

Technology evaluation of Chinese hybrid electric bus demonstration

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Abstract The development of new energy vehicles (NEVs) in China is important to address energy and environmental issues. Conducting product and technology assessments of NEVs will help accelerate improved performance and enhance demonstration policies and programs. Relying on the project of *Ten Cities & One Thousand Units* in 2009, this evaluation mainly focused on hybrid electric buses (HEBs). A comprehensive research framework was adopted, including on-road driving tests, daily operation data collection, and a questionnaire survey. The technology evaluation focused on operating performance, including vehicle reliability, energy consumption and its affecting factors, and emissions. We selected and assessed 44 HEBs in eight demonstration cities—Kunming, Hangzhou, Shanghai, Dalian, Ji’nan, Zhengzhou, Wuhan, and Zhuzhou, China. The evaluation covered 17 HEB models (including 11 propulsion systems) from 16 bus manufacturers. As with technological progress, in general, HEB technology has become increasingly mature, with a number of good HEB models emerging. The fuel efficiency of some domestically manufactured HEB models is close to the international advanced level. This evaluation provides a basis for decision-making and evidence of the need to modify Chinese HEB demonstration policy. Recommendations include the promotion of the technical application of idling start-stop and brake energy recovery, the expansion of demonstrations nationwide, and continuous financial support for HEBs.

Keywords Hybrid electric bus · Technology evaluation · Idling start-stop · Brake energy recovery · Fuel consumption · Reliability

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1 Introduction

The development of energy-saving and new energy vehicles (NEVs) is an effective way of conserving energy and the environment and promoting the sustainable development of the China auto industry. It is also a strategic move to speed up the transformation of the auto industry and foster new economic growth. Because NEVs are still in the early stages of commercialization, it is necessary to strengthen policy support, actively promote pilot demonstration, and speed up nurturing of the market to promote technological progress and industrial development (State Council 2012). Chinese NEV demonstrations date back to 1998 and have gone through four periods within the four 5-year plans (FYPs) (namely the 9th through 12th FYP periods). The first stage was the demonstration project on Nan'ao Island, Shantou, Guangdong Province, during the 9th FYP period. The second stage was the small-scale demonstration in the late 10th FYP period. The third stage was the large-scale intensive demonstration during the 2008 Beijing Olympic Games. The fourth stage refers to the *Ten Cities & One Thousand Units* which was launched in 2009 (DRC et al. 2012). These demonstrations have promoted the development of the Chinese auto industry and enhanced its innovation ability. By the end of 2013, the NEVs in the national new vehicle registration catalog amounted to 1351 models (CVTSC 2014), and by the end of March 2013, up to 39,800 vehicles had been involved in the demonstrations (HTRDC 2013).

Evaluation of new technologies is an integral part of technology demonstration. Developed countries entrust the relevant research institutes to carry out evaluation during NEV demonstration (DRC et al. 2012). For example, NEV demonstration evaluation in the United States (U.S.) is led by the U.S. Department of Energy (DOE). Its national laboratories carry out testing and evaluation of vehicle technology under the advanced vehicle testing activity (AVTA) program. Evaluations have been completed for many hybrid electric vehicle (HEV) models under the AVTA program, including transit buses and United Parcel Service (UPS) delivery trucks. Coca-Cola and other companies have been involved in multiple demonstration regions. DOE established a specialized data management system (INL and NREL 2013). In Germany's pilot demonstration of electric mobility, the national organization hydrogen and fuel cell technology (NOW) evaluated, among other factors, vehicles, infrastructure, and consumer acceptance (Tenkhoff et al. 2012). In Japan's pilot demonstration of electric vehicle and plug-in hybrid electric vehicle (*EV-PHV*) *Town*, the local governments of demonstration cities implemented evaluation programs that involved EV promotional activities, infrastructure construction, financial subsidy, etc. (METI 2013). In the past, China NEV demonstrations, evaluation of vehicle technical status, and operation effects were not performed regularly. The only exception was the demonstration at the 2008 Beijing Olympic Games during which researchers selected 12 hybrid electric buses (HEBs) and evaluated their operating effects. According to the report from that effort, the average fuel consumption of the HEBs was 35 L per hundred kilometer (L/100 km) (CATARC 2008).

The China Ministry of Finance (MOF), Ministry of Science and Technology (MOST), Ministry of Industry and Information Technology (MIIT), and National Development and Reform Commission (NDRC) jointly launched the project *Ten Cities & One Thousand Units* in 2009 (MOF 2009). Over several years of implementation, China has established a large-scale multi-model demonstration program mainly with HEBs. With a large numbers of NEVs on the road, it has become necessary to evaluate the technological performance of NEVs. Such evaluation is important to speed up technology improvements, to refine recommendation policies, and to nurture the development of Chinese automotive energy-saving and new energy technologies. Considering the number of vehicles in demonstration, the commercialization level, and vehicle application segments, this evaluation focused mainly on HEBs. The

evaluation adopted a comprehensive research framework by including on-road driving tests, daily operation data collection, and a questionnaire survey. Our intention was to objectively examine HEB technology development and applications. We anticipated that the evaluation would play a crucial role in HEB technology development and demonstration policy refinement. This evaluation provides a basis for decision-making regarding national policy refinement and for considering expanding HEB demonstrations nationwide. For the demonstration cities, this evaluation can provide critical inputs to improve demonstration management and a business model of technology innovation. For vehicle manufacturing companies, this evaluation provides results for further optimizing HEB technologies.

First, we introduce the study methodology and data collection. Second, we present evaluation analysis of demonstrated HEBs with their operation performance, energy consumption and affected factors, and emissions. Then, we discuss policy implications for promoting advanced technologies and commercialization of HEBs. Last, we present conclusions from the study.

2 Methodology and data

2.1 Overview

We adopted a comprehensive research framework, comprising on-road driving tests, daily operation data collection, and a questionnaire survey. On-road driving tests recorded the real-time fuel consumption and emissions of the selected demonstration vehicles. Daily operation data collected fuel consumption, failure frequency, and other information for different models during certain periods in the demonstration cities. A survey was conducted aimed at the drivers and passengers and study subjective feeling to HEB.

