

Article

Research on Adaptability Testing and Evaluation of Battery Electric Vehicles in Cold Environments

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Abstract

To address the limitations of existing low-temperature evaluation methods for battery electric vehicles (BEVs) in terms of real-world road adaptability, test consistency, and multi-dimensional performance assessment, this study proposes a standardized on-road testing and multidimensional adaptability evaluation system for BEVs in frigid environments. To address the issues that conventional bench tests cannot adequately replicate real-world road environments, routine road tests lack consistency, and existing evaluation indicators pay insufficient attention to charging efficiency and cabin heating performance, this study defines the ambient temperature for road testing, low-speed steady-state driving conditions, and the conditions for ensuring consistency in road testing. It also establishes a cold-environment adaptability evaluation system comprising three dimensions—driving range, charging efficiency, and heating, ventilation, and air conditioning (HVAC) heating performance—and four evaluation indicators: the driving range degradation rate in cold environments, charging time per 100 km, HVAC heating duration, and HVAC heating energy consumption per unit cabin volume. Field tests were conducted on 10 representative BEVs in real-world road conditions near -20°C in Heihe City, Heilongjiang Province, China. The results indicate that the average range degradation rate for these 10 models in cold environments was 60.7%, and approximately 60% of the vehicles could complete a 100 km charge in under 30 min; the average HVAC heating time was 34 min, with an average power consumption of 9.2 kWh. The tests also revealed that the heating efficiency and thermal comfort of single-heat-pump HVAC systems at -20°C still have room for improvement, and that the uniformity of cabin temperature distribution and consistency in foot temperature between the left and right sides significantly affect thermal comfort. The evaluation method proposed in this study can serve as a reference for testing the cold-weather adaptability of BEVs, as well as for optimizing thermal management systems and developing vehicle performance.

Keywords: BEVs; cold climate; environmental adaptability; testing and evaluation; HVAC



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1. Introduction

Driven by global decarbonization [1] and the transformation of transportation energy systems [2], battery electric vehicles (BEVs) have become an important pathway for

reducing fossil fuel dependence [3] and improving vehicle energy efficiency [4]. Recent advances in battery systems, electric drive integration [5], vehicle energy management [6], and fast-charging technologies [7] have improved the usability of BEVs under normal operating conditions. However, the real-world performance of BEVs remains highly sensitive to extreme environmental conditions, particularly in frigid regions where low ambient temperatures affect battery available capacity, internal resistance, charging acceptance [8], heating, ventilation, and air conditioning (HVAC) heating demand, and cabin thermal comfort. Therefore, a standardized testing and evaluation method that reflects real-world cold-environment operation is necessary for assessing BEV adaptability beyond conventional laboratory conditions.

Given these factors, numerous studies in recent years have explored the low-temperature adaptability of BEVs from various perspectives. Al-Wreikat et al. [9] utilized real-world driving data collected on roads in the West Midlands, United Kingdom, to investigate the relationship between external ambient temperature and driving distance, parking percentage, and average speed for electric vehicles, thereby assessing their energy consumption under different driving and environmental conditions. Lee et al. [10] conducted a comprehensive evaluation of energy efficiency using both chassis dynamometer testing and real-world driving environments. The results indicate that in real-world driving conditions, energy efficiency at most driving endpoints under moderate temperatures exceeds certified values. When HVAC [11] activates, battery energy consumption increases by 4.5% in summer and 12% in winter. An et al. [12] employed the continuous cycle test method from GB/T 18386.1-2021, developing a rapid cycle test method for electric vehicle range at low temperatures based on the China light-duty vehicle test cycle (CLTC) [13]. This method analyzes low-temperature discharge energy characteristics, establishes representative cycle counts and weighting factors, and incorporates both dynamic and constant-speed segments. Most of these studies rely on chassis dynamometers [9,10] with fixed standard test cycles (e.g., worldwide harmonized light-duty test cycle (WLTC) or CLTC) or real-world vehicle testing influenced by traffic flow and driving styles. They quantify the direct impact on overall vehicle energy consumption through metrics such as energy consumption per 100 km, energy flow distribution, and driving range.

