Study on emission characteristics of hybrid bus under driving cycles in typical Chinese city

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Abstract. In this study, hybrid city bus was taken as the research object, through the vehicle drum test, the vehicle emissions of hybrid bus, the transient emissions of gas pollutants, as well as the particle size and number distribution were surveyed. The results of the studies are listed as follows: First, compared to traditional fuel bus, hybrid bus could reduce about 44% of the NOx emissions, 33% of the total hydrocarbon emissions, and 51% of the particles emissions. Furthermore, the distribution of particles number concentration of test vehicle became high in middle and low in both sides. More specifically, the particle number concentration was mainly concentrated in the range from 0.021 to 0.755 μm, the maximum was 0.2 μm, and particle size of particulate matter (PM) less than 1.2 μm accounted for 95% of the total number concentration. Particulate mass concentration was increased with increment of particle size, and the maximum of particulate mass (PM) concentration was 6.2 μm. On average, whether traditional fuel bus or hybrid bus, the particle size of particulate matter (PM) less than 2.5 μm accounted for more than 98% in the particles emission. It is found that the particles are more likely to deposit to the lung, respiratory bronchioles and alveoli, causing respiratory and lung diseases. Therefore, how to control the PM emissions of hybrid bus is the key factor of the study.

1. Introduction
Hybrid vehicle is currently acknowledged to be one of the effective ways to solve energy crisis and to alleviate the pressure of environmental protection[1-3]. At present, the annual growth of hybrid bus has been around 10000, representing an annual average growth over 50%. The working situation of the hybrid city bus is centered on engine external characteristics, especially near the middle and high speed region. The idling operation in typical urban road spectrum can reach 20%. The fuel consumption in idling operation is not used for vehicle working, and emission in the idle condition is higher than in normal running condition. So far, researches on hybrid vehicle emissions at home and abroad have not been deep enough[4-9]. On one hand, the evaluation basis of heavy vehicle emission is certificated by engine test, but the engine test condition always deviates from the real driving cycle. Whether the strict emission regulations can effectively reduce the vehicle's actual emission greatly depends on if the test cycle can represent the real driving cycle. Furthermore, the emission test cycle has made a lot of change and development. Take the European regulation as an example. From the steady working condition ECE and ESC to transient working condition ETC, the test cycle is much closer to engine’s actual working condition. Whereas WHTC test cycle is more close to engine’s actual working condition of heavy vehicle, and at the same time it increases the cold start test.
other hand, in China, only particulate mate (PM) mass emission is restricted by emission regulation, the particle size and number have not been explored, so the damage of particles released by heavy vehicle to environment and human health can not be evaluated.

Under the background of global energy conservation and emission reduction, emission limit reduces greatly around the world. However, many researchers observe that the actual emissions of heavy vehicle increase with the emission regulations tightened. Specifically, the emissions of Euro III, EuroⅣ and Euro V in actual driving road don’t live up to the lightened emission regulations, which are particularly obvious in city driving cycle. Similarly, part of national Ⅳ bus's actual particle emissions are higher than national Ⅲ bus. Therefore, it is advisable to study the real particle emissions of hybrid bus which are suitable for Chinese urban roads under CCBC.

How is the energy consumption of hybrid bus under Chinese City Bus Cycle (CCBC) ? What are the characteristics of nitrogen oxides(NOX), total hydrocarbon(THC) and particles emissions? Especially the distribution characteristics of particle size and number? Few previous studies are referred to the above questions, and most of the studies are lack of experimental data reference. This study is devoted to reveal the vehicle emissions, as well as the particle size and number distribution characteristics under driving cycle through the vehicle drum test.

2. Testing Equipment and program

2.1 Testing equipment
Burke Dynamometer 7349, AVL CVS(constant volume sampling) i60, AVL AMAi60 analyzer, AVL GEM201 exhaust test system, FLUKE data collector, Electronic low-pressure impactor (ELPI). ELPI is mainly used for measuring the particle number and size distribution of vehicle exhaust. by using filter, it can measure the particle size ranges from 7 nm to 10 um. Figure 1 is the emission test site for hybrid bus.