The demonstration cities were selected with consideration of the demonstration fleet size, vehicle and technology type, and representativeness of the geographical location and traffic conditions. On the basis of these criteria, among the 25 pilot demonstration cities, we selected Kunming, Hangzhou, Shanghai, Dalian, Ji'nan, Zhengzhou, Wuhan, and Zhuzhou, China to conduct the on-road driving tests.

In the on-road driving tests, we chose 44 HEBs from 16 manufacturers (with 11 propulsion systems and 17 models) and eight diesel buses, which covered the mainstream vehicle models from the major domestic manufacturers. In the daily operation data collection, information on 702 HEBs was gathered from Kunming, Zhengzhou, Dalian, and Shanghai. Some operating data of diesel buses also were collected for comparison. The questionnaire survey was conducted in eight pilot cities; 396 completed surveys were obtained, which involved 18 models (including 11 propulsion systems from 17 manufacturers), covering the 17 models tested on-road.

2.2 Data collection

2.2.1 Vehicle samples and test routes

For each vehicle model in one city, we chose two to three vehicles as test targets. At the same time, we chose one diesel bus with the same level to conduct parallel testing. We selected test routes for on-road driving tests in eight demonstration cities—Kunming, Hangzhou, Shanghai, Dalian, Ji'nan, Zhengzhou, Wuhan, and Zhuzhou (Fig. 1). We tested 13 models in Kunming

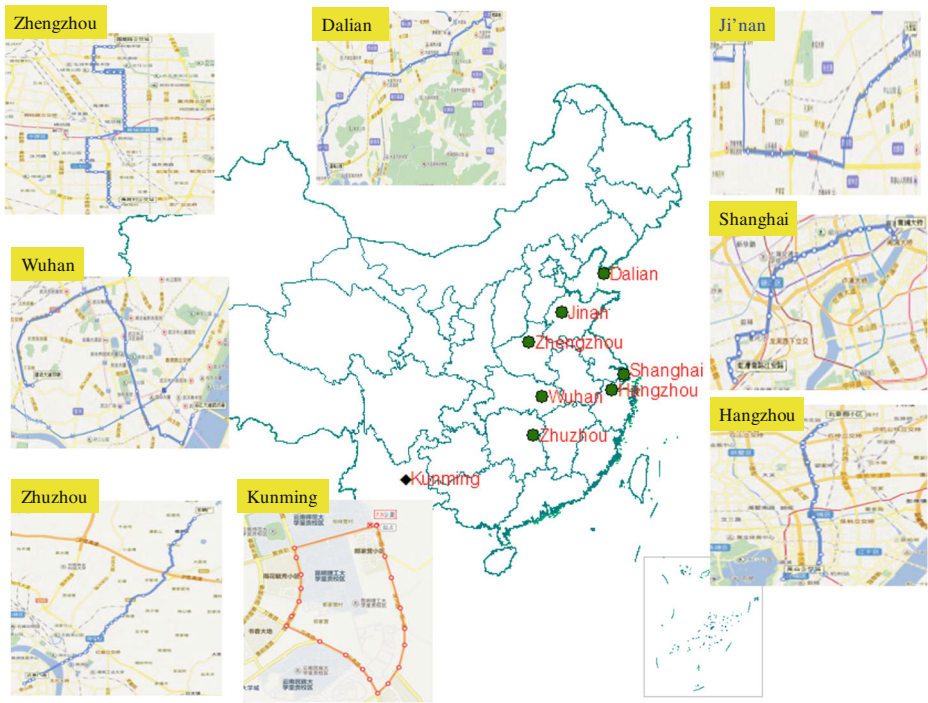


Fig. 1 On-road driving tests involved test routes (blue or red highlight line) in eight China cities

and one model in other each city, and the tested models in Hangzhou, Dalian, and Zhengzhou are covered in Kunming.

2.2.2 On-road fixed operating conditions test in Kunming

A large number of vehicles from 14 HEB manufacturers were involved in Kunming's demonstration. These vehicles had different propulsion system configurations, with both parallel and series-parallel hybrid systems, and various energy storage systems, including batteries, super capacitors (SCs), and batteries plus SCs. In order to compare the fuel consumption among different vehicle models, we tested the selected 13 manufacturers' vehicle models in the fixed operating conditions. The tests were carried out according to the relevant requirements in national standard GB19754-2005 (GB/T19754 2005), with vehicles loaded to 65 % of the rated load capacity. However, we conducted the tests in different ways than the GB19754-2005 in terms of test operating conditions and test site.

The tests were performed under 65 % of rated load capacity. First, we weighted the non-loaded vehicle. Then the load was attached by using standard sandbags. The total load, including sandbags, test equipment, driver, and the tester was 65 % of the rated load capacity. Table 1 summarizes the attributes and load information of the tested vehicles in Kunming, which contains China South Locomotive and Rolling (CSR) Times, First Automobile Workshop (FAW), and Guangzhou Automobile Group Company Limited (GAC), and 13 vehicle brands.

Before the test, test operating conditions at Kunming were established. First, eight vehicles in three representative bus routes were tracked and the driving data were recorded; 40,000 s-by-second data were obtained. The collected data were analyzed using the method established

Table 1 Attributes and load information of tested vehicles in Kunming

No.	Vehicle brand	Curb weight (kg)	Length (m)	Engine power (kW)	Motor power (kW)	Battery type	Load capacity (kg)	Added weight (kg)	Diesel bus for comparison
1	Golden Dragon	12,600	12	147	90	LFP, SC	5400	3510	Golden Dragon, Jinling
2	CSR Times	13,500	12	170	110	SC	4500	2925	
3	Sunlong	12,500	12	147	90	LFP, SC	4420	2873	
4	Higer	12,400	12	162	96	LFP, SC	5600	3640	
5	Asiastar	12,500	12	155	90	LFP, SC	5500	3575	
6	Ankai	11,500	12	158	65	LFP, SC	5200	3380	
7	Foton	11,600	12	165	26	LMO	6350	4128	
8	Kinglong	12,400	12	147	90	LFP, SC	5600	3640	
9	GAC	12,230	12	132	50	LFP	5200	3380	
10	Yutong	11,700	11.7	147	95	SC	4800	3120	
11	FAW	11,374	12	162	30	NI-MH	6626	4307	
12	Huanghai	12,800	12	132	63	NI-MH	5200	3380	
13	Wuzhoulong	11,800	11.4	136	90	LFP	4700	3055	

in the national 863 program's study on the construction of driving cycle for typical cities in China (Li et al. 2005) to acquire the representative operating conditions of Kunming buses in fixed operating conditions tests. Table 2 shows the statistical parameters of the representative operating condition.