However, the natural environment of on-road testing presents entirely new challenges for conducting multi-vehicle consistency evaluations of cold-weather adaptability. Currently, mainstream testing methods fall into two main categories. First, bench testing using a chassis dynamometer strictly adheres to standard operating condition curves to ensure a high degree of consistency and repeatability in testing conditions. To address issues such as insufficient representativeness and the risk of test cheating caused by a single fixed standard operating condition, Xu et al. [14] defined an equivalent excitation at the wheel end based on vehicle longitudinal dynamics. They employed a two-dimensional Markov state model combining velocity and acceleration with Monte Carlo simulation to generate new state chains, thereby creating random operating conditions equivalent to the energy consumption of the China light-duty vehicle test cycle for passenger cars (CLTC-P). Ultimately, they completed dual verification through simulation and chassis dynamometer testing, with maximum energy consumption deviations of only 0.77% and 1.79%, respectively. Second, actual road testing [4,15] accurately reflects a vehicle's comprehensive performance under complex traffic flows and real-world environments. However, both methods exhibit significant limitations in cold environment adaptability testing. While bench testing offers high precision and repeatability, it struggles to fully simulate real-world rolling resistance and variations in road surface friction coefficients. Conversely, conventional on-road testing, though closer to real-world scenarios, is heavily influenced by factors such as traffic flow (e.g., interference from preceding vehicles) and driver behavior. This makes it difficult

to precisely replicate standard test conditions, leading to significant variations in speed curves between different vehicles and tests. Consequently, the consistency of test results is greatly compromised. To further bridge the gap between test bench results and users' actual driving experiences, Xu et al. [16] subsequently proposed a method for generating random driving scenarios based on a dual-filtering framework, using actual user driving data as a reference. This method generated multiple random driving scenarios comparable to users' energy consumption, and the energy consumption consistency was verified on a chassis dynamometer, with a maximum deviation of only 2.144%. Therefore, establishing a repeatable standardized evaluation system under real-world frigid road conditions has become a critical issue requiring urgent resolution in this field.

It is noteworthy that increased demand for HVAC heating during winter significantly exacerbates overall vehicle energy consumption. Gopi et al. [17] investigated the effect of localized lower-body radiant heating on the thermal comfort of occupants in BEVs under low-temperature conditions. Their results indicate that, under a 40 min test scenario, lowering the HVAC setpoint from 25 °C to 18 °C and combining it with localized lower-body radiant heating can reduce energy consumption associated with cabin thermal comfort control by 45.3% while maintaining occupant thermal comfort. Lokur et al. [18] simulated cabin energy consumption by establishing a thermal model. Seo et al. [19] investigated the impact of HVAC systems on vehicle performance at different temperatures, using energy efficiency as a key parameter, and noted that real-world road tests often exhibit greater variability due to external interference. Most of the above studies are based on standard driving cycles or simulation models established using real vehicle test data. Currently, there is a lack of a unified, quantifiable evaluation parameter that can directly reflect the impact of the HVAC system on the environmental adaptability of BEVs in low-temperature environments. Therefore, it is necessary to establish a standardized HVAC heating test procedure.

Simultaneously, energy replenishment efficiency in frigid conditions is another core factor triggering range anxiety among BEV users. Under low temperatures, the electrochemical dynamics of lithium-ion batteries deteriorate significantly, with increased polarization resistance. Forcing high-rate charging can cause irreversible capacity degradation and even trigger thermal runaway [20]. To address the challenge of low-temperature fast charging, Wang et al. [21] proposed a compact integrated heating-charging operation mode capable of battery preheating, charging, and simultaneous heating-charging (SHC). This approach enables charging from 20% to 80% state of charge (SOC) in just 39 min at −20 °C. Existing research primarily focuses on optimizing battery preheating [22,23] and battery thermal management system (BTMS) optimization [24–26] to address low charging efficiency at low temperatures. However, when vehicles are exposed to prolonged immersion in −20 °C extreme cold environments, these charging strategies often perform poorly at public charging stations. Most existing energy replenishment studies are conducted under controlled laboratory conditions with constant temperatures or ideal grid power outputs, failing to accurately reflect the actual performance of different vehicle thermal management architectures in extreme cold environments. Therefore, evaluating key parameters such as driving range, energy replenishment efficiency, and HVAC heating energy consumption under frigid conditions is essential for assessing the cold-environment adaptability of BEVs.

Therefore, existing research lacks a testing and evaluation framework for BEV adaptability that can simultaneously ensure road realism, operational consistency, and multidimensional performance evaluation under real-world cold-climate road conditions. This study utilizes the characteristics of the WLTC to perform short-trip segmentation, filtering, and low-speed steady-state processing, thereby establishing simplified driving conditions suitable for real-world road testing in cold regions. Additionally, a portable driver assis-

tance system (referred to as “Driver Assist”) is introduced to guide drivers in real-world road environments via visual or auditory signals, enabling them to follow target speed curves in real time and thereby reducing the impact of driver operation variations on test results. Building on this, this study establishes an adaptability evaluation system for cold-weather environments covering three dimensions—driving range, charging efficiency, and HVAC heating performance—and four evaluation metrics. Field tests were conducted on 10 mainstream BEVs in real-world road conditions in Heihe City, Heilongjiang Province, where temperatures approached -20°C .

