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Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions

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ABSTRACT

Battery electric buses can reduce energy use and carbon dioxide (CO_2) emissions in China's transportation system. On-road testing is necessary to evaluate these benefits compared to their diesel counterparts through life-cycle assessment for both the upstream fuel production and operation stages. Three electric buses from China are operated and charged in Macao under different air-conditioning, load, and speed settings. In the minimum load scenario, the two 12-m buses achieve 138–175 kWh/100 km, and the 8-m bus achieves 79 kWh/100 km (system charging loss included). When air-conditioning and load are at their maximum values, the energy consumption increases by 21–27%; however, air-conditioning usage exerts a greater impact than passenger load. The diesel bus on-road performance increases more significantly than the electric bus performance under low speeds, higher load, and air-conditioning use, while the electric bus energy and CO_2 emission benefits increase. Across a wide range of conditions, the electric bus reduces petroleum use by 85–87% compared to a diesel bus and achieves a 32–46% reduction in fossil fuel use and 19–35% in CO_2 emissions from a life-cycle perspective. A cleaner power grid and an increase in system charging efficiency (if better than 60–84%) would enhance the future benefits of electric buses.

1. Introduction

New propulsion and alternative fuel technologies are among the potential strategies for future sustainable vehicle development. Government and vehicle OEMs (original equipment manufacturers) worldwide have shown great interest in EV (electric vehicles). Global annual sales of HEVs (hybrid electric vehicles) reached 1.2 million units in 2012, while the global population of PHEVs (plug-in hybrid electric vehicles) and BEVs (battery electric vehicles) exceeded 180 thousand units [1]. The Chinese government is paying substantial attention to electric vehicles for the purpose of providing energy security, achieving reductions in greenhouse gases [2] and meeting air pollutant emission criteria [3]. In 2009, China implemented a *Ten Cities and Thousands of Units* programme to motivate energy savings and new energy vehicle purchases in 25 cities [4]. In 2012, China published a national plan with a target of 5 million cumulative PHEVs and BEVs by the year 2020 [5].

Among various types of BEVs, the battery electric bus (BEB) played an important role in early demonstration projects in China, such as the Shanghai Expo 2010 [6] and other high-profile national events [7], and demonstrated the technology in the regular urban transit bus fleets [8]. The real-world energy consumption (EC) of BEBs is a key performance index of great concern to policy-makers, greatly influencing whether to promote BEB technology because the real-world EC significantly impacts the energy, environmental and economic benefits from the BEBs [9]. Notably, most researchers previously employed a dynamometer to measure the EC for EVs under predetermined cycles [10,11] and applied the laboratory results for further analysis at the cycle level [12]. For example,

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Nomenclature

η	efficiency
D	diesel density
EC	energy consumption
EF	emission factor
FC	fuel consumption
i	current
l	liter
s	distance
t	time
u	voltage
v	velocity
W	carbon content of diesel

Subscripts

batt	battery
c	condition
C/D	charging and discharging
CO	carbon monoxide
CO_2	carbon dioxide
EVSE	electric vehicle supply equipment
grid	power grid
HC	hydrocarbon
sys	system

Abbreviations

AC	air conditioning
AER	all electric range
BEB	battery electric bus
BEV	battery electric vehicle
DB	diesel bus
EL	empty load
EV	electric vehicle, including PHEVs and BEVs
FL	full load
GPS	Global Positioning System
GREET	The Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
HEV	hybrid electric vehicle
HL	half load
LCA	life-cycle assessment
NG	natural gas
PEMS	portable emission measurement system
OBD	on-board diagnostics
OEM	original equipment manufacturer
PHEV	plug-in hybrid electric vehicle
SoC	state of charge
TTW	tank-to-wheels
VKT	vehicle kilometres travelled
WTT	well-to-tank
WTW	well-to-wheels

Karabasoglu and Michalek highlighted that different driving cycles could result in wide variations in AER (all electric range) for a BEV, from 100 to 170 miles [13], and Millo et al. revealed that the engine-emitted and WTW (well-to-wheels) CO_2 emission factors for a PHEV ranged from 12 to 41 g/km and from 74 to 120 g/km, respectively, depending on different driving cycles [14]. However, increasing criticism has accumulated against the representativeness of the laboratory testing [15,16], as the test cycles may not accurately represent real-world conditions and the laboratory conditions may be artificially optimized [16]. Recent real-world EC measurements have been conducted for EVs [17] and HEVs [18], but mainly for light-duty vehicles. In China, BEB OEMs typically only label the nominal EC and the expected AER based on limited test cycles or constant speed tests [19]. The scarcity of on-road tests for BEBs logically motivates us to evaluate their real-world EC.

For conventional and hybrid buses, it is common to employ a PEMS (portable emission measurement system) or on-board sensors (e.g., oxygen level, engine revolution, air intake and fuel injection) to measure instantaneous emissions and EC [20]. For BEBs, due to their zero tailpipe emissions at the vehicle operation stage, an appropriate OBD (on-board diagnostics) decoder paired with a GPS (global positioning system) receiver could be used to collect real-time information regarding SoC (state of charge), motor power, and traffic conditions (e.g., speed and acceleration). In addition, the complex effects of real-world operating conditions can be further explored for BEBs, including traffic conditions, AC (air conditioning) usage, load mass, and charging loss [20]. For example, Suh et al. designed an AC management system in a BEB charged using on-road dynamic wireless technology and secured a target maximum of 20% motor power for cooling [21]. Thus, a clear on-road EC profile is needed to analyse the influence of these key factors and to better evaluate the BEB benefits in light of driving patterns.

Macao is an internationally renowned tourism city, where on-road passenger transportation plays an essential role in supporting the flourishing gaming industry. The on-road transportation sector accounted for approximately 25% of Macao's total energy use in 2014 [22] and has also become a major local source of air pollution problems (e.g., exceedance of the ambient limit of nitrogen dioxides in traffic-populated areas) [23]. The public bus fleet has significantly expanded to satisfy increasing transit demand in Macao, doubling during 2010–2014. The public buses in Macao are only responsible for 0.5% of total vehicle population so far, but we estimate that they are responsible for approximately 17% of total on-road CO_2 emissions due to their high CO_2 emission factor and annual vehicle kilometres travelled (VKT) [24]. To mitigate petroleum use and emissions, Macao launched a 2-month pilot demonstration project in late 2013 to assess the real-world performance of BEBs [25], including their real-world EC and related factors as well as charging efficiency. Thus, localized and fundamental data can be obtained from this demonstration project to assess the possible penetration of BEBs in Macao.

In this research, three BEB models were tested on-road while participating in the demonstration project in Macao. OBD data collectors and a local power company billing monitoring system were used to measure their on-road EC across a wide range of operating conditions (e.g., traffic conditions, load mass, and AC usage), including both the battery EC and the system charging efficiency. Based on the first-hand data, we applied the LCA (life-cycle assessment) method [9], used in energy [26] and environmental assessments [27] for alternative fuel options and battery systems [28], to estimate the WTW EC, petroleum use and CO_2 emissions for BEBs; we also estimated their total economic costs over a typical lifespan for the public transit bus fleet in Macao.

2. Methodology

2.1. Battery electric buses

The three BEBs used in the study were all designed as urban transit buses by different OEMs in Mainland China (see Table 1). Each bus is given an identifying name (Table 1) based on the vehicle manufacturer (i.e., the initial letter of the OEM). The two 12-m