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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

Table 1
Key vehicle parameters of three tested BEBs and one reference DB model in Macao.

Manufacturer	Ankai	BYD	Dongfeng Yangzijiang	King long
Code name	BEB A	BEB B	BEB D	DB (the reference model)[a]
Model type	HFF6128G03EV	K9D	WG6820BEV HK	KLQ6101GE3 A/T
Length (m)	12.0	12.0	8.2	10.0
Gross vehicle weight (kg)	18,000	18,000	12,500	15,500
Curb weight (kg)	13,800	13,800	8,800	10,500
Battery capacity (kWh) or engine displacement (l)	320 Ah/538 V/ 170 kWh	600 Ah/540 V/ 324 kWh	180 Ah/578 V/ 104 kWh	6.7 l
Battery weight (kg)	1800	3654	1340	
Motor type	420 YS-XS100 100 kW × 2	1PV5138−4WS24.85 80kW × 1	75kW × 2	
C/D cycle	>1,500	>6,000	2,000	
In service	<1 year	<1 year	<1 year	~2 years

[a] We used the average results of five King Long diesel buses as the reference [18].

buses, BEB A and BEB B, were commercial models serving the cities of Mainland China, and the one 8-m bus, BEB D, was a prototype model for the demonstration project in Macao. All of the BEBs were equipped with lithium-ion batteries with a cathode material of $LiFePO_4$. The nominal battery capacities of BEB A, B, and D are 170, 324, and 104 kWh, respectively.

2.2. Electric vehicle supply equipment

The BEBs were parked at three different bus terminals (Fig. S1), and each used a specific EVSE (electric vehicle supply equipment) with different charging couplers. The charging machine for BEB B weighed 50 kg and was mounted on the wall, while the chargers for the other two BEBs, with a gross weight of over 500 kg, were positioned on the floor. Local electricity network safety and tolerance levels limit the charging power of the BEBs. For example, the charging power of BEB B was only 20% of the rated power. As shown in Table 2, the typical data reflected a stable charging period in which the dashboard displayed SoC remained in the range of approximately 80–90%. During the tests, the BEB SoCs seldom fell below 60% because they were charged immediately after each route.

2.3. Energy consumption calculation

In this study, we defined the system charging efficiency to evaluate the electricity delivered from the power grid to the motors, consisting of the EVSE efficiency (the percentage of distribution network electricity to rectified electricity delivered to the battery) and the battery C/D (charging/discharging) efficiency (percentage of rectified electricity in the battery delivered to the motor). During each testing cycle, the following key data were collected: 1) local power grid EC from the billing system provided by the local power company and 2) charging machine output data (i.e., electricity sent to the batteries). The BEBs began every test routine with a full charge, and the real-time current and voltage data of the batteries were recorded using dedicated OBD decoders provided by the OEMs. The charging machine output data of BEB B were not collected along with the real-time battery data, so we applied the battery C/D efficiency testing results previously obtained by the OEM for further calculations.

The EC of each testing route i is calculated using Eq. (1), below:

$$EC_{j,i} = \frac{EC_{grid,i}}{s_i} \times 100 = \frac{EC_{batt,i}}{s_i \times \eta_{sys}} \times 100 = \frac{\int_{t_0}^{t_1} u_j i_j dt}{s_i \times \eta_{C/D} \times \eta_{EVSE}} \times 100 \tag{1}$$

where $EC_{j,i}$ is the specific energy consumption of BEB j in testing route i, kWh/100 km; $EC_{grid,i}$ is the total power grid EC of testing route i, kWh; s_i is the route distance, km; $EC_{batt,i}$ is the total electricity delivered from the battery in route i, kWh; u_j is the second-by-second battery output voltage of BEB j, V; i_j is the second-by-second battery output current of BEB j, A; η_{system} is the system charging efficiency, %; η_{EVSE} is the EVSE efficiency, %; and $\eta_{C/D}$ is the battery C/D efficiency, %.

2.4. Test route and conditions

The test route for the BEBs consisted of major arterial roads and expressways in the downtown and business centre of Macao (i.e., the Macao Peninsula) (see Fig. S1). The top instantaneous speed for the tested BEBs was no higher than approximately 50 km/h, which is typically the maximum allowed for transit buses in this congested city. Eventually, for each bus, the accumulated total on-road testing distance exceeded 500 km. All of the buses were operated on this 8.8 km route by experienced bus drivers who were requested to follow their usual driving behaviours for regular transit buses, such as simulating frequent stops for receiving and discharging passengers.

To compare on-road performance, we established a two-stage test with different focuses, namely a benchmark scenario and multiple operating condition scenarios. First, under the benchmark scenario, the BEBs ran with the AC off and without "passengers" (i.e., EL (empty load)), carrying only one driver and one tester. For each BEB sample, the speed-dependent EC function under the benchmark scenario (i.e., AC off and empty load) was fitted using a power function (see Eq. (2)) according to its field measurement results. As shown in Fig. S2, the hourly speeds for the three BEB mostly ranged from 10 km/h to 20 km/h, and the overall average speeds for BEBs A, B and D were 13.2 km/h, 15.8 km/h, and 15.3 km/h, respectively. Therefore, to observe the sensitivity to variations in driving speed, we selected three driving speed values of 10 km/h, 15 km/h and 20 km/h to represent typical heavy (i.e., rush hour), normal and light traffic conditions, respectively (see results in section 3.2).

In the second stage, various test conditions with different AC usage and load mass values were designed to measure the effects of

Table 2
Charging facility parameters.