It should be noted that the method proposed in this study is not a simple transfer of laboratory chassis dynamometer testing to real-world roads, nor is it intended to construct an alternative cycle that is completely equivalent to the original WLTC in terms of energy consumption. The main innovation of this method lies in establishing a standardized on-road testing framework that simultaneously considers the physical realism of real-world road environments and the consistency of multi-vehicle testing. Compared with chassis dynamometer testing, this framework preserves practical factors under real-world frigid road conditions, such as tire–road rolling resistance, variations in road-surface friction under low-adhesion conditions, natural aerodynamic resistance, and microscopic road disturbances. Compared with conventional on-road testing, this framework standardizes key boundary conditions, including the vehicle input speed profile, ambient temperature range, cold-soaking condition, and test load, through standard-cycle feature extraction, short-trip segmentation, speed curve filtering, sub-motion segment merging, low-speed steady-state processing, and portable driver-assistance-based speed following. Therefore, this method improves the consistency and comparability of multi-vehicle on-road test results without completely sacrificing the physical characteristics of real-world roads.

Meanwhile, the role of the proposed data filtering and segment merging framework is not to completely eliminate the stochasticity of real-world road environments. Rather, it is intended to decouple random traffic interference, driver operation differences, and high-frequency speed fluctuations from the main test inputs, allowing vehicles to be compared under the same target speed profile, temperature boundary, and test procedure. After these treatments, the differences among test results for different vehicles more directly reflect differences in vehicle architecture and system strategies, including low-temperature discharge capability of the traction battery, vehicle energy management strategy, HVAC heating strategy, actual tire–road interaction, and low-temperature fast-charging acceptance. Therefore, the proposed method establishes an executable, reproducible, and engineering-relevant comprehensive evaluation framework between chassis dynamometer baseline testing and fully uncontrolled on-road testing.

The main contributions of this study are as follows:

- (1) A standardized on-road testing method based on simplified WLTC low-speed steady-state cycle reconstruction is proposed for BEVs in frigid environments. This method improves the safety, feasibility, and repeatability of real-world cold-region road testing while preserving the main characteristics of typical driving conditions.
- (2) A consistency control method for real-world road testing was established. Through measures such as environmental temperature boundary constraints, vehicle cold-weather immersion, and independent power supply for portable driver assistance systems and external testing equipment, the comparability of cold-weather road test results across multiple vehicle models was improved.
- (3) A multidimensional adaptability evaluation system was developed, covering driving range degradation, charging time per 100 km, HVAC heating duration, and HVAC heating energy consumption per unit cabin volume. This expands cold-environment

adaptability evaluation from a single-dimensional range assessment to an integrated evaluation of driving, recharging, and heating performance.

- (4) Based on real-world road test data from 10 mainstream BEVs, we conducted a quantitative analysis of key issues such as range degradation, low-temperature charging efficiency, HVAC heating energy consumption, and foot temperature consistency under $-20\text{ }^{\circ}\text{C}$ conditions. This provides experimental evidence for developing thermal management systems for BEVs in cold environments.

This study is organized as follows: Section 2 defines test boundary conditions including ambient temperature, driving conditions, road test consistency, and sensor installation. Section 3 presents the test procedures for driving range, rapid charging, and HVAC heating under extremely cold conditions. Section 4 presents evaluation results and discussion. Finally, the concluding remarks of the study are provided in Section 5.

2. Definition of Test Boundary Conditions

To conduct freezing-cold environment testing more effectively on real roads, it is necessary to define key factors affecting test consistency—such as typical temperatures and driving conditions—to eliminate errors caused by environmental conditions and human operation.

2.1. Environmental Temperature Determination

To better study the typical temperature range in extreme cold environments, this study investigated the temperature distribution across 65 cities in Northeast and Northwest China in 2023, as shown in Figure 1. Based on the average temperatures for daytime, nighttime, and combined daytime-nighttime periods, the average temperatures across these 65 cities primarily fall within the range of $-25\text{ }^{\circ}\text{C}$ to $-1.5\text{ }^{\circ}\text{C}$. Statistical analysis of these temperatures reveals that, as shown in Figure 2, the winter low-temperature range of $-25\text{ }^{\circ}\text{C}$ to $-11.2\text{ }^{\circ}\text{C}$ essentially covers the majority of urban areas, beyond the $(-7 \pm 3)\text{ }^{\circ}\text{C}$ range specified by regulations. Consequently, a representative extreme winter temperature of $(-20 \pm 5)\text{ }^{\circ}\text{C}$ was selected to supplement the temperature range beyond regulatory coverage.