Figure 1: The emission test site for hybrid bus

2.2 Prototype parameter
Bus is an important part of the urban public transportation. And bus emission control is an effective way to improve the air pollution in cities. Due to the fixed lines, convenient charging and other factors, hybrid technology greatly applied in the field of city bus. Therefore, this study choose bus as the research object.
Table 1: Basic information for testing vehicle

| Project                      | Parameter                           |
|------------------------------|-------------------------------------|
| Engine type                  | Inline six-cylinder turbocharged inter-cooled diesel engine |
| emissions/ml                 | 6494                                |
| rated power/speed(kW/（r/min）) | 155/2500                            |
| Maximum Torque/speed (N.m/（r/min）) | 710/1500                           |
| motor type                   | SHS4-ZDKQ three-phase asynchronous motor |
| main power supply            | lithium battery/Supercapacitor      |
| all-electric range/km        | 35                                  |

The testing vehicle was the parallel hybrid electric bus. When the speed ranged from 0 km/h to 20 km/h, the engine wasn’t driven and it kept stable, the vehicle was driven by the electric motor, and the vehicle was in series working mode; when the speed surpassed 20 km/h, the vehicle was driven simultaneously by engine and electric motor, and the vehicle was in parallel working mode. Table 1 is the main parameters of testing vehicle. In addition, the vehicle was in full load condition when testing. And besides, diesel oil used in the test meet the requirements of China No. three fuel quality standards.

2.3 Test basis

CCBC is set on the basis of city bus operation data in Beijing, Shanghai and Guangzhou. The cycle better reflects the bus’ actual operation condition, and also reflects the actual vehicle emission more realistic. So the emission evaluation is more scientific and reasonable. Therefore, this study adopt CCBC test.

Testing cycle and testing process were invoked according to “testing method of heavy duty hybrid electric vehicles’ energy consumption”(GB/T 19754-2005) . The state of charge(SOC), the change of power battery voltage, and the change of net energy(NEC) were beyond the scope of this measurement. Chassis dynamometer was set in terms of “testing method of heavy commercial vehicles’ fuel consumption”(GB/T27840-2011). Emission test was held in the light of GB17691-2005 “compression ignition (C.I.) engines of automobile and park ignition gas engine, along with the emission limits and test measurement of automobile pollutants (phase III , IV, V in China)”(GB17691-2005). According to the emission under CCBC, each working condition of testing vehicle was measured twice. The speed set is shown in Figure 2.

Figure 2: Typical urban bus transport cycle in China

3. Test Results and Analysis

3.1 CCBC cycle discharge

The operation condition of city bus is complicated. The operating point of CCBC was obtained by the
data collection of speed, driving distance, fuel consumption, engine speed, and intake pressure. Compared to America’s FTP test cycle and European’s ETC test cycle which were widely applied in some parts of the country, the emissions data tested by CCBC was more typical, and can truly reflect the influence of city bus on air pollution[10-14].

Figure 3 shows emission comparison of traditional fuel bus and hybrid city bus. From the figure, we can see that the total hydrocarbon(THC) emission of traditional fuel bus reached up to 4.83 g/km, while the total hydrocarbon(THC) emission of hybrid city bus was about 3.26 g/km; the nitrogen oxide(NOx) emission of traditional fuel bus reached up to 7.98 g/km, while the nitrogen oxide(NOx) emission of hybrid city bus was about 4.47 g/km; the particulate matter(PM) emission of traditional fuel bus was about 0.0215 g/km, while the particulate matter(PM) emission of hybrid city bus was about 0.0105 g/km. To sum up, in contrast to the traditional fuel bus, about 44% of the NOX emission, 33% of the THC emission and 51% of the particulate matter(PM) emission of hybrid bus were reduced.

![Emission comparison graph](image)

Figure 3: Emission comparison of traditional fuel bus and hybrid city bus

### 3.2 Transient emission of gases pollutant

Figure 4 shows the real-time emission comparison of gaseous pollutant between traditional fuel bus and hybrid city bus. As shown, the differences of gaseous pollutant emission between the two models focused on the middle and low speed region, where the emission was relatively low. When in low and medium speed, the hybrid bus was driven by electricity, so the speed was low, and the emission was also relatively low. When in high speed, the hybrid bus was driven by engine, there was little difference of mission between two models. The average concentration of HC emission of hybrid bus was 41.3x10^-6, and the average concentration of HC emission of traditional bus was 48.6x10^-6. The average concentration of NOx emission of hybrid bus was 24.4x10^-6, and the average concentration of NOx emission of hybrid bus was 26.9x10^-6. The average concentration of CO2 emission of hybrid bus was 0.18%, the average concentration of CO2 emission of hybrid bus was 0.26%.

![Emission concentration graph](image)

(a) HC emission concentration
3.3 Number and mass distribution characteristics of PM

Ultra-fine particles and nano particles are more likely to enter the lungs, staying for a longer time, which may induce a variety of serious diseases. Therefore, hybrid bus faces the double challenges of particulate emission number and mass\cite{15-16}. In terms of aerodynamic equivalent diameter, the particulate matter (PM) was divided into 12 grades, measuring the particle’s mass concentration and number distribution of traditional fuel bus and hybrid city bus, respectively, under CCBC. This study took the average value of particles mass and number concentration measured twice as the research data.

