiliary work of the electric motor between different road types can be judged by the variations of CO₂ EFs in different road types. The CO₂ EFs under highway, rural, and urban roads are reduced by 3.5%, 25.4%, and 71.5%, respectively, for the PHEV under fully charged state relative to that under uncharged state. The CO₂ EFs under different initial battery SoC presented statistically significant differences on the rural road and especially on the urban road, but exhibited no obvious differences on the highway, which is consistent with the results of Al-Samari et al[14]. This fact indicates that the electric motor contributes the largest auxiliary work in the urban road, while the lowest on the highway.

Consistent with the largest decrease in CO₂ EFs on the urban road, the EFs of CO and NOₓ also present the largest decrease ratios on the urban road for the PHEV under fully charged state compared to that under uncharged state, with values being reduced by 84.3% and 88.2%, respectively. In addition, the CO EFs on the rural and highway are reduced by 53.6% and 77.3%, respectively. However, no obvious differences between different initial battery SoC can be found for NOₓ EFs on the highway and rural road. This phenomenon may be explained by the fact that under medium and high-speed conditions, the electric motor can usually only participate in auxiliary work at the moment of acceleration and thus beneficial to the reduction in CO that is easy to produce during the acceleration phase. For the steady driving conditions that easily happened during medium- and high-speed conditions, the electric engine can not participate for a long time and thus unfavorable to reduce the production of NOₓ and CO₂, which is easily produced by complete combustion under uniform speed conditions. Furthermore, the larger decrease ratio on the rural road for CO₂ compared to NOₓ may be related to the susceptibility of NOₓ to the working state of the internal combustion engine[6].

### Table 4 Real-world distance-based PHEV EFs of NOₓ, CO₂, and CO

| Road type | Power states | NOₓ (g/km) | CO₂ (g/km) | CO (g/km) |
|-----------|--------------|------------|------------|-----------|
| Highway   | Fully charged| 0.58±0.53  | 212±34     | 0.24±0.1  |
|           | Uncharged    | 0.51±0.26  | 220±33     | 1.08±0.15 |
| Rural     | Fully charged| 0.25±0.16  | 125±10     | 0.13±0.08 |
|           | Uncharged    | 0.26±0.18  | 167±9      | 0.28±0.36 |
| Urban     | Fully charged| 0.05±0.02  | 41±13      | 0.03±0.03 |
|           | Uncharged    | 0.42±0.14  | 146±15     | 0.19±0.11 |
| Trip      | Fully charged| 0.28±0.21  | 123±18     | 0.13±0.01 |
|           | Uncharged    | 0.39±0.19  | 174±7      | 0.47±0.20 |

3.2. Effects of driving speed on exhaust emissions

The relationships between average speed and average speed-bin gaseous EFs (yellow diamonds) for the tested PHEV are illustrated in Figure 1. Curve fitting is also performed based on the average EFs in the speed interval and the mean speed of the corresponding speed interval. The average speed-bin CO EFs exhibits an obvious exponential function relationship with vehicle speed, while the average speed-bin NOₓ and CO₂ EFs present obvious quadratic polynomial function relationships with vehicle speed.

Although the average speed-bin CO EFs under fully and uncharged states both exhibit increasing trends with the speed increase, the average speed-bin CO EFs under the uncharged state is significantly lower than that in the uncharged state, especially when the speed exceeds 100 km/h. For CO₂ and NOₓ, when the speed is below 70 km/h, the average speed-bin EFs under fully charged state exhibit lower values relative to that under uncharged state, and the differences generally decrease with speed increase. However, when the speed is above 70 km/h, average speed-bin CO₂ and NOₓ EFs under fully and uncharged states both exhibit increasing trends with the speed increase, and no obvious differences can be found between different initial battery SoC.
3.3. Effects of operating mode on exhaust emissions

