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Comparison of real-world fuel economy and emissions from parallel hybrid and conventional diesel buses fitted with selective catalytic reduction systems

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HIGHLIGHTS

- We conducted experiments on hybrid and conventional buses with SCR system using PEMS.
- Hybrid diesel buses with small battery consume less fuel but with a higher BSFC.
- Hybrid diesel buses emit higher NO_X because of lower efficiency of SCR system.
- Exhaust temperature is key factors for NO_X emissions from diesel buses.
- More loads may raise fuel consumption but reduce NO_X emissions for buses with SCR system.

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ABSTRACT

In this research, two parallel hybrid- and two diesel-buses fitted with selective catalytic reduction systems were tested in real world conditions using portable emission measurement systems. The hybrid buses were chosen to operate in either hybrid mode or diesel mode. In hybrid mode, the buses consumed less fuel, but the brake specific fuel consumptions were higher. The hybrid buses produced less engine-out NO_X emissions than diesel buses, but as a result of lower exhaust temperature and lower efficiencies of SCR systems, the tailpipe NO_X emissions from hybrid buses were a little higher. The brake specific NO_X emissions from hybrid buses were very high and beyond the limit value of Euro-IV standard. History effect was also important for the efficiency of SCR system. The CO emissions from hybrid buses were lower in the unit of g/s, but the fuel-based CO emissions were higher than diesel buses.

1. Introduction

With the potential of reducing fuel consumption and emissions, hybrid electric vehicles (HEVs) have been researched and developed as attractive and effective replacements for conventional vehicles [1–4]. Except for internal combustion engines (ICEs), HEVs have other types of energy converters, such as electric motors, to propel the wheels. Normally, according to the configuration of drive chain, non-plug-in HEV can be divided into three types: series, parallel and complex HEVs [5]. In a parallel HEV, the ICE and motor are usually smaller and lighter, as they provide driving power to the vehicle in parallel. In addition, the energy from the ICE can be directly used without multiple energy conversions carried on in series and complex HEVs [6]. Hence, parallel HEVs are expected to have better fuel economy than series HEVs. Parallel HEVs also have advantages over complex HEVs in aspects of cost, control strategy and total weight [5]. Bishop et al. regarded parallel hybrid as one of the most cost-effective ways of reducing CO_2 emissions and fuel consumption [7]. Plug-in HEVs, with the ability to recharge from external electrical sources, can further reduce fuel consumption and emissions from the vehicles [8,9]. But their prices are higher than normal HEVs because of the cost of larger battery [5].

Non-plug-in parallel HEVs are believed to have higher energy efficiency and less CO_2 emissions than conventional vehicles for two main reasons. First, with the presence of electric motors/generators, parallel HEVs can regenerate braking energy

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which are usually wasted in the form of friction and heat in conventional vehicles [10], although this benefit may be affected by averaging speeds, driving patterns and air conditioning usage [11–13]. The regenerative energy can be further used by electric motor to power vehicles, and hence reduces fuel consumption and emissions from ICE. Second, appropriate control strategy can make ICE work with higher efficiencies with electric motors as buffers [12,14].

Although most of the traditional researches conducted in laboratory gave results showing better fuel economy and less CO_2, CO, THC and PM emissions for hybrid diesel vehicles [15–17], there was always a contradictory about NO_X emissions. Lin et al. conducted experiments in chassis dynamometer following Urban Dynamometer Driving Schedule (UDDS cycle). The results showed that hybrid truck decreased fuel consumption by more than 20% at the expense of 7% more NO_X emissions [17,18]. Hallmark et al. evaluated in-use emissions from hybrid and regular transit buses on road. Average NO_X emissions were higher for all conditions for the hybrid buses than those for the control buses [17,18]. Wayne et al. compared emissions from hybrid and conventional transit buses with Diesel Oxidation Catalysts (DOCs) and Diesel Particulate Filters (DPFs) in the Transportable Heavy-duty Vehicle Emissions Testing Laboratory. The results showed that hybrid diesel buses had lower NO_X emissions, and the reduction ratio depended on the testing cycles [19,20]. Brodrick et al. tested conventional and hybrid diesel buses with DPFs in chassis dynamometer with a variety of different cycles and pointed out that NO_X emissions from the hybrid diesel bus were lower than those from conventional diesel bus [19,20]. Zhang et al. measured emissions from four diesel buses by on-road testing, and concluded that Euro IV diesel hybrid buses performed better than Euro V diesel buses in respect to NO_X emissions [21].