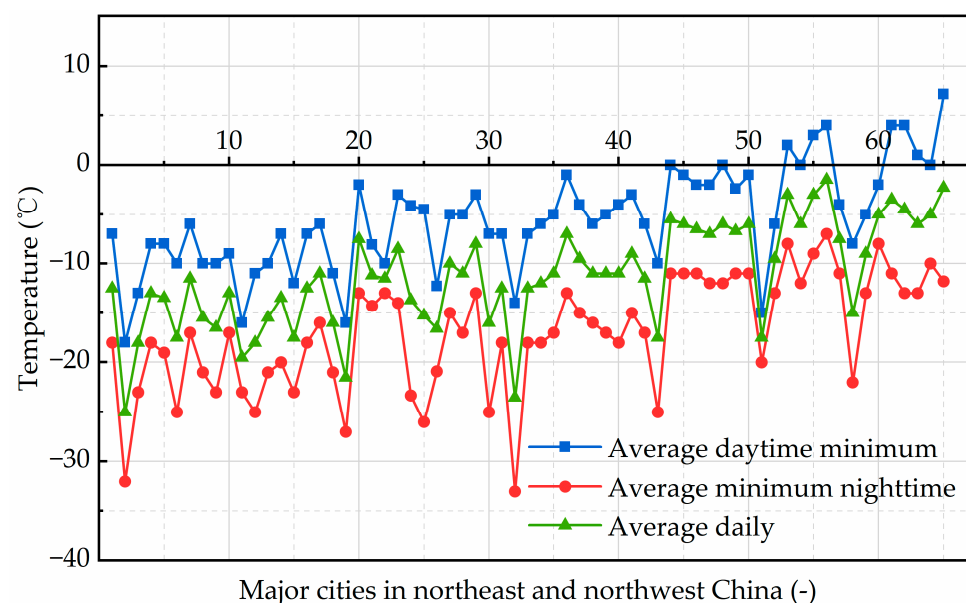


Figure 1. Winter temperatures in 65 major cities in Northeast and Northwest China.

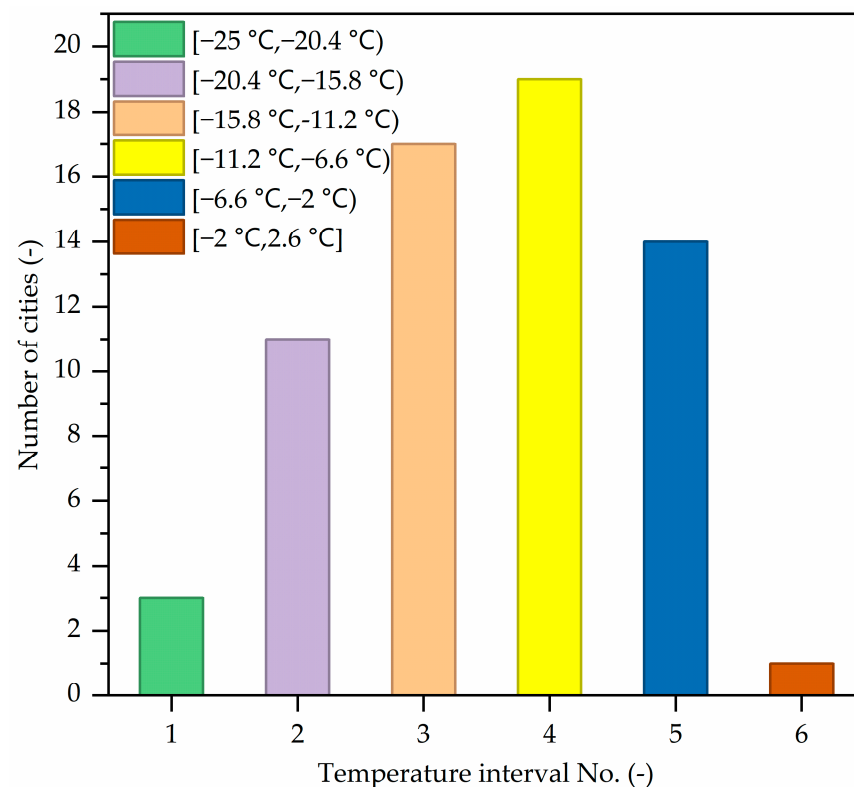


Figure 2. Winter temperature distribution across 65 major cities.

2.2. Driving Condition Determination

To facilitate real-world driving range testing on actual roads while addressing safety, operability, and consistency requirements for road trials, it is necessary to develop a test cycle featuring low-speed steady-state characteristics based on the parameter characteristics of existing standard cycles. This study modifies the WLTC by applying low-speed steady-state adjustments to create a driving cycle suitable for road testing in frigid regions.

(1) Short-Cycle Segment Division. To better stabilize low-speed conditions in the WLTC, as shown in Figure 3, this study divides the WLTC into eight short-cycle segments (each cycle starting from 0 km/h, undergoing acceleration, steady-state driving, deceleration, and returning to 0 km/h).