We selected a route in the Chenggong District of Kunming, which is 9.6 km long with little traffic and no traffic lights. This operating condition was favorable to make the bus operate according to the designed operating condition. In May 2012, we carried out a 3-week test with 1-week preparation. For each HEB model, two buses were selected and tested twice under the operating conditions. When significant differences existed between test results, we conducted the test for a third time. Moreover, two designated drivers were employed to drive all the vehicles to eliminate driver variation effect.

Table 2 Statistical parameters of representative operating conditions in the vehicle study

Parameter of operating conditions	Parameter value
Duration time	2146 s
Idling share	27.7 %
0–10 km/h share	7.6 %
10–20 km/h share	19.0 %
20–30 km/h share	24.6 %
30–40 km/h share	18.2 %
40–50 km/h share	2.9 %
Distance	9.78 km
Average speed	16.41 km/h
Max. speed	50 km/h
Max. acceleration	0.91 m/s ²
Max. deceleration	1.55 m/s ²

2.2.3 On-road real-world traffic condition test

We selected the test route according to three principles: (1) the route represents bus operating behaviors in the city, including bus stations, passenger flows, and peak flow characteristics; (2) the route is mainly in an urban area; and (3) the one-way distance is 10 to 15 km. The tests were conducted between June and September 2012 and with 2 weeks for each city. For each city, we selected two to three HEBs and one diesel bus for comparison testing. Each bus was tested for two round trips, covering the morning and evening peak and also the off-peak at noon. Table 3 summarizes the attributes and load information of tested vehicles in the seven other demonstration cities.

2.2.4 Specific technology test

Three vehicle models had the start-stop function in the Kunming test. The start-stop system of one bus could be manually switched on and off. The other two buses had automatic start-stop functions that could not be switched off. To study the impact of the start-stop function on vehicle fuel consumption, we measured fuel consumption for the manual start-stop bus twice; once when the start-stop system was on and once when it was off. We measured fuel consumption for each of the other two bus models once.

2.3 Calculations

2.3.1 Fuel consumption correction

Compared with diesel buses, HEBs are equipped with additional electric propulsion systems, such as batteries and motors, which are more efficient than internal combustion engines on diesel buses, thus yielding better fuel consumption performance. When calculating the fuel consumption of HEBs, we considered both diesel consumption and electricity consumption.

According to GB/T19754-2005, electricity consumption is converted to equivalent diesel consumption based on Eq. (1). The conversion factor 3.02 was derived based on the electricity generation efficiency, that is, units of primary energy needed to generate one unit of electricity energy.

$$V_{\text{fuel}} = \frac{E_k}{3.02} \quad (1)$$

Table 3 Attributes and load information of tested vehicles in the seven China demonstration cities

No.	City	Vehicle brand	Curb weight (kg)	Length (m)	Engine power (kW)	Motor power (kW)	Battery type	Diesel bus for comparison
1	Wuhan	Dongfeng	11,000	11	118	60	NI-MH	Dongfeng
2	Dalian	FAW	11,374	12	162	30	NI-MH	FAW
3	Zhuzhou	CSR Times	11,090	10.5	162	45	SC	CSR Times
4	Hangzhou	Golden Dragon	12,600	12	147	90	LFP, SC	Golden Dragon
5	Shanghai	Sunwin	12,600	11.8	185	160	LFP	Sunwin
6	Ji'nan	Zhongtong	11,600	11.9	155	44	LMO	Youngman
7	Zhengzhou	Yutong	11,700	11.7	147	95	SC	Yutong

Where E_k (kilowatt-hour, kWh) is the electricity consumption and V_{fuel} (liter, L) is the diesel consumption equivalent.

2.3.2 Energy recovery and recovery efficiency

The net energy changes (NECs) of the battery and SC system before and after the on-road driving test were obtained based on the GB19754 NEC calculation methods by integrating the instantaneous power (voltage * current) times the time, which can be estimated by Eq. (2). In the tests, we measured the real-time voltage and current changes of both ends of the battery or SC with an electric power meter and calculated NEC second by second of the integral step.

$$\text{NEC} = \int_{\text{initial}}^{\text{final}} U \cdot I dt \quad (2)$$

Where NEC (Joule, J) is the net energy changes; I (ampere, A) is the trunk current at the input or output side of the power battery; U (voltage, V) is the voltage of the battery; and t (second, s) is the time.

Increasing attention has been paid to the brake energy recovery and it has been widely applied in HEVs. We employed the recovery efficiency as an indicator to evaluate this function, which can be obtained by dividing energy recovery with the vehicle kinetic energy reduction, as shown in Eq. (3).

$$\eta = \frac{\text{NEC}}{\frac{1}{2}mv_1^2 - \frac{1}{2}mv_2^2} * 100\% \quad (3)$$

Where η (%) is the recovery efficiency; NEC (J) is the net energy change, which represents the energy recovery; m (kilogram, kg) is the vehicle total mass; v_1 (meter per second, m/s) is the vehicle speed before the brake; and v_2 (m/s) is the vehicle speed after the brake.

3 Results and discussion

3.1 Operating conditions

Figure 2 shows the average speeds of on-road driving tests in eight demonstration cities. The average speeds of on-road driving tests were between 13 and 17 km per hour (km/h), with a mean of 14.7 km/h.

Figure 3 shows the operating condition statistical characteristics of on-road driving tests in the seven demonstration cities. The operating conditions in the demonstration cities varied. The share of idling was higher in Hangzhou, Shanghai, and Zhengzhou, with up to 32 % in Zhengzhou; the share of high-speed driving (higher than 30 km/h) was higher in Shanghai and Ji'nan than in the other cities. In addition, compared with the Chinese City Bus Cycle (CCBC), the share of high-speed operation (speed greater than 50 km/h) was less for most of the demonstration cities. These findings show that traffic conditions in most of the demonstration cities were more congested than the average condition recorded in CCBC and that the share of high speed (speed greater than 50 km/h) was less than that of the CCBC.