Code name	BEB A	BEB B	BEB D
Model type	SCM-75-I-T	EVA080KG/01	DQCJ-600Y80
Rated output current (A)	100	126	83
Rated output voltage (V)	DC 360-600	AC 342-440	DC 400-620
Typical charging voltage (V)	575	660	564
Typical charging current (A)	61	24	51
Typical charging power (kW)	35	16	29

other real-world operating conditions on battery performance (Table 3; see also the results in section 3.3), among which the benchmark scenario (AC off and empty load) should be the most favourable for EC. The AC was on/off with a low temperature of 16 °C and the highest fan speed. In addition, load levels varied among empty load (5–10% of maximum carrying capacity), half load (HL, 40–45%), and full load (FL, 59–81%). The daily typical speed of 15 ± 2 km/h was selected to compare performance in each of the six scenarios. To eliminate speed variance, a 4 km/h speed range (13–17 km/h) was set with the central speed of 15 km/h (see Fig. S3). The observed EC in this range was normalized to 15 km/h in each scenario, and the average normalized results for the different scenarios were compared. For each valid observation, $(\overline{v_i}EE_{j,i}(\overline{v_i}))$ inside the 13–17 km/h range, Eq. (3) was used for normalization.

$$\overline{EC_{j,c}}(\overline{v}) = a_{j,c}\overline{v}^{b_{j,c}} \tag{2}$$

$$EC'_{j,c}\left(\overline{v_i}\right) = EC_{j,i}\left(\overline{v_i}\right) \times \frac{\overline{EC_{j,c}}(15)}{\overline{EC_{j,c}}\left(\overline{v_i}\right)} \tag{3}$$

where $\overline{EC_{j,c}}(\overline{v})$ is BEB j's power fitting EC at $\overline{v}$ under scenario c, kWh/100 km; $a_{j,c}$ and $b_{j,c}$ are the fitting factors of the speed-EC curve in scenario c; and $EC'_{j,c}(\overline{v_i})$ is the normalized EC at the average speed of $\overline{v_i}$, kWh/100 km.

2.5. Life-cycle assessment of real-world energy consumption and CO_2 emissions for BEBs and diesel buses

We applied the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model) [29,30], a tool widely used to conduct LCA for vehicle technology options, to compare the EC, petroleum use and CO_2 emissions between BEBs and their diesel counterparts. In general, the GREET model divides the full life-cycle energy consumption and environmental impacts into two parallel parts: the fuel cycle (i.e., WTW [31], including WTT (well-to-tank) - the extraction, refinery, transport and distribution processes of vehicle fuels, and TTW (tank-to-wheels) - fuel use during the operation stage) and the vehicle cycle (i.e., the manufacture, assembly and recycling of vehicle materials) [32]. Recent studies have proven that, for conventional vehicles [26], HEVs [33], PHEVs [33] and BEVs [34], the fuel-cycle pathway significantly contributes (e.g., 70%–90%) to the full life-cycle EC and emissions. Due to the very limited data available for assessing the vehicle-cycle energy consumption and CO_2 emissions for buses in China, we only estimated the fuel-cycle (i.e., WTW) EC (petroleum fuel use and fossil fuel use separately) and CO_2 emissions in this study.

Table 3
Load level definition of the three tested BEBs.

Load index	BEB A	BEB B	BEB D
Max load capacity (kg)	4,200	4,200	3,700
Max passenger	67	80	60
Empty load (kg)	400[a]	200[b]	200[b]
Empty load ratio	10%	5%	5%
Half load (kg)	1,900[c]	1,700	–
Half load ratio	45%	40%	–
Full load (kg)	3,400	3,200	2,200[d]
Full load ratio	81%	76%	59%

[a] Including essential motor and battery inspection and maintenance (I/M) equipment.
[b] Including the weight of the driver and one tester.
[c] Standard 4.5-gallon water containers used as load.
[d] BEB D's motor supplier suggested the safe and sustainable level.

A modified version of the fuel cycle with a Chinese database [9,35] was applied to evaluate the WTW benefits of BEBs in terms of petroleum use, fossil fuel use (including coal, NG (natural gas) and petroleum) and CO_2 emissions (Table S1). The fuel-cycle inventory was constructed to analyse the upstream processes for each fuel pathway (i.e., electricity and diesel). Notably, the local power generation mix was a key parameter for the electricity pathway [9,35]. Macao relies heavily on imported electricity from China's Southern Power Grid [36]. Therefore, the leading power sources for Macao's electricity mix are coal (56%) and hydropower (24%) [36,37], as shown in Table S2. Using the upstream inputs for the electricity pathway, the GREET model converted the first-hand on-road data to the WTW results.

We selected one popular DB (diesel bus) model in Macao (see Table 1) to serve as the reference vehicle model to evaluate the WTW fuel saving and CO_2 emission reduction benefits of BEBs. Similar to the analysis of BEBs, the upstream fuel pathway and the on-road EC were key parameters in the GREET model to calculate the WTW results for DBs. On-road measurements for the reference DB model (a total of 5 DBs previously tested) in Macao were accomplished using a PEMS to measure the exhaust emissions of carbonaceous gases (e.g., CO_2), and a carbon balance method was used to estimate the real-world EC for DBs [24]. In addition, the relative changes in EC and CO_2 emissions due to variations in AC usage and load mass were also developed with reference to our previous measurements [20,38]. The key parameters for the reference DB model are listed in Table S3. Therefore, we estimated the EC values in Table 4 for the reference DB model under various operating condition scenarios corresponding to the scenarios designed for BEBs.