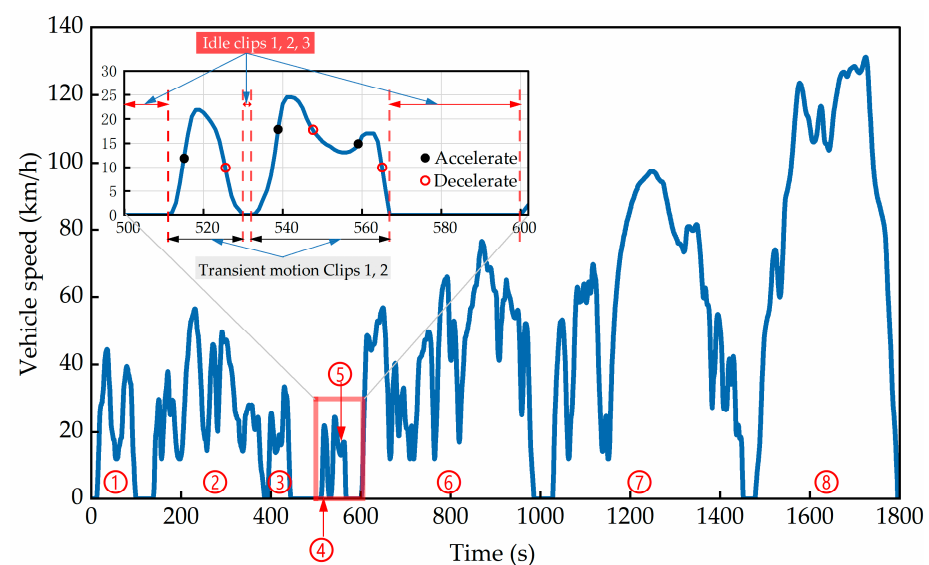


Figure 3. Eight short-trip segments in the WLTC.

(2) Segmentation of Short-Travel Segments and Filtering of Operating Condition Curves. First, the original WLTC speed sequence was processed using a 10-point moving average filter. This treatment reduces the influence of local high-frequency fluctuations and pseudo-local extrema on segment division while preserving the overall speed variation trend and the main acceleration–deceleration characteristics of the original cycle. Second, within each short-trip segment, adjacent local minimum speed points after filtering were identified as transient velocity boundaries. The speed curve between two adjacent velocity boundaries was defined as an initial sub-motion segment, which generally contains a local acceleration process, a relatively stable driving process, a deceleration process, and a transition to the next velocity boundary. Through this procedure, the eight WLTC short-trip segments were initially divided into 29 sub-motion segments. Within each short-travel segment, adjacent minimum vehicle speeds can be used to divide the segment into multiple smaller sub-motion segments. To prevent excessive fragmentation caused by numerous local minimum values, the WLTC operating condition curve requires filtering. This ensures the vehicle speed curve remains distortion-free while achieving maximum smoothing, as illustrated in Figure 4.