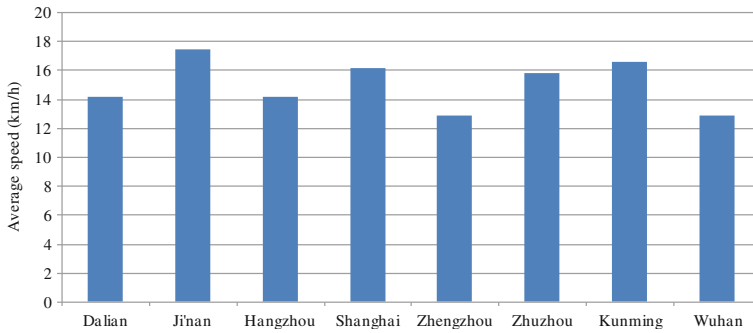


Fig. 2 Average speeds of on-road driving tests in the eight demonstration cities were between 13 and 17 km/h

3.2 Energy consumption

3.2.1 On-road fixed operating conditions tests in Kunming

Figure 4 shows the fuel consumption under on-road fixed operating conditions tests in Kunming. Among the buses, numbers (nos.) 1 through 13 were HEBs; no. 14 was a conventional automatic transmission diesel bus. The average fuel consumption values are shown in Fig. 4. The fuel consumption of HEBs was 24 to 31 L/100 km, with an average fuel consumption of around 27.5 L/100 km. The average fuel savings was 28.15 %, with some HEB models reaching up to more than 35 %.

3.2.2 On-road real-world traffic condition tests in the other demonstration cities

Figure 5 shows the fuel consumption under real-world traffic condition tests in the seven other demonstration cities. The fuel consumption of HEBs was 31 to 49 L/100 km, while the fuel

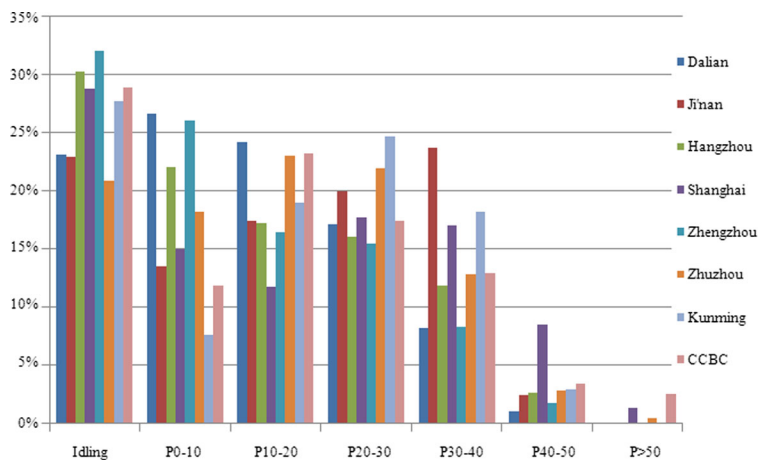


Fig. 3 Distribution of idling operations and speed ranges of on-road tests varied among the seven China demonstration cities

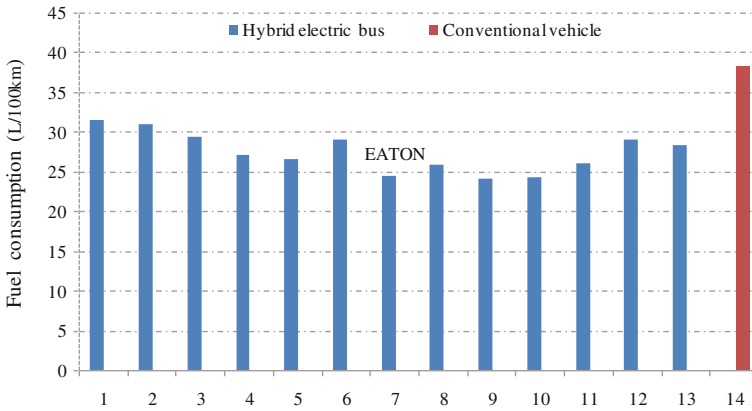


Fig. 4 Fuel consumption results of on-road fixed operating conditions tests in Kunming

consumption of conventional diesel buses was 40 to 54 L/100 km; average fuel savings reached up to 19.1 %. Moreover, because of higher environmental temperature (and the resultant use of air conditioning), fuel consumptions (including hybrid and conventional buses) in Hangzhou and Shanghai were higher than in the other cities. Meanwhile, due to propulsion system technology (HEBs in Wuhan are equipped with the earliest propulsion system), fuel saving in Wuhan is smaller than in the other cities.

3.2.3 Progress in energy-saving by HEBs

The average fuel consumption of 12 HEBs that operated in the 2008 demonstration was 35 L/100 km (CATARC 2008). Compared with the test results in Kunming, we found that after nearly 3 years of technology improvements, China’s HEBs have undergone a remarkable progress in fuel savings, with a 21.4 % reduction on average. Compared with HEBs equipped with the foreign advanced system (Eaton system, no. 7 model in Fig. 4), some domestic HEB models have reached or surpassed their fuel-saving capacity.