3. Results

3.1. Real-time battery performance of BEBs

The OBD data collector recorded on-road battery performance. In Fig. 1, we present the second-by-second power and speed of a normal-traffic testing route in the benchmark scenario. The negative power values indicate that the batteries are charged during braking via the brake energy recycling system, while positive values indicate EC to power the wheels. The BEBs switch frequently between charging and discharging. The peak power delivered by the batteries is approximately 130 kW, and the braking-charging power can reach 50–100 kW, albeit for a very short period. When idling, the battery output is at low levels, 2–3 kW, which is significantly lower than the EC during DB idling. The battery uses 15.3 kWh of electricity over the entire 8.8 km route, including EVSE loss and battery C/D loss. The total EC is 174 kWh/100 km for an average route speed of 14.4 km/h. This result represents one observation point for BEB A in Fig. 2. In addition, the braking-charging system of BEB A extended the AER by over 25%. Other BEBs have similar systems and operating modes that have proven to be efficient energy saving technologies.

3.2. Energy consumption of the BEBs in the benchmark scenario

Each bus's EC curves at different speeds, including EVSE charging losses, are shown in Fig. 2. This figure indicates that BEBs consume more energy at low average speeds, when frequent starts and stops occur; under these conditions, electric motors cannot work under steady conditions and require extra electricity for acceleration. During rush hour conditions (10 km/h), the three BEBs' EC values increased by 10%, 18%, and 29%, respectively, compared to the 15 km/h speeds and, in contrast, decreased by 9%, 11%, and 16% under light traffic conditions (20 km/h). Power functions clearly

Table 4
On-road EC settings of the reference DB model in this study.

Index	Condition	EC of DB (l/100 km)
Speed impact	10 km/h	62.2
	15 km/h (benchmark)	49.3
	20 km/h	41.8
AC and load impact (15 km/h)	Empty load, AC off (benchmark)	49.3
	Empty load, AC on	60.6
	Half load, AC off	54.2
	Half load, AC on	66.7
	Full load, AC off	59.2
	Full load, AC on	72.8

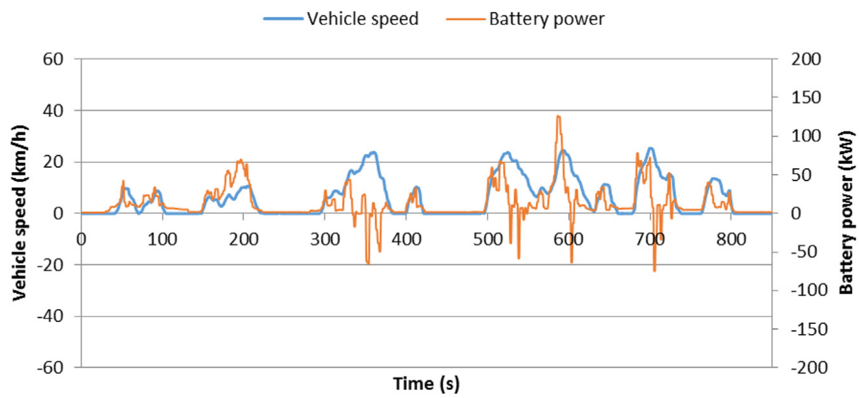

Fig. 1. Operational results of BEB A on Jan. 10th test cycle (first 800 s), benchmark scenario.

provide the best fit for the relationship between EC and average speed, with strong correlations (i.e., $R^2 = 0.73–0.76$). Based on Eq. (2), the normalized EC values at 15 km/h were 175, 138, and 79 kWh/100 km for BEBs A, B, and D, respectively, under the benchmark scenario (AC off and empty load).

The impact of speed on the real-world EC for 12-m BEBs was less significant than for lighter-weighted BEBs. This phenomenon was similar to the trend shown for DBs. For comparison, the reference 10 m DB's EC increases by 26% during rush hour relative to normal traffic and decreases by 16% under light traffic conditions (Table 4). Under the benchmark scenario, the 10 m DB's EC tends to be more sensitive to speed than the two 12 m BEBs, especially during rush hour. One probable reason for this difference is the idling EC difference between BEBs and DBs. When idling, the BEB motor stands by, and the battery power is 2–3 kW to support the auxiliary equipment, while the DB engine continues rotating at hundreds of times per minute. The BEBs are thus better designed for downtown traffic jams than their diesel counterparts.

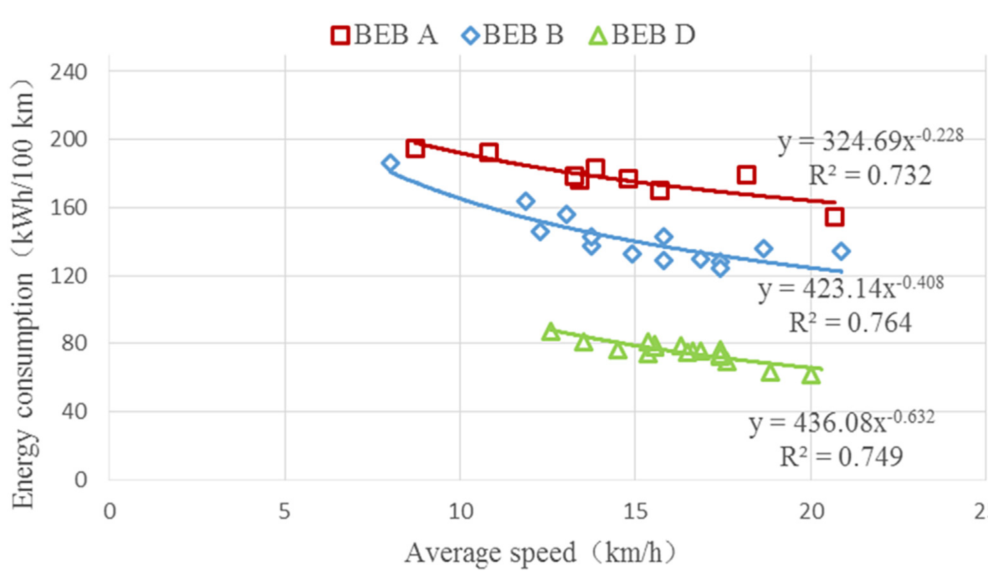

Fig. 2. Speed-dependent functions for EC of BEBs under the benchmark scenario.