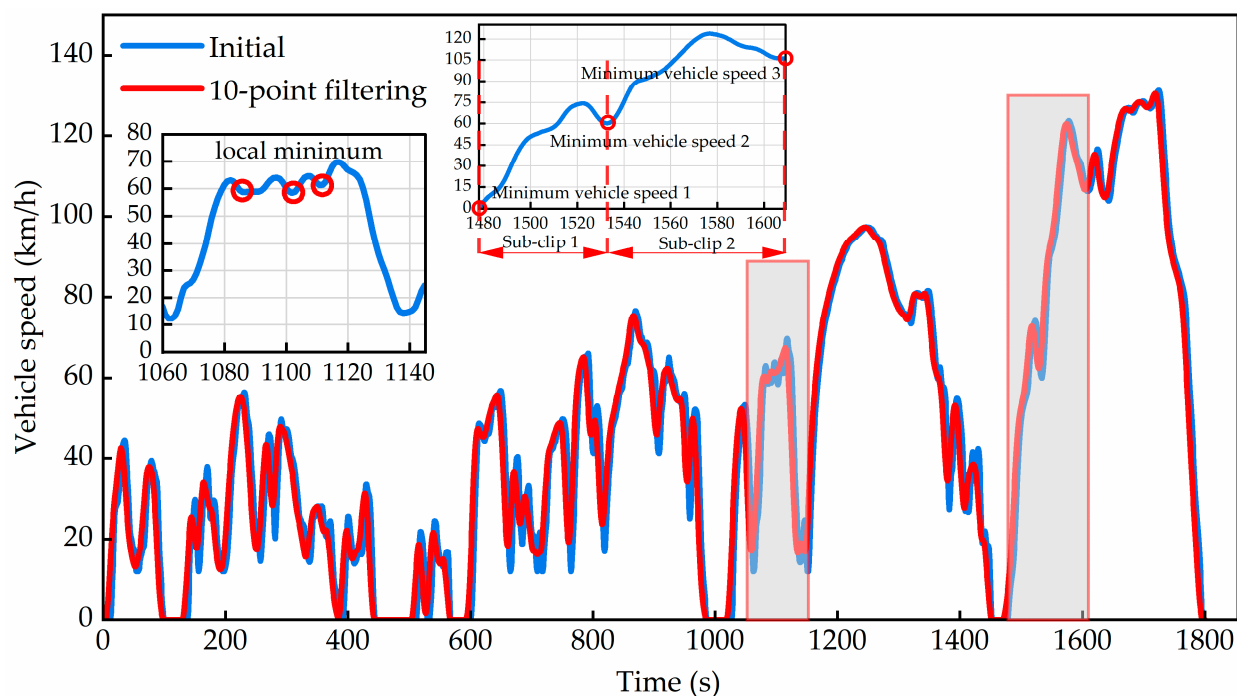


Figure 4. Filtered smoothing for WLTC.

(3) Merging Sub-Motion Segments. After the initial segmentation, the maximum speed, segment duration, average acceleration, and average deceleration of each sub-motion segment were calculated. To improve the executability of the target speed profile during real-world road testing in frigid environments and to avoid frequent acceleration and deceleration caused by excessively short segments, adjacent sub-motion segments were merged according to two criteria. First, when the maximum-speed difference between two adjacent sub-motion segments was no greater than 5 km/h, the two segments were considered to have similar speed levels; therefore, merging them would not significantly change the main speed characteristics of the original cycle. Second, when the duration of a sub-motion segment was no greater than 45 s, the segment was considered too short to be stably followed by the driver on icy or low-adhesion winter roads and was therefore merged with an adjacent segment. Based on these criteria, the 29 initial sub-motion

segments obtained after filtering were finally consolidated into 18 sub-motion segments, as listed in Table 1.

Table 1. Merging of sub-motion segments in WLTC.

Short-Travel Segment	Sub-Motion Segment Number	Maximum Speed (km/h)	Segment Duration	Combine Motion Segments
1	1	44.5	51	1
	2	39.5	38	
2	3	29.8	26	2
	4	38	38	
	5	56.5	59	3
	6	46	26	
	7	49.8	54	4
	8	28.2	47	5
3	9	25.6	26	6
	10	33.5	29	
4	11	21.9	21	7
5	12	24.5	36	
6	13	56.9	71	8
	14	40.5	20	
	15	33.2	32	
	16	49.8	47	9
	17	66	55	10
	18	76.6	89	11
	19	65.1	73	12
	20	53.3	43	13
7	21	69.7	76	
	22	97.4	178	14
	23	81.6	66	15
	24	54.9	28	
	25	42.5	36	
	26	74.1	60	16
8	27	123.7	76	17
	28	116.7	32	
	29	131.3	150	18

(4) Steady-State Processing of Transient Motion Segments. Following the principle of “vehicle speed 0 km/h → constant acceleration → constant velocity → constant deceleration → vehicle speed 0 km/h,” transient motion segments undergo steady-state processing, as shown in Figure 5, where the constant velocity segment speed V_{cst} is as follows:

$$V_{cst} = 0.8V_{max}, \quad (1)$$

where V_{cst} [km/h] represents the vehicle speed during the constant motion segment within a single motion segment, and V_{max} [km/h] denotes the maximum vehicle speed for that motion segment. For a single kinematic segment, the expressions for acceleration duration T_{acc} , deceleration duration T_{dec} , and constant velocity duration T_{cst} are given by Equations (2)–(4):

$$T_{\text{acc}} = \frac{V_{\text{cst}}}{3.6a_{\text{acc,avg}}} - 1, \quad (2)$$

$$T_{\text{dec}} = \frac{V_{\text{cst}}}{3.6|a_{\text{dec,avg}}|} - 1, \quad (3)$$

$$T_{\text{cst}} = T_{\text{mot}} - T_{\text{acc}} - T_{\text{dec}}, \quad (4)$$

where $a_{\text{acc,avg}}$ [m/s^2] denotes the average acceleration of a single motion segment, $a_{\text{dec,avg}}$ [m/s^2] denotes the average deceleration of a single motion segment, and T_{mot} [s] denotes the duration of each motion segment. Equation (2) is used to calculate the time required for a vehicle to accelerate uniformly from 0 km/h to a target constant speed; Equation (3) is used to calculate the time required for a vehicle to decelerate uniformly from the target constant speed to 0 km/h. To correct for potential timing duplication at the boundary points of acceleration, constant-speed, and deceleration segments in discrete time series, this study applies a 1 s correction to both the acceleration and deceleration times. Equation (4) is used to determine the constant-speed travel time by subtracting the acceleration and deceleration durations, given the total duration of the motion segment. The expression for the constant time interval $T_{\text{cst},i}$ in the i -th sub-segment is given by Equation (5):