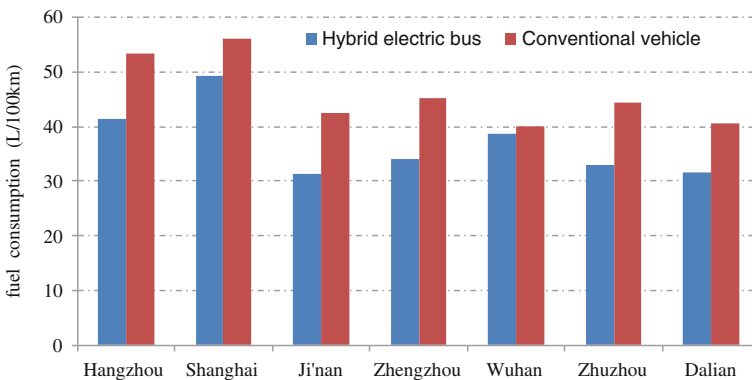


Fig. 5 Fuel consumption results of on-road real-world traffic condition tests in the seven China demonstration cities

Table 4 The traffic characteristics of the 11 routes selected and tested in Zhengzhou

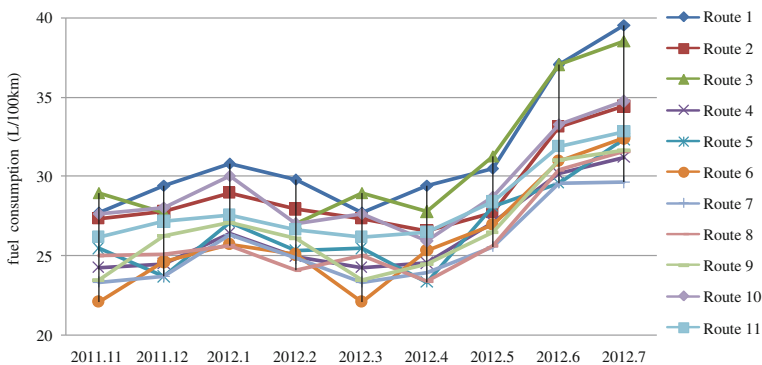
Routes	Distance (km)	Average time (min)	Average speed (km/h)
Route 1	8.60	42.00	12.29
Route 2	20.40	98.00	12.49
Route 3	19.80	101.00	11.76
Route 4	18.50	90.00	12.33
Route 5	6.10	31.00	11.81
Route 6	16.00	69.00	13.91
Route 7	11.50	55.00	12.55
Route 8	18.50	87.00	12.76
Route 9	14.10	65.00	13.02
Route 10	14.00	70.00	12.00
Route 11	11.90	59.00	12.10

3.2.4 Energy consumption for daily operation data

Fuel consumption varied from city to city because of differences in the HEB models tested, traffic situations, and environmental conditions. We employed the Zhengzhou case as an example.

We collected the fuel consumption data of 11 bus routes, with 250 HEBs operating for 9 months. Table 4 shows the traffic characteristics of the 11 routes selected. Figure 6 presents the average fuel consumption of each bus route. The fuel consumption varied by 15 to 25 % under different traffic situations. Fuel consumptions before May 2012 were quite constant. However, there was a major surge in June and July 2012, which can be mostly attributed to air-conditioner use during the summer months. This change highlights the significant effect of air-conditioner use on fuel consumption of transit buses.

For the diesel buses, which had manual transmissions because of vehicle model availability, we collected fuel consumption data on ten bus routes for 9 months. Figure 7 shows the fuel consumptions of HEBs and internal combustion engine vehicles (ICEVs). Seasonal fuel consumption changes were similar between HEBs and diesel buses. Compared with diesel buses, the fuel efficiency of HEBs was 27.8 to 34.7 % higher, with an average of 31.1 %.

**Fig. 6** Fuel consumption of HEBs for 11 bus routes in Zhengzhou varied by 15 to 25 %

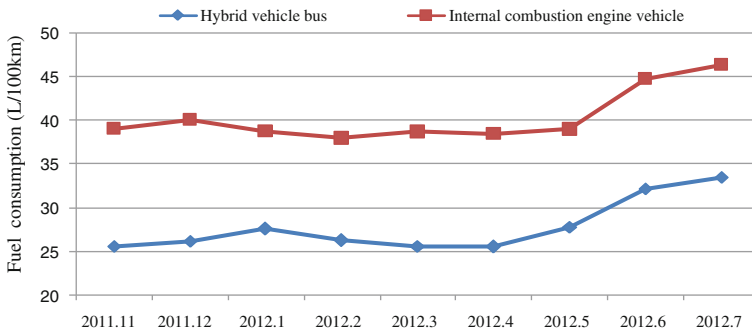


Fig. 7 Fuel consumption of HEBs and ICEVs in Zhengzhou

3.3 Factors affecting energy consumption

3.3.1 Impacts of on-road traffic conditions on energy consumption

Some HEB models were involved in both fixed operating conditions tests in Kunming and real-world traffic condition tests in the seven other demonstration cities. Figure 8 shows the test results of two models under these two sets of operating conditions. Fuel consumptions under the two test conditions were close when air-conditioner use was not considered. Fuel consumptions under on-road real-world traffic condition tests in Dalian and Zhengzhou were 7 to 10 % higher than that of under on-road fixed operating conditions tests in Kunming, which can be attributed mostly to different operating conditions.

3.3.2 Impacts of air-conditioner use on energy consumption

In some cities, we tested fuel consumption for the same model with the air conditioner on and then off. Figure 9 shows the comparison of fuel consumption of buses with and without the air conditioning being on, with a small difference between the indoor and outdoor temperature (within 2 °C temperature difference in the cities of Ji’na, Zhengzhou, and Zhuzhou). The influence of air-conditioner use on fuel consumption was similar among the tests, which was

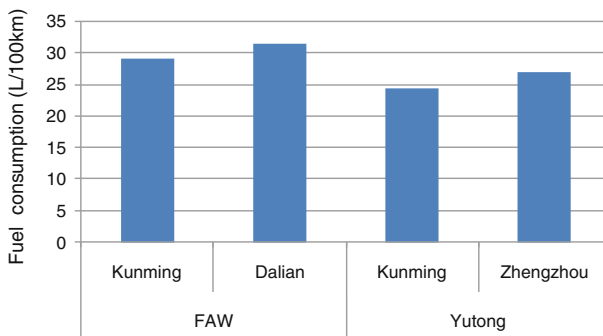


Fig. 8 Fuel consumption comparison of HEBs in China cities

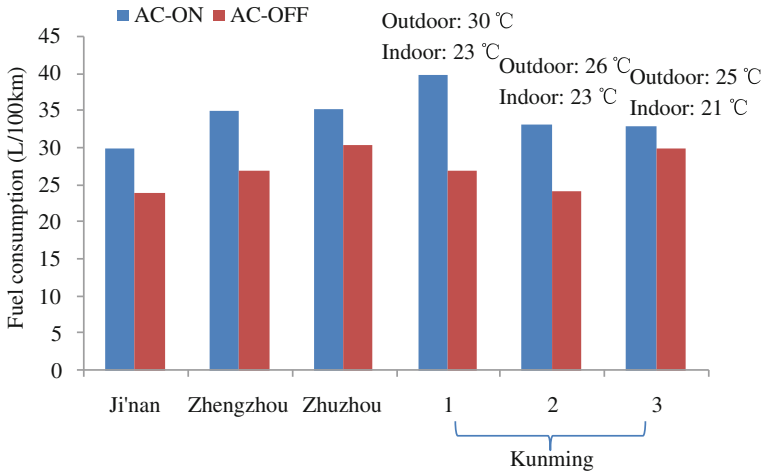


Fig. 9 Automobiel air conditioner use impacted fuel consumption under on-road driving tests