3.3. Energy consumption of BEBs in multiple condition scenarios

The AC use and passenger load conditions were varied for these buses to compare the differences, as summarized in Fig. 3. Based on Eq. (3), the typical speed of 15 km/h and a 4 km/h range were used to mitigate speed bias. Compared to the benchmark scenario, a full passenger load adds 9–11% EC for BEBs (20% for DB), and half passenger loads increase EC by 1–5% for the 12 m BEBs. BEB A has a roughly linear relationship between EC and passenger load; approximately 1000 kg of additional load requires an additional 5 kWh/100 km. The EC of BEB B changes only slightly under a half load, adding only 1%, while under a full load, it requires 10% more fuel.

Conversely, AC has a large impact on EC at each passenger load level. For example, compared to empty, half, and full passenger loads with AC in the off position, turning the AC on in the BEBs requires another 10–17%, 12–16%, and 10–25% of fuel, respectively, compared to 24% for DBs. AC clearly affects EC more strongly than passenger load. In the worst-case scenario, when the AC is on with a full passenger load, BEBs consume 21–27% more fuel to complete the same route compared to the benchmark scenario. For comparison, the DB model may use up to 48% more diesel fuel under the same worst-case conditions relative to the benchmark scenario (Table 4). The BEB testing was performed in the winter in Macao, when the daytime temperature varies from 15 to 25 °C, lower than the summer daytime temperature of approximately 30–35 °C. Increased temperatures tend to increase EC. If BEBs operate in the summer in Macao, AC could become the major contributor to the EC and AER.

As shown in Fig. 4, the expected AER for each BEB can be estimated by adding the designed energy capacity of each battery (SoC must remain above 10% for module safety). In normal traffic conditions, BEBs can easily operate for over 100 km in the benchmark scenario. Some of the BEBs may reach over 300 km before needing to recharge. As expected, AER decreases upon turning on the AC and increasing passenger load. In tropical areas, AC is a necessity, and the purpose of the city bus is to carry passengers, so the benchmark scenario rarely occurs. Thus, during the worst-case conditions with a full load and the AC on, the AER would be shortened by 17–21% in normal traffic. If this set of conditions occurred during rush hour (i.e., 10 km/h), defined as the extreme worst-case condition, the real-world AER would decrease by 25–40% (Fig. 4) compared to the benchmark conditions. A 150 km AER BEB could only operate for 80–90 km in the extreme worst-case conditions while easily running over 150 km on the expressway in the benchmark scenario. Larger battery capacity would increase the expected AER but also increase the purchase and maintenance costs [39]. In the real world, travel demand and charging strategy should consider these important factors.

3.4. System charging efficiency

Fig. 5 indicates that BEBs need to resolve concerns with charging losses that further directly impact WTW fuel and emissions. The overall system charging efficiencies for BEB A, B and D were 69%, 60% and 84%, respectively. The intra-vehicle variation in system charging efficiency for each BEB was not as significant as the inter-vehicle range during the charging process, which was barely affected by charging volumes (see Fig. S4). Compared to the battery C/D efficiency, which had a smaller bias (i.e., 86%–92%), a significantly wide range of EVSE efficiency (i.e., 65%–94%) was discerned among the three individual BEBs. Several direct reasons could cause EVSE loss, such as line loss, rectification of the current, internal loss, and current frequency difference loss, as well as the charging conditions (e.g., charging amperage, voltage and frequency). For example, researchers have demonstrated that a full-power charging strategy could limit charging losses [40,41]. However, the charging amperage for BEB B is approximately 20% of the design level due to external limitations (e.g., the terminal's power limitations), far from the optimal charging conditions. Therefore, the EVSE efficiency for the BEB B was only 65%. Previous experiments indicated that the EVSE efficiency could reach 85–95% [40–42], while the system charging loss could be limited to less than 10% [42]. However, in reality, the charging loss may be larger than that in the experiment. Similarly, for light-duty BEVs, Faria et al. found the system charging loss to be approximately 15–27% using various charging modes [43]. Therefore, future efforts to mitigate EC for BEBs should focus not only on the battery itself but also on enhancing the compatibility between the battery and the EVSE.

3.5. Speed-dependent WTW energy consumption and CO_2 emissions under the benchmark scenario

In this section, the benchmark scenario compared the speed-dependent WTW results between BEBs (the average results of two 12-m BEBs) and the reference DB model regarding two EC

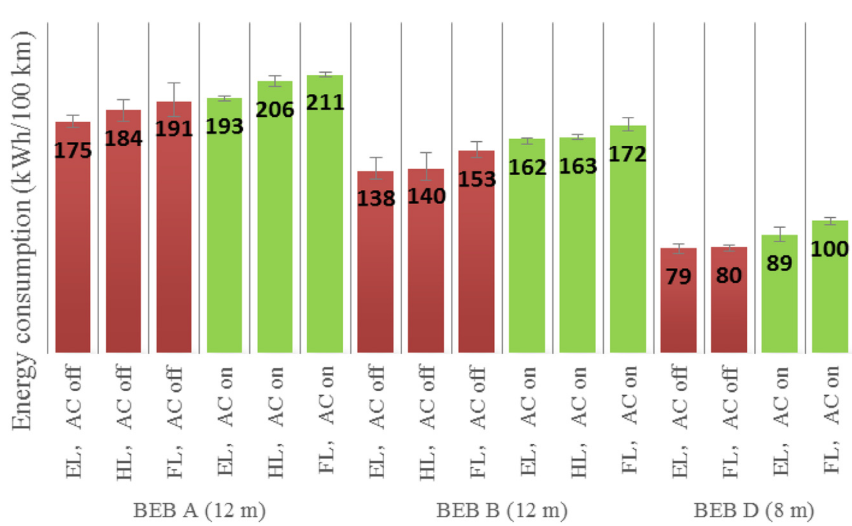

Fig. 3. EC of 3 BEBs under multiple AC and passenger load scenarios. EL: empty (passenger) load; HL: half load; FL: full load.