$$T_{\text{cst},i} = \frac{T_{\text{sub},i}}{T_{\text{mot}}} \cdot T_{\text{cst}}, \quad (5)$$

where $T_{\text{sub},i}$ [s] is the duration of the i -th sub-motion segment within the motion segment. Here, $T_{\text{cst},i}$ [s] is the constant-speed duration assigned to the i -th sub-motion segment in the merged motion segment. Equation (5) represents the allocation of the total constant-speed time T_{cst} [s] based on the ratio of each sub-motion segment's original duration to the total duration of the merged segment. This approach allows the merged speed curve to be more easily executed during road testing while preserving the time weights of each sub-segment.

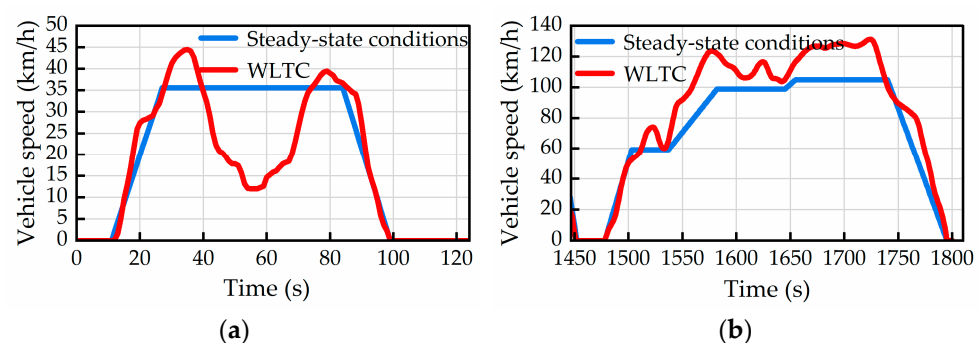


Figure 5. Steady-state stabilization of transient particle motion segments: (a) single motion clip; (b) merged motion clip.

(5) Simplified Treatment of Steady-State Driving Conditions. Considering road test safety, the maximum test vehicle speed is limited to 80 km/h. For driver convenience, the average acceleration and deceleration during acceleration/deceleration segments are set to constant values, eliminating multi-stage acceleration/deceleration and rounding speeds during constant-speed segments. This ultimately forms the low-speed steady-state condition of the WLTC, as shown in Figure 6. Comparing the WLTC and the simplified cycle

(as shown in Table 2), the four key cycle parameters—duration, distance traveled, average speed, and average acceleration—remain largely consistent. Through the aforementioned modifications, the simplified cycle achieves low-speed, average, and steady-state processing.

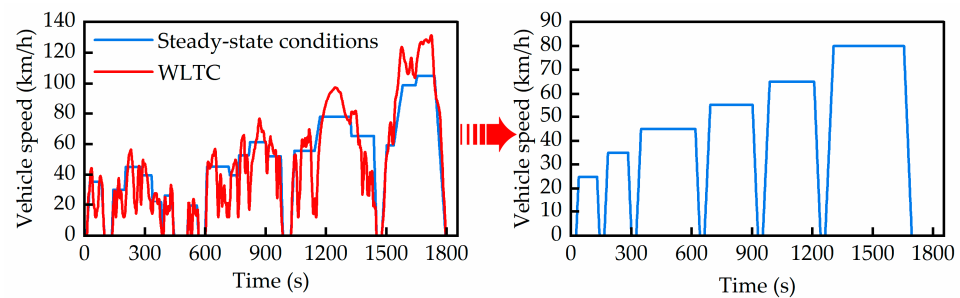


Figure 6. Low-speed steady-state treatment for WLTC.

Table 2. Comparison of low-speed steady-state conditions with WLTC characteristic values. The red markings indicate that the WLTC and the simplified test cycle proposed in this study are essentially consistent in six key parameters: duration, driving distance, average speed, average operating speed, average acceleration, and average deceleration.