The average emission rates of CO, NO\textsubscript{x}, and CO\textsubscript{2} by operating mode for the tested vehicle are presented in Figure 2. The gaseous emission rates for the PHEV under fully charged and uncharged states generally increase with VSP in the low- (bins 11-16), medium- (bins 21-30), and high-speed (bins 33-40) ranges, which is in accordance with the result in a previous study \cite{15}. For the PHEV under uncharged state, the highest peak VSP-bin CO emission rate in each speed range occurs in the high-speed interval, while the lowest peak happens in the low-speed interval. The peak VSP-bin CO emission rate in the high-speed (5.1×10\textsuperscript{-1} g/s) is significantly larger than the peaks in the low- (4.2×10\textsuperscript{-3} g/s) and medium-speed (3.2×10\textsuperscript{-1} g/s) ranges, indicating that the CO emissions of the test vehicle are mainly affected by high driving speed conditions with heavy engine load. For NO\textsubscript{x} and CO\textsubscript{2}, however, the peak VSP-bin emission rates in the medium-speed range are closer to those in the high-speed range, and even the peak VSP-bin emission rate of NO\textsubscript{x} in the medium-speed range is much larger than that in the high-speed range. Thus, compared to CO, CO\textsubscript{2} and especially NO\textsubscript{x} are more susceptible to high engine load conditions. Specifically, the peak emission rates of NO\textsubscript{x} in the low-, medium-, and high-speed ranges are 7.8×10\textsuperscript{-3}, 4.8×10\textsuperscript{-2}, and 1.6×10\textsuperscript{2} g/s, respectively; while the peak emission rates of CO\textsubscript{2} in the corresponding speed ranges are 2.4, 12.8 and 11.5 g/s, respectively.

Compared to the emissions emitted by the PHEV under uncharged state, the average VSP-bin emission rates of CO under fully charged state are significantly reduced. For example, the peak average VSP-bin emission rates of CO in the low-, medium-, and high-speed ranges are 1.5×10\textsuperscript{-3}, 1.2×10\textsuperscript{-3}, and 3.3×10\textsuperscript{-2} g/s, respectively, which are lowered by 64.3\%, 63.0\%, and 93.5\%, respectively. However, the average VSP-bin emission rates of NO\textsubscript{x} and CO\textsubscript{2} only exhibit lower values in the low- and medium-speed ranges, but no significant difference can be found in the high-speed range. This fact may be
because the electric motor mainly participates in auxiliary work in the low- and medium-speed range with relatively low engine load.

Figure 2. Variations of average VSP-bin gaseous emission rates of (a) CO, (b) NO\textsubscript{x}, and (c) CO\textsubscript{2}.

4. Conclusions
To obtain the effect of initial battery SoC on real-world driving emissions of PHEV, the emissions of CO, NO\textsubscript{x}, and CO\textsubscript{2} emitted by a Euro V PHEV under fully charged and uncharged states were tested and analyzed. Relevant conclusions drawn in this study are as follows:

1. Under different initial battery SoC, obvious differences can be found in the exhaust emissions for the PHEV. The average EFs of CO, NO\textsubscript{x}, and CO\textsubscript{2} are reduced by 72.2%, 27.8%, and 29.0%, respectively, for the PHEV under fully charged state relative to that under uncharged state. Moreover, compared to the differences in emissions between different initial battery SoC on the rural road and highway, the difference on the urban road occupies the most prominence, which is mainly due to the largest auxiliary work of the electric motor on the urban road.

2. Obvious differences in average speed-bin gaseous EFs also exist between different initial battery SoC. The average speed-bin CO EFs, especially those with speed above 100 km/h, are obviously lower for the PHEV under fully charged state compared to that under uncharged state. However, the average speed-bin NO\textsubscript{x} and CO\textsubscript{2} EFs under fully charged state only exhibit lower values when the speed is below 70 km/h, and no obvious differences can be found between different initial battery SoC when the speed is above 70 km/h.

3. For the differences in average VSP-bin gaseous emission rates between different initial battery SoC, the average VSP-bin CO emission rates in the low-, medium-, and high-speed ranges are generally lower for those under fully charged state compared to those under uncharged state. However, the average VSP-bin emission rates of NO\textsubscript{x} and CO\textsubscript{2} only exhibit lower values in the low- and medium-speed ranges, but no obvious difference can be found in the high-speed range.

It should be noted that only CO, NO\textsubscript{x}, and CO\textsubscript{2} emissions from a PHEV were measured, which is not sufficient to acquire the effectiveness of the initial battery SoC on emission reductions of these vehicle emissions.
types. Further researches about the real-world gaseous and particle emissions of PHEV under different driving conditions are required to be conducted.

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