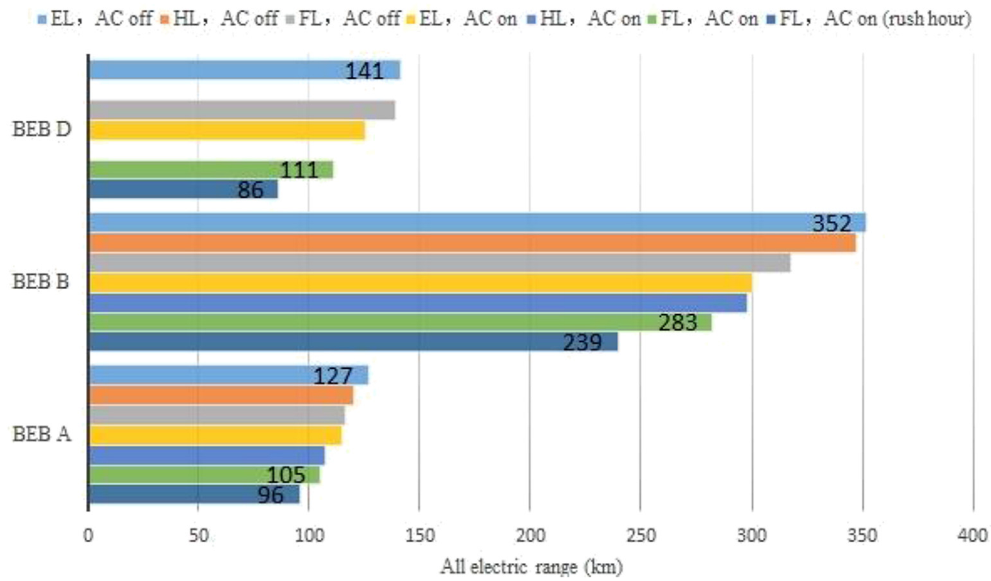

Fig. 4. Expected AERs of BEBs under multiple conditions.

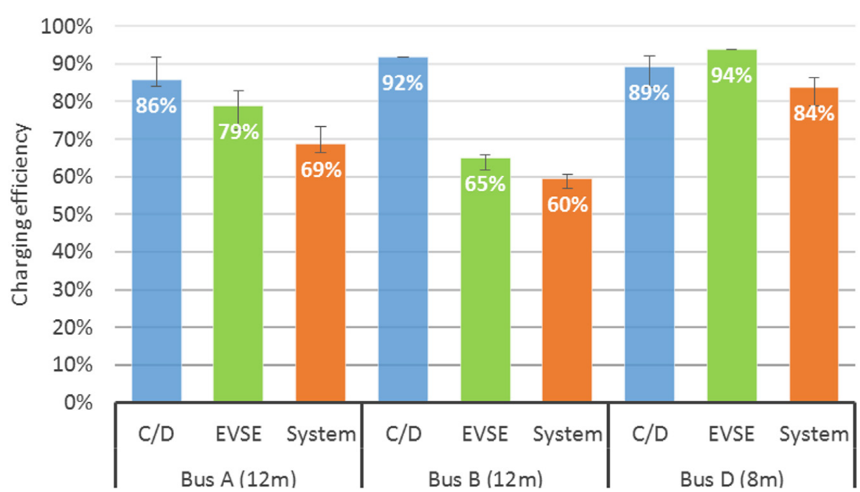

Fig. 5. System charging efficiency of three BEBs. Battery: battery C/D efficiency; EVSE: electric vehicle supply equipment efficiency.

indicators (i.e., petroleum fuel use and fossil fuel use) and CO_2 emissions. Later, in section 3.6, multiple operating condition scenarios are addressed to evaluate other impacts such as load mass and AC usage.

BEBs clearly reduce petroleum use in the vehicle operation (i.e., TTW) stage as well as in the WTW stage because the main petroleum (diesel) consumption occurs in the operation stage. As illustrated in Fig. 6a, BEBs in Macao can save 94–95% of the TTW petroleum use and 86–87% of the WTW stage use compared to DBs. For upstream fuel-cycle pathways, neither diesel production nor electricity generation use petroleum as the main primary energy. Compared to normal traffic conditions, the BEB and the DB increased WTW petroleum use by 14% and 20% in heavy traffic, while saving 13% and 15% in light traffic. Approximately 60% of China's crude petroleum consumed in 2014 was imported from other countries [44], posing a substantial challenge to national energy security. The petroleum saving potential of promoting BEBs can significantly ease China's energy independence in the future.

Fossil fuel use includes coal, petroleum and NG. The BEBs reduce fossil fuel use by 33% under normal speed conditions compared to DBs (see Fig. 6b). This reduction is due to the energy efficiency of the electricity pathway being higher than for the diesel pathway as well as due to the non-fossil electricity (e.g., hydro and nuclear) contained in China's Southern Power Grid (see Table S2). The majority of BEB energy demand is transferred to upstream energy production, as shown in Fig. 6b. The WTT fossil fuel use accounts for 64–65% of total fossil fuel use. Similarly, as shown in section 3.2, DBs are more speed-sensitive than BEBs from the WTW perspective. The BEBs could achieve a larger ratio of fossil fuel savings under heavy traffic conditions.