about a 15 % increase in fuel consumption. In addition, we tested three HEB models in Kunming, when the indoor and outdoor temperature difference was significant; air-conditioner use can cause a fuel consumption increase as high as 30 %.

3.3.3 Brake energy recovery effect on energy consumption

Figure 10 shows the statistics of the brake deceleration characteristic under the same operating conditions. The figure shows the share of braking deceleration for four different HEB models. It can be seen that the share of braking deceleration differed among the four HEB models. However, there were some common patterns; for example, the share of braking with less intensive deceleration of $-0.25 \sim 0$ m per second squared (m/s^2) was dominant. In the whole process of braking, mild-braking of deceleration less than $0.25 m/s^2$ was close to 50 %.

Second, we examined brake energy recovery under different braking strengths for four HEB models. Figure 11 shows the relationship between energy recovery and brake deceleration in the testing. It can be seen that four HEB models present three different control strategies.

For the no. 2 and no. 3 buses, with a decrease in the brake deceleration intensity, the amount of electricity recovered decreased. For the no. 1 bus, the recovered electricity remained nearly

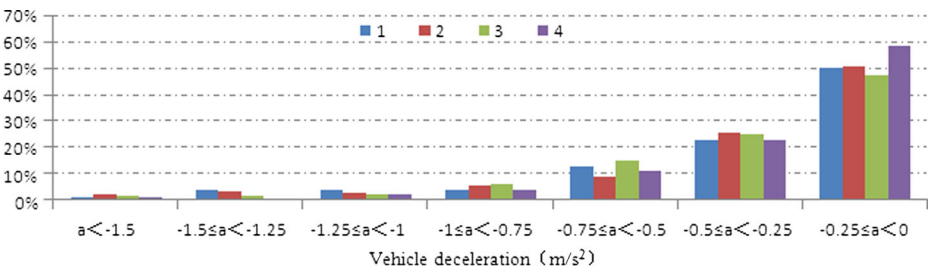


Fig. 10 Statistics of brake deceleration characteristic in operating conditions

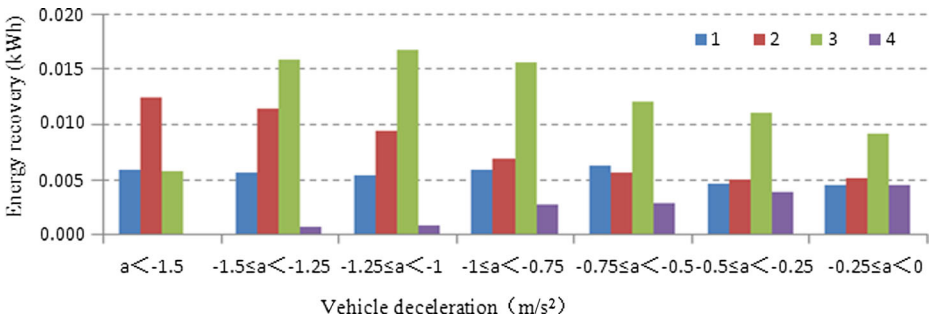


Fig. 11 Energy recovered under different brake deceleration intensities

unchanged during the whole braking regime; for the no. 4 bus, the amount of electricity recovered was small in hard braking deceleration.

Third, Fig. 12 shows the braking energy recovery efficiency. With the decrease in braking deceleration intensity, braking energy recovery efficiency improved. When brake deceleration was under 0.25 m/s², the recovery efficiency was about 15 %. The share of electric braking force was larger during lighter braking, while the share of mechanical braking force was larger during harder braking. In addition, the recovery efficiency of the no. 3 bus was greater than the other HEBs because the SC is more efficient to charge and discharge.

Finally, we examined the influences of different battery types (model 1 with a LiMnO₄ battery [LMO], model 2 with a LiFePO₄ battery [LFP], model 3 with a SC, and model 4 with a nickel-metal hydride battery [NI-MH]). Under the same operating conditions, for braking energy recovery, the SC was larger than the lithium battery and the lithium battery was larger than NI-MH battery. Electricity recovery of 3.12 kWh by using a SC was the largest, electricity recovery of 1.75 kWh by using a lithium battery was the second largest, and electricity recovery of 1.01 kWh by using a NI-MH battery was the smallest (Fig. 13). In terms of braking energy recovery efficiency, the average recovery efficiency ranged from 4 to 9 % in a single cycle and the average recovery efficiency of all kinds of batteries is about 5.6 % (see Fig. 13).

3.3.4 Impacts of idling start-stop function on energy consumption

In order to measure the fuel-saving effect of the idling start-stop device, we conducted four tests on three vehicles with start-stop devices under on-road fixed operating conditions tests in Kunming. Table 5 shows the statistical characteristics of the four driving schedules.