The results of the studies are listed as follows: the elements of particle size less than 50nm was the volatile organic compound and sulfur, called nucleation mode particle\cite{17-19}. The elements of particles size more than 50nm is the carbon particle aggregates and absorbate produced by incomplete combustion of fuel oil, called aggregation mode particle. Figure 5 shows the comparison of particles quantity emission between the two models. It can be seen that particle number concentration of test vehicle became high in middle and low in both sides. More specifically, the particle number concentration was mainly concentrated in the range from 0.021 to 0.755μm, the maximum was 0.2μm, and particle size of particulate matter(PM) less than 1.2μm accounted for 95% of the total number concentration. The number concentration of nucleation mode particle of hybrid bus was higher than traditional fuel bus, while aggregation mode particle of hybrid bus was lower than traditional fuel bus. The drive mode optimized the operating characteristics of the engine, the engine was working in middle and high speed condition. The mixing of fuel and air were accelerated, and the combustion process was improved, and the aggregation mode particles produced by incomplete combustion were reduced. In general, whether traditional fuel bus or hybrid bus, the particle size of particulate matter(PM) less than 2.5μm accounted for more than 98% in the particles emissions. It is found that the particles are more likely to deposit to the lung, respiratory bronchioles and alveoli, causing respiratory and lung diseases. Therefore, how to control the PM emissions of hybrid bus is the key
factor of the study.

Figure 5: Comparison of particulate matter emission number distribution

Figure 6 shows the comparison of particles mass emission between two models. We can see that there was apparent distinction between PM mass distribution and PM number distribution. PM mass concentration of the two models increased with increment of particle size, and the maximum of PM mass concentration was 6.2 μm. The number concentration of PM more than 1.2μm was very low, while the mass concentration was high. Because the elements of PM size more than 1.2μm were carbon granules and adsorb-ate, its volume and density were large, and the PM may deposit in the cylinder head or the exhaust pipe wall, and the emission was random and uncertain. And it had little relation to engine’s real-time working condition. From the perspective of PM mass emission, hybrid bus can decrease about 38% PM mass emission according to the CCBC.

Figure 6: Comparison of particulate matter emission mass distribution

3.4 Operation condition and PM emission

At present, the studies of diesel engine performance and emission control focused on the diesel engine’s steady state. But in practice, diesel engine is under unsteady transient condition in most time, especially, in extreme ambient transient condition. Under that condition, cyclic air inflow, fuel injection, and lubricating oil consumption of engine were changing constantly, causing the deviation of air-fuel ratio and combustion regime, which had a significant influence on the diesel emission especially the PM emission\(^{(20-23)}\).
Figure 7: The particle number concentration in different operating condition

Figure 8: The particle mass concentration in different operating condition

Figure 7 and Figure 8 are the PM number concentration emission and mass concentration emission of hybrid bus under different working condition such as idle, uniform, acceleration, deceleration and so on. As shown, vehicle driving cycle had little effects on PM emission of particle size less than 2μm. And the number concentration of PM within the above scope reached highest under uniform working condition. As to particle size ranged from 2 to 8μm, the vehicle driving cycle has much effects on number concentration. the number concentration of PM emission within the above scope reached peak under accelerating condition, and middle under decelerating condition, and low under idle condition. For particle size ranged from 5 to 10μm, vehicle driving cycle had much effect on mass concentration. Under accelerating condition, the number concentration of PM within the above scope decreased dramatically, but the mass concentration increased rapidly. It was demonstrated that the combustion status was poor under accelerating condition, and it was easy to cause PM emission such as carbon to rise. On the whole, PM number emission under the accelerating condition was about 2.6 times that of idle condition, and 1.8 times that of uniform condition. PM mass emission in the accelerating condition was about 4.8 times that of idle condition, and 3 times that of uniform condition.

4. Conclusions
The key to carry out research in hybrid bus emission control is exactly understand the differences between type approval test condition of emission regulation and the actual condition of the vehicle. To Chinese city road, CCBC emission test cycle can better reflect the real vehicle emissions, and the emission test results have more directive significance.

(1) Compared to traditional fuel bus, hybrid bus can reduce about 44% of the NOx emissions, 33% of the total hydrocarbon emissions, and 51% of the particles emissions.

(2) the distribution of particles number concentration of test vehicle became high in middle and low in both sides. More specifically, the particle number concentration was mainly concentrated in the range from 0.021 to 0.755μm, the maximum was 0.2μm, and particle size of particulate matter(PM) less than 1.2 μm accounted for 95% of the total number concentration. Particulate mass concentration increased with increment of particle size, and the maximum of particulate mass concentration was 6.2 μm.

(3) whether traditional fuel bus or hybrid bus, the particle size of particulate matter(PM) less than
2.5μm accounted for more than 98% in the particles emissions. It is found that the particles are more likely to deposit to the lung, respiratory bronchioles and alveoli, causing respiratory and lung diseases. Therefore, how to control the PM emissions of hybrid bus is the key factor of the study.

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