In terms of WTW CO_2 emissions (see Fig. 6c), although the BEB released zero CO_2 emissions during the TTW stage, coal-fired power plants contributed a major part of the upstream electricity generation (Table S2) and emitted a significant amount of CO_2. As a result, the BEB could only reduce WTW CO_2 emissions by 19–24% compared to the DB. Under the benchmark scenario, the BEB emits 1.1 kg CO_2/km on average and can reduce WTW CO_2 emissions by 20% compared the DB (1.4 kg/km). During rush hours, both BEB and DB would increase CO_2 emissions, but the increase for DB would be higher. Similar to the fossil fuel situation, the DB is more sensitive to

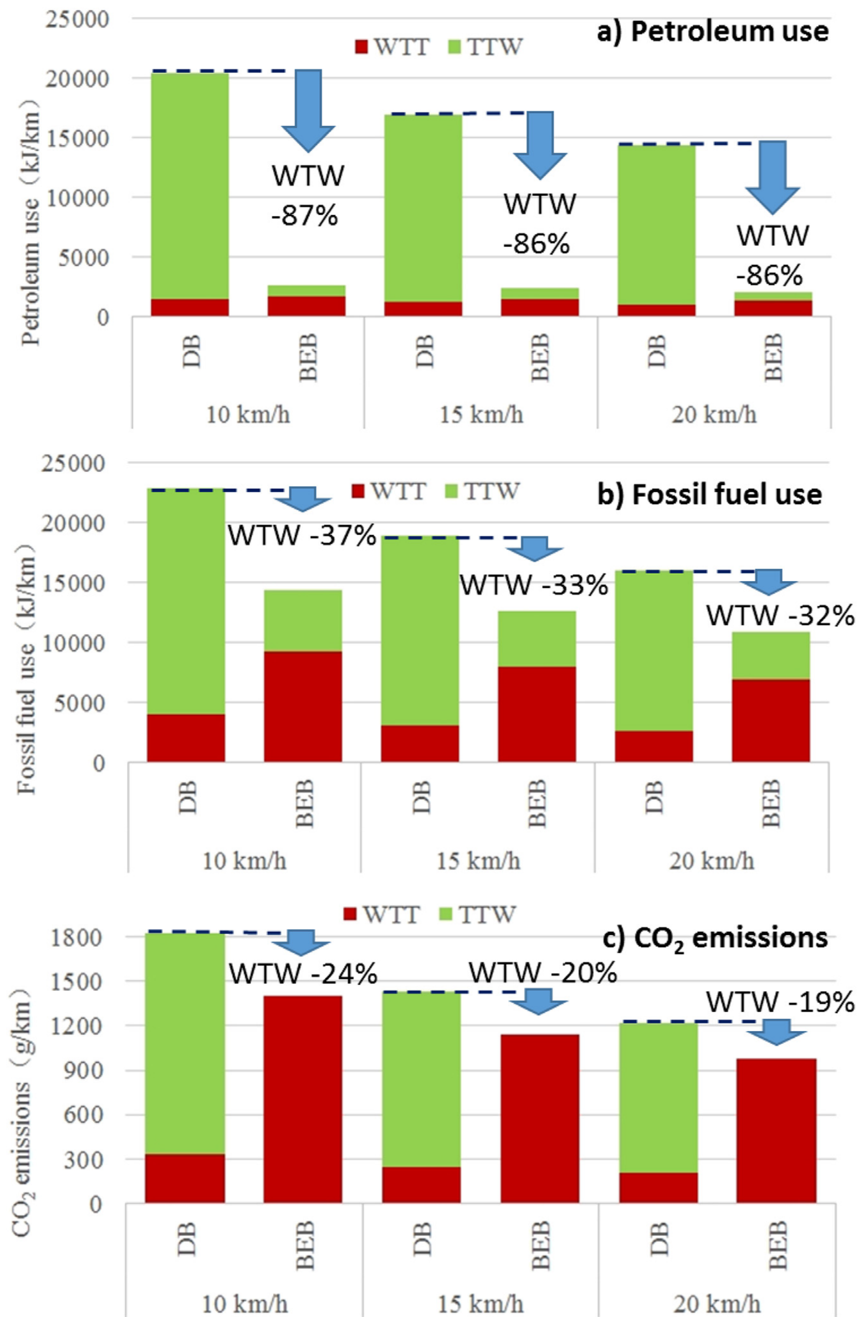

Fig. 6. WTW a) petroleum use; b) fossil fuel use; and c) CO_2 emissions at different speeds.

traffic conditions than the BEBs. Similar findings also indicated that electrification could yield substantial mitigation of CO_2 emissions for urban transportation, while the attainable CO_2 reductions for inter-city transportation are much smaller [45]. Therefore, the BEBs can achieve more CO_2 reduction benefit over DBs under heavy traffic conditions (e.g., decreasing by 24% during rush hour) that are commonly seen in Macao.

3.6. Impacts of load mass and AC usage on WTW energy consumption and CO_2 emissions

Regardless of the operating scenario, BEBs could save at least 85% of WTW petroleum use under normal traffic conditions. As shown in Fig. 7a, when considering AC or passenger load impacts independently, turning the AC on increases BEB petroleum use by 14–16%, while going from empty load to full passenger load increases the petroleum use of the BEB by only 6%. Clearly, the AC usage affected petroleum use more significantly than the load mass for both BEBs and DBs, and similar results were found in the fossil fuel and CO_2 emissions comparisons. Under the worst-case conditions (i.e., full load and AC on), the WTW petroleum use of the BEBs increased by 23% compared to the benchmark scenario, while for DBs, the value increased by 48%, indicating greater sensitivity than the BEBs.