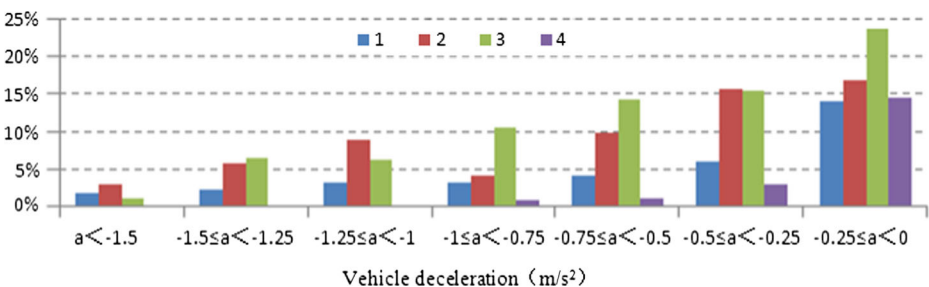


Fig. 12 Proportion of braking energy recovery efficiency under different brake deceleration intensities

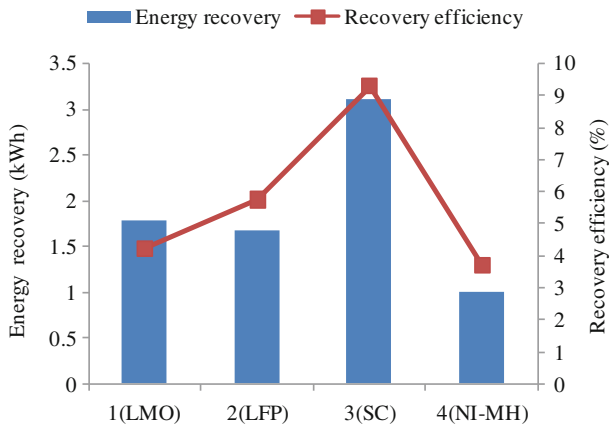


Fig. 13 Braking energy recovered and recovery efficiency in the vehicle tests

According to the vehicle operating conditions, we calculated the effect of vehicle fuel saving caused by the start-stop function (Fig. 14). It can be concluded that the start-stop function can reduce fuel consumption by about 0.2 L/100 km, with a fuel-saving rate of about 8.5 to 9.5 %.

3.4 Emissions analysis

In the on-road real-world traffic condition tests in Hangzhou and Zhuzhou, we selected one HEB in each city and tested the emissions. The method of emissions testing was the same as for on-road driving tests. Table 6 gives the testing data.

Figure 15 shows the HEB emissions test results of this evaluation and conventional vehicle (CV) emissions test results of diesel bus on-road in the real-world of Beijing in 2010. Compared with the conventional diesel buses, hydrocarbon (HC) emissions are lower and have made remarkable progress, but carbon monoxide (CO) emissions have increased. Meanwhile, nitrogen oxide (NO_x) emissions have decreased a little, but the improvement is not obvious.

3.5 Bus reliability analysis

3.5.1 Failure frequency analysis

In daily operation data collection, we collected a total of 168 failures for 10 propulsion models of HEBs during a period of 8 months in Kunming. Figure 16 shows failure frequency in

Table 5 Characteristics of the driving schedules for the start-stop function evaluation

Running duration time (s)	Distance (km)	Idling duration (s)	Proportion of idling (%)
2146	9.563	571	26.61
2146	9.6	603	28.10
2146	9.376	575	26.79
2146	9.177	583	27.17

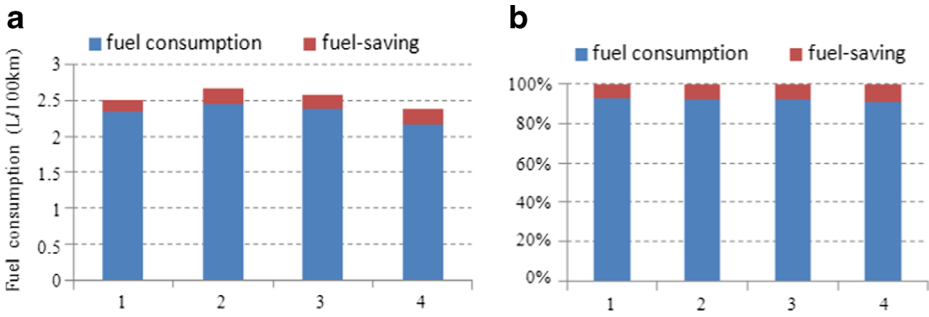


Fig. 14 a, b Estimated fuel savings of vehicle idling start-stop technology

Kunming; we can see that the lowest failure frequency was 0.39 failures per 10,000 km for the Foton HEB that uses the Eaton system. Failure frequency of most HEB models that use the domestic hybrid systems was above 1 failure per 10,000 km. In addition, according to survey data of the public transit companies, the failure frequency of conventional diesel buses was 0.39 failures per 10,000 km. It can be seen that the failure frequency of HEBs with the domestic system was higher than that for the HEBs with the foreign system (Eaton) and conventional diesel buses.

3.5.2 Failure intensity analysis

Powertrain system failure can be grouped into level 1, level 2, level 3, and other. Level 1 failure refers to the failure where a vehicle cannot continue to be driven and requires professional services. Level 2 failure refers to the failure where a vehicle can continue to drive after a driver makes a simple fix, but requires professional services for diagnosis. Level 3 failure refers to the one where a restart of a vehicle will help continue to drive the vehicle. Other failures mean powertrain system failures other than levels 1, 2, and 3 failures (HTRDC 2013). Figure 17 shows various failure frequencies of different HEB models. It can be seen that Foton has very low levels 1 and 2 failures, and in most cases can be repaired in a short time. Huanghai, CSR Times and FAW have a high probability of levels 1 and 2 failures.

Table 6 Vehicle emissions testing information in Hangzhou and Zhuzhou, China

City	Bus route		Time (s)	Distance (km)	Traffic condition
	Start station	End station			
Hangzhou	Beijingyuan Community	Wushan Bus Station	2986	10.62	Normal
	Wushan Bus Station	Beijingyuan Community	3419	12.96	Congestion
Zhuzhou	Yandi Square	Vehicle Factory	1600	7.55	Normal
	Vehicle Factory	Yandi Square	2695	7.43	Congestion
	Yandi Square	Vehicle Factory	1491	1.58	Congestion
	Vehicle Factory	Yandi Square	2213	19.69	Normal

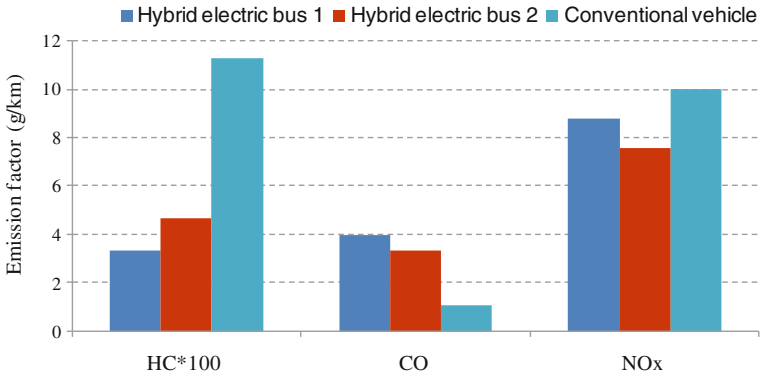


Fig. 15 Carbon and nitrogen emissions from HEB and CV tests

3.5.3 Failure content analysis

According to the questionnaire survey, the main failures of HEBs for powertrain system are shown in Table 7. In particular, the main failures include the vehicle control system, battery system, and motor system, and the share of these three failure types can be more than 80 %.