The main reason for this contradiction was that ICE will produce more NO_X emissions while operating in regions of high efficiencies because of the higher temperature and sufficient airs, namely the tradeoff between NO_X emissions and fuel economy for diesel engines [22]. Hence, under control strategies which optimize only fuel economy [17,18], NO_X emissions may be higher than those from conventional vehicles because the emission benefits resulting from regenerative braking may not offset the NO_X increases as a result of high efficiency combustion. Conversely, under control strategies which optimize both fuel economy and emissions, NO_X emissions from parallel hybrid diesel vehicles may be lower than those from conventional diesel vehicles [19,20,23].

In the studies mentioned above, most of the hybrid and conventional diesel vehicles were fitted with Diesel Particulate Filters (DPFs). But in developing countries such as China, the higher fuel sulfur content constrains the application of DPFs and hence selective catalytic reduction (SCR) systems are the mainstream aftertreatment devices facing stringent emission standards such as Euro-IV and Euro-V legislations [24]. Except for engine-out NO_X emissions, exhaust temperature and accordingly the NO_X reduction efficiencies of SCR systems were also affected by the control strategy of hybrid buses [25]. Hence the NO_X emissions from hybrid buses with SCR systems may be more complex than those with DPFs. Moreover, in those studies, most of the buses were tested in chassis dynamometers following driving cycles, upon which fuel consumption and emissions were optimized. Hence, they may not be representative of the real-world benefits, especially for urban driving conditions [26,27]. In this study, fuel economy and emissions from conventional and non-plug-in parallel hybrid diesel buses with SCR systems were tested on road in Beijing urban areas with portable emission measurement system (PEMS). Meanwhile, NO_X emissions were paid special attention to.

2. Methods

2.1. Test vehicles

Two non-plug-in parallel hybrid diesel buses (bus 1, 2) and two conventional diesel buses (bus 3, 4) were tested in this research. The details of these buses were summarized in Table 1. Diesel engines of these buses, belonging to the same series of the manufacturer, were same in displacement and cylinder number but different in maximum power and torque curves. Bus 1 and 2 could also be powered by a 44 kW motor which could act as a generator when generative braking happened. The energy storage system was a 346 V battery pack with a capacity of 16 A h. All the buses were fitted with Vanadium-based selective catalytic reduction (SCR) systems to meet China national-IV (Euro-IV) emission standard. Although the engines belonged to the same series, the buses were made by three different manufacturers. Hence, their actual idle speeds were different, which can be attributed to the different accessories and powertrain configurations of the buses. Bus 3 was a little heavier than bus 1 and 2. Bus 4 was the heaviest in all the buses but its engine power was smaller. A cargo weighted 1500 kg was loaded into the bus 1, 3 and 4 to simulate the weight of passengers. The cargo of bus 2 was 3500 kg heavier than bus 1 to research the effect of payload on fuel economy and emissions.

The parallel hybrid buses, bus 1 and 2, could operate in either "hybrid mode" or conventional "diesel mode" using mode chosen button in panel board. In conventional diesel mode, the electric motor/generator did not work all the time and the bus was only propelled by the diesel engine.

2.2. Equipment

A SEMTECH-DS analyzer, a portable emission measurement system (PEMS) made by Sensors, Inc., was used to measure gaseous pollutants from these buses. The analyzer utilized a non-dispersive infrared (NDIR) module to measure concentrations of carbon dioxide (CO_2) and carbon monoxide (CO), a heated flame ionization detector (HFID) module to measure total hydrocarbon (THC), and a non-dispersive ultraviolet (NDUV) module to measure nitrogen oxides (NO_X). An exhaust flow meter (EFM) was used to measure the flow rate and temperature of the exhaust. A two meter long silicone rubber tube was used to connect the outlet of

Table 1
Specifications of tested buses.

Specification	Bus 1	Bus 2	Bus 3	Bus 4
Type	Parallel hybrid	Parallel hybrid	Conventional	Conventional
Mileage (km)	42,897	45,367	59,200	75,743
Curb weight (kg)	11,200	11,200	12,500	15,720
Payload (kg)	1500	5000	1500	1500
Length (m)	12	12	12	15.4
Emission standards	Euro-IV	Euro-IV	Euro-IV	Euro-IV
Fuel	Diesel	Diesel	Diesel	Diesel
Number of cylinders	6	6	6	6
Displacement (L)	6.7	6.7	6.7	6.7
Idle speed (rpm)	725	725	600	675
Engine max power (kW)	165	165	165	151
After-treatment	SCR	SCR	SCR	SCR
Transmission	6-speed AMT	6-speed AMT	6-speed AT	6-speed AT
Battery system voltage (V)	346	346	/	/
Battery capacity (A h)	16	16	/	/
Electric motor/generator power (kW)	44	44	/	/