Fossil fuel use and CO_2 emissions follow similar trends between BEBs and DBs (Fig. 7b and c). BEBs could save 35–46% of life-cycle fossil fuel while reducing CO_2 emissions by 23–35%. The high carbon intensity of Chinese electricity generation eliminates the zero

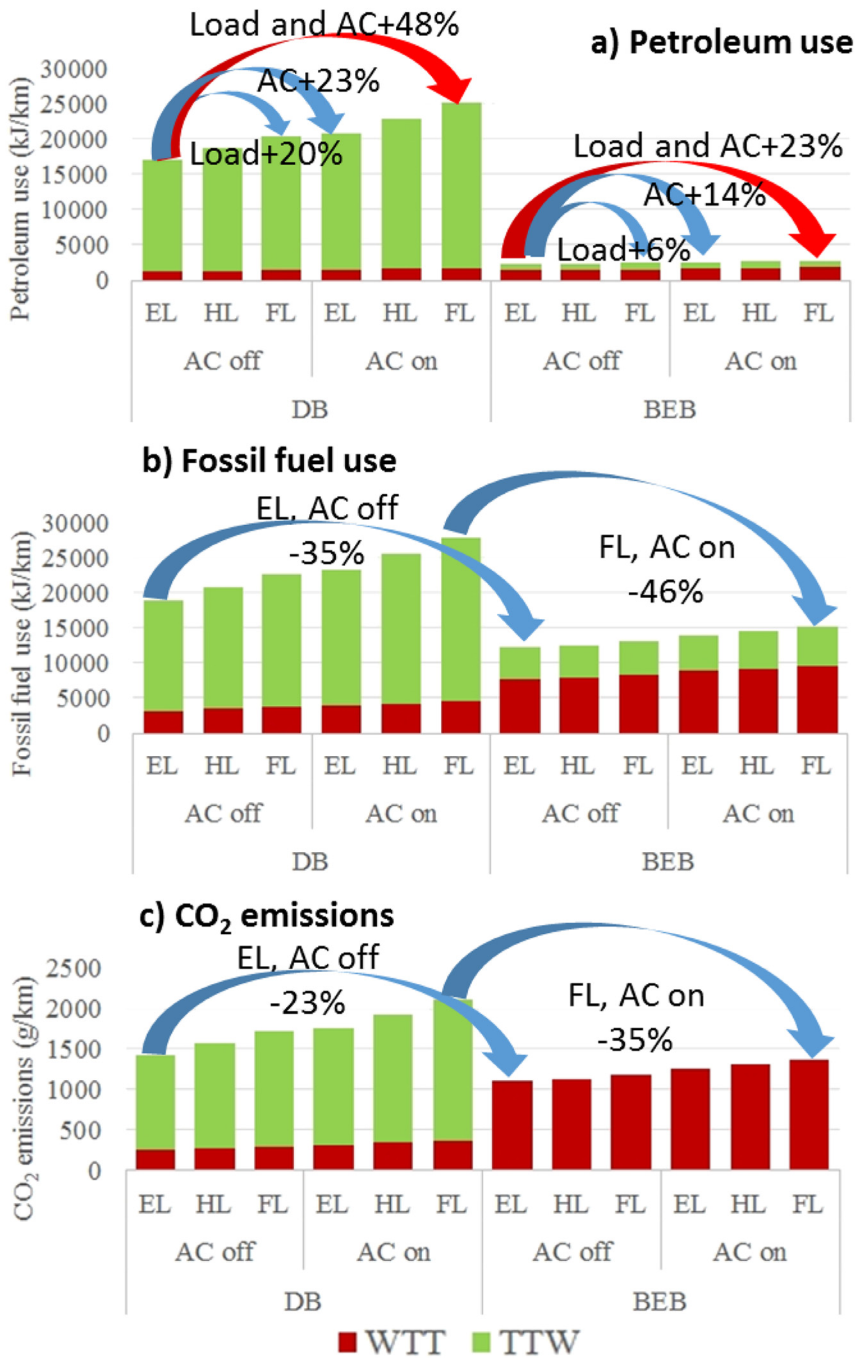

Fig. 7. WTW a) petroleum use; b) fossil fuel use; and c) CO_2 emissions under multiple condition scenarios.

emission advantage for BEB in the TTW stage, but the WTW CO_2 emission reduction benefit does exist in all of the scenarios. Under worst-case conditions, the DB and BEB emit a maximum of 2.1 kg and 1.4 kg WTW CO_2 per km (see Fig. 7c), respectively, an increase of 48% and 23% relative to the benchmark conditions, respectively. However, the BEBs achieve better fossil fuel savings and CO_2 emission level reductions compared to DBs under this condition. If operating busy routes in hot weather while carrying a significant passenger load, BEBs provide significant energy and environmental benefits.

Combining these factors, BEBs are a good replacement for DBs with regard to greater petroleum and fossil fuel savings and CO_2 emission reductions from a fuel-cycle perspective. Buses in mega-city downtown areas have a high probability of operating under significant load (with the AC on in hot weather) and congested traffic situations. BEBs perform better in these difficult load and speed conditions than DBs and would increase the environmental benefit compared to DBs.

4. Discussion

We have demonstrated substantial impacts of operating conditions on the real-world EC for BEBs, and the operating conditions are highly associated with local traffic and weather conditions, as well as the driving behaviours of bus operators. Limited BEBs were available for field tests in Macao at this stage, prior to a significant

Table 5
Itemized costs of typical BEB and DB models during their use life under two scenarios.