4 Policy implications

The above analysis and discussion present a summary of the technical development and applications of Chinese HEBs in eight demonstration cities. Policy recommendations to improve HEB technologies and to promote further demonstration are discussed below.

First, we discuss some policies about product technologies. This study implies that the start-stop technology contributed about 9 % to fuel savings and to emission reductions. However, of the 17 models in the study, only 3 had this technology. We recommend the promotion of the start-stop technology. Congested cities should especially promote the application of this technology in buses.

Furthermore, we recommend the promotion of braking energy recovery with optimized control strategies. Even though the vehicle braking energy recovery technology is widely used in HEBs, its control system limits the effect on fuel consumption and safety.

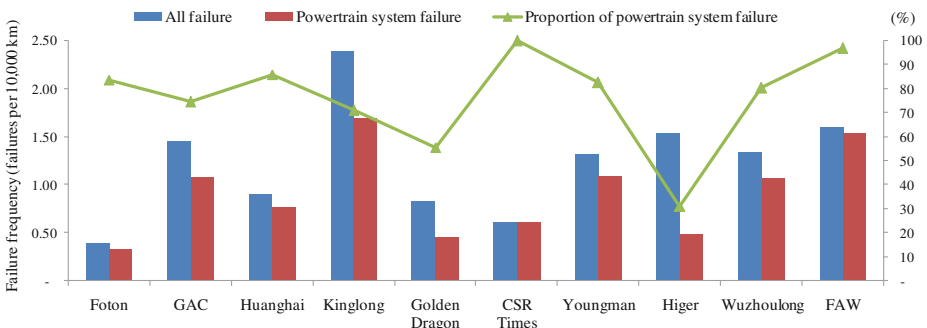


Fig. 16 Failure of HEB models in Kunming

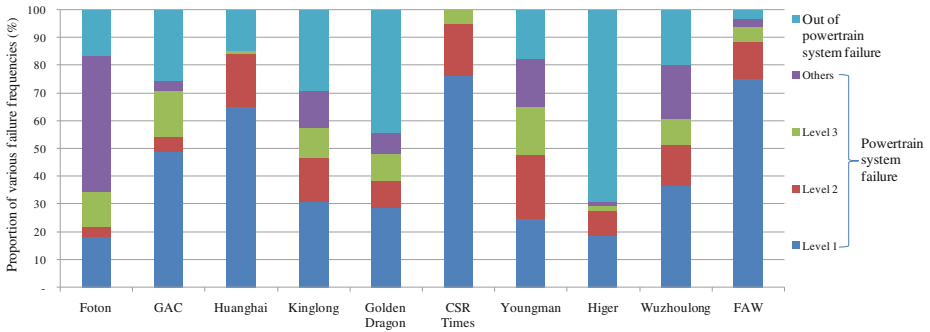


Fig. 17 HEB models and the frequency of failures in various tests

The demonstrated HEBs have shown improvements in fuel consumption, but vehicle reliability is still a problem. The failure of the powertrain system is especially frequent, and, as a result, the maintenance cost of HEB operation is high. Thus, it is necessary to improve the reliability of HEBs. Furthermore, research should be conducted to develop energy-efficient vehicle parts such as efficient air-conditioning systems. Air conditioning has a large impact on fuel efficiency, especially in hot weather. We recommend continuing support of research and development in HEB system optimization and in the development of high-efficiency vehicle parts.

Second, we discuss some policies to promote vehicle demonstration. After 3 years of demonstration, HEBs have made significant technical progress and achieved significant fuel savings. Plus, some models have reached a reliability level close to that of conventional diesel buses. In addition, according to the user survey, some models yield relatively high satisfaction. In conclusion, HEBs are well placed for large-scale commercial promotion. Therefore, we recommend that HEB demonstrations be expanded nationwide to encourage further advancement of hybrid technologies for the ultimate competitive HEB market. Meanwhile, a strong monitoring mechanism should be established to evaluate HEB performance.

We also recommend continuing financial support for HEBs. HEB technologies are still in development and the cost remains high. Before the technologies become fully mature with improved fuel efficiency and functionality, the cost will not decrease quickly. In addition, HEB maintenance cost is relatively high compared with conventional diesel buses. Thus, HEBs will still need financial subsidies before they become mature technologies.

Table 7 Causes of HEB powertrain system failures

Failure content	Proportion of main failures
Vehicle control system	29 %
Battery system	28 %
Motor system	24 %
Coupled system	14 %
Engine system	5 %

5 Conclusions

NEVs are still in the early stages of commercialization. NEV technology evaluation is the central link to NEV demonstration and technology improvements. With 44 HEBs in eight demonstration cities, we summarized the technical development and applications of HEBs in China.

Our evaluation showed that the average fuel saving by HEBs is 28 % with on-road fixed operating conditions tests and 19 % with on-road real-world traffic condition tests. Meanwhile, compared with testing data during the 2008 Beijing Olympic Games, HEBs have made a significant technological progress.

We also found that the operation of air conditioning can reduce fuel consumption by 15 % in mild climates and up to 30 % in hot climates. The idling start-stop technology can contribute to fuel savings of about 9 % and with emission reduction. The braking energy recovery technology can also achieve fuel savings. However, large variations in fuel savings by the braking energy recovery technology remain, primarily because of control strategies deployed for the technology.

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