Major itemized cost throughout the vehicle lifespan	Empty load and AC off		Full load and AC on	
	DB[a]	BEB[a]	DB	BEB
1) Subsidized vehicle price, thousand RMB[b]	800[b]	1800[b]	800	1800
2) Fuel cost, thousand RMB	2667	733	3938	913
3) Charging service cost, thousand RMB		733[c]		913[c]
4) Maintenance cost, thousand RMB	278 [9]	88 [9] [d]	278	88[d]
Total cost throughout lifespan, thousand RMB	3745	3354	5016	3715
Cumulative CO_2 emissions throughout lifespan, t	840	660	1320	780

[a] Typical 12 m DB and BEB models are used in this comparison. A 12 m model, namely the BEB B (BYD K9D) presented in Table 1, is selected in this cost analysis because its battery system has a high number of C/D cycles and is estimated to be capable of covering a typical lifespan for public buses in Macao (e.g., 8 years).
[b] For the BEB model, the original purchase cost is approximately 2.8 million RMB. In addition, the purchase subsidies from central and local governments are considered, both estimated as 0.5 million RMB (i.e., a total of 1 million RMB) for potential BEB purchases. Both DB and BEB purchases are free of taxes in Macao.
[c] Based on our local interview, Macao's utility company, as the major player in charging facility construction, usually doubles the electricity tariffs as the total charging fee. Therefore, the extra cost along with the electricity cost could be regarded as part of the charging service cost.
[d] For the BEB, we estimate the maintenance cost assuming that the battery service age matches the vehicle lifetime.

future penetration. Although we requested the experienced bus drivers to not change their driving behaviours, we could still observe the uncertainty in the real-world EC of the same BEB when operated by different drivers. For example, two drivers operating BEB B presented different driving behaviours under normal traffic conditions (13–17 km/h) (see Table S4). Within the speed range, intra-driver EC deviations for BEB B were −15%~9% and −3%~3%, respectively, for the two drivers. The inter-driver EC deviation between the two drivers was 11%. Nevertheless, we consider this extent of uncertainty to be acceptable, as the bias of both values against the normalized average value (138 kWh/100 km, see Fig. 2) is within ±10%.

In promoting BEB technology, public bus companies are more aware of and interested in actual cost than in the climate and environmental benefits achieved from BEB penetration. Therefore, we further estimated the itemized costs for typical DB and BEB models during their typical service lifespan, which primarily consist of subsidized purchase cost, fuel cost, charging service cost and other operation and maintenance costs [9]. According to typical lifespan and mileage values for buses in Macao (see Table S5), we estimated vehicle-specific lifetime costs under two operating conditions (i.e., empty load and AC off vs. full load and AC on) to determine the sensitivity. Under both operating scenarios, BEBs demonstrated clear advantages in economic performance as well as in CO_2 emission mitigation (see Table 5). For example, compared to a conventional DB counterpart, a BEB (note: BEB B was selected in this comparison) can reduce total cost by 11–26% and WTW CO_2 emissions by 21–41%, although the initial purchase cost of a BEB is higher than a DB. Greater economic and environmental benefits could be achieved under the full load and AC on scenario, which is very frequent for this highly populated tropical city. As mentioned in section 2.5, although the vehicle-cycle assessment is beyond the scope of this research, for a given BEB model (e.g., battery specifications), it is believed that the longer the distance the vehicle travels during its lifespan, the smaller the vehicle-cycle share of the total life-cycle EC and CO_2 emissions would be, presuming that the battery lifespan could cover the expected vehicle service lifespan (e.g., typically 8 years in Macao). Because the production of vehicle batteries is an energy-intensive process [46], local BEB usage information (e.g., VKT and battery lifespan) should be carefully investigated in the future to refine local vehicle-cycle assessments.

Previous studies have clearly indicated that the WTW CO_2 emissions of EVs are highly sensitive to the carbon intensity of the power generation mix [14]. Thus, policy-makers must carefully consider the regional heterogeneity of the power grid mixes prior to recommending the use of BEBs to reduce the WTW emissions of CO_2. The South China region has the highest penetration of non-fossil-fuel electricity generation in China, producing relatively low CO_2 emissions compared to other regions (e.g., 96% of North China's 2010 electricity generation mix is coal) [37]. The WTW CO_2 emission reduction benefits for BEBs might be diminished in other regions of China such as the North or East China regions, a point to which policy-makers should pay careful attention [9].

5. Conclusions

Many factors affect the on-road EC performance of BEBs, and in this study, we focused on traffic condition, passenger load, AC operation and system charging efficiency. A BEB tends to achieve higher fuel saving potential over a DB under difficult conditions, such as heavy traffic, AC operation, and a full passenger load. AC contributes more to the BEB's EC than passenger load in multiple scenarios; system charging efficiency ranges from 60% to 84%, leaving substantial room for improvement; and EVSE efficiency is a key factor in achieving the benefits of life-cycle CO_2 emission control relative to DBs.

From a life-cycle perspective, BEBs in Macao can reduce WTW petroleum by more than 85%, WTW fossil fuel by over 32% and total WTW CO_2 emissions by 19–35% compared to DBs across all road and vehicle conditions. DB's WTW on-road performance is more sensitive to speed and load changes than BEBs, especially under low-speed and worst-case conditions. Therefore, BEB's WTW environmental benefits increase when operating under worst-case conditions, such as heavy traffic, full passenger load, and AC usage. Meanwhile, our lifetime cost analysis also supports the adoption of BEBs in Macao. This result leads to a judgement that BEBs are a good replacement for DBs in mega-city downtown areas, where they have a high probability of operating under significant load and congested traffic situations. A cleaner power grid and increased system charging efficiency (if better than 60–84%) would enhance the future benefits of BEBs.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2015.12.041.

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