No.	Characteristic Value	Unit	Operating Conditions	
			WLTC	Simplified Operating Conditions
1	Duration T	s	1800	1725
2	Driving distance S	km	23.27	22.42
3	Maximum speed $V_{\max}$	km/h	131.3	80
4	Average speed V_{avg}	km/h	46.5	46.76
5	Average operating speed $V_{\text{avg,mr}}$	km/h	53.49	52.18
6	Maximum acceleration $A_{\max}$	m/s^2	1.67	0.53
7	Maximum deceleration $D_{\max}$	m/s^2	−1.5	−0.57
8	Average acceleration A_{avg}	m/s^2	0.53	0.53
9	Average deceleration D_{avg}	m/s^2	−0.57	−0.57
10	Acceleration duration ratio P_a	%	32	9.3
11	Deceleration duration ratio P_d	%	30.1	8.6
12	Constant speed duration ratio P_c	%	24.8	71.7
13	Idle duration ratio P_i	%	13.1	10.4

It should be noted that the purpose of filtering, segmenting, and stabilizing the low-speed conditions of the WLTC in this study is not to directly construct a bench test cycle that is fully equivalent to the original WLTC energy consumption. Rather, it is to address the safety, operability, and consistency requirements of real-world cold-weather road testing by reducing the demands on driver tracking accuracy caused by drastic speed fluctuations and high-speed segments. This study primarily maintains the fundamental consistency between the simplified test conditions and the original WLTC by utilizing key characteristic parameters such as average speed, distance traveled, average acceleration, and average deceleration. Additionally, it ensures consistency in speed tracking during road testing through the use of a portable driver assistance system and a speed tolerance band of ± 5 km/h.

To ensure the safety and reproducibility of real-world road testing in extremely cold regions, this study simplifies the test conditions by limiting the maximum speed to 80 km/h. While this approach reduces coverage of the original WLTC high-speed segment, the focus of this study is on real-vehicle, real-road testing in extremely cold environments around -20 °C. This scenario involves uncertainties such as icy and snowy road surfaces,

low coefficient of friction, and changes in tire performance at low temperatures. Directly executing the high-speed segment would pose significant safety risks and markedly reduce the consistency of driver speed following. Additionally, low-temperature road rolling resistance and the adhesion characteristics of icy and snowy surfaces are difficult to simulate with complete accuracy using traditional dynamometer resistance curves. Therefore, this study opts to conduct testing in a real-world road environment while retaining the key features of the WLTC within safe limits.

2.3. Ensuring Consistency in Road Testing

To conduct range testing on actual roads while accounting for real-world vehicle energy consumption factors, this study minimizes the influence of driver behavior during testing. Focusing solely on road and environmental constraints, it prioritizes comparing vehicle performance metrics. Therefore, consistency in road test conditions must be ensured. The low-speed steady-state conditions developed in Section 2.2 were input into the portable driver assistant, as shown in Figure 7. This guided drivers on actual roads to follow the condition curve, ensuring consistency in driver style and speed tracking across all speed segments during range testing, as illustrated in Figure 8. Similarly, considering the impact of actual testing environments on vehicle performance, this study monitored temperature variations throughout each test cycle. By tracking weekly temperatures, the average temperature during testing was maintained within the range of $(-18$ to $-22)$ °C to ensure consistency in environmental temperature conditions, as shown in Figure 9.

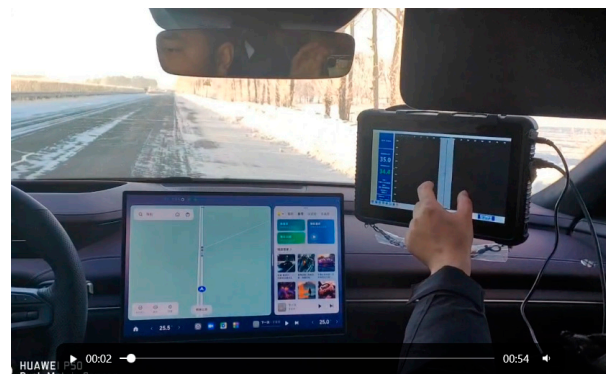


Figure 7. Portable driver assistant.

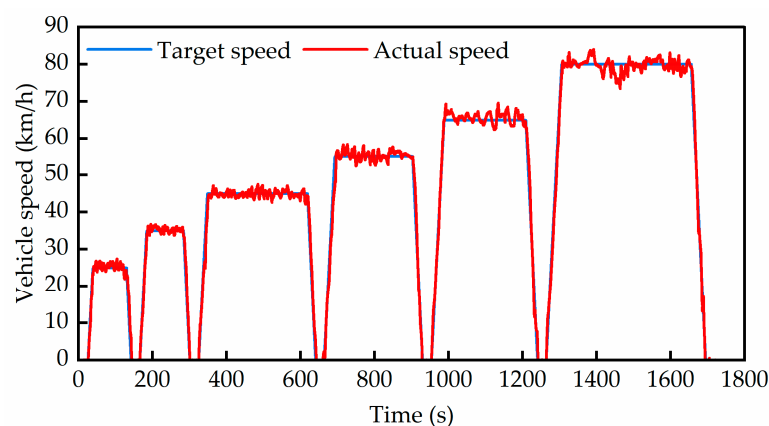


Figure 8. Consistency of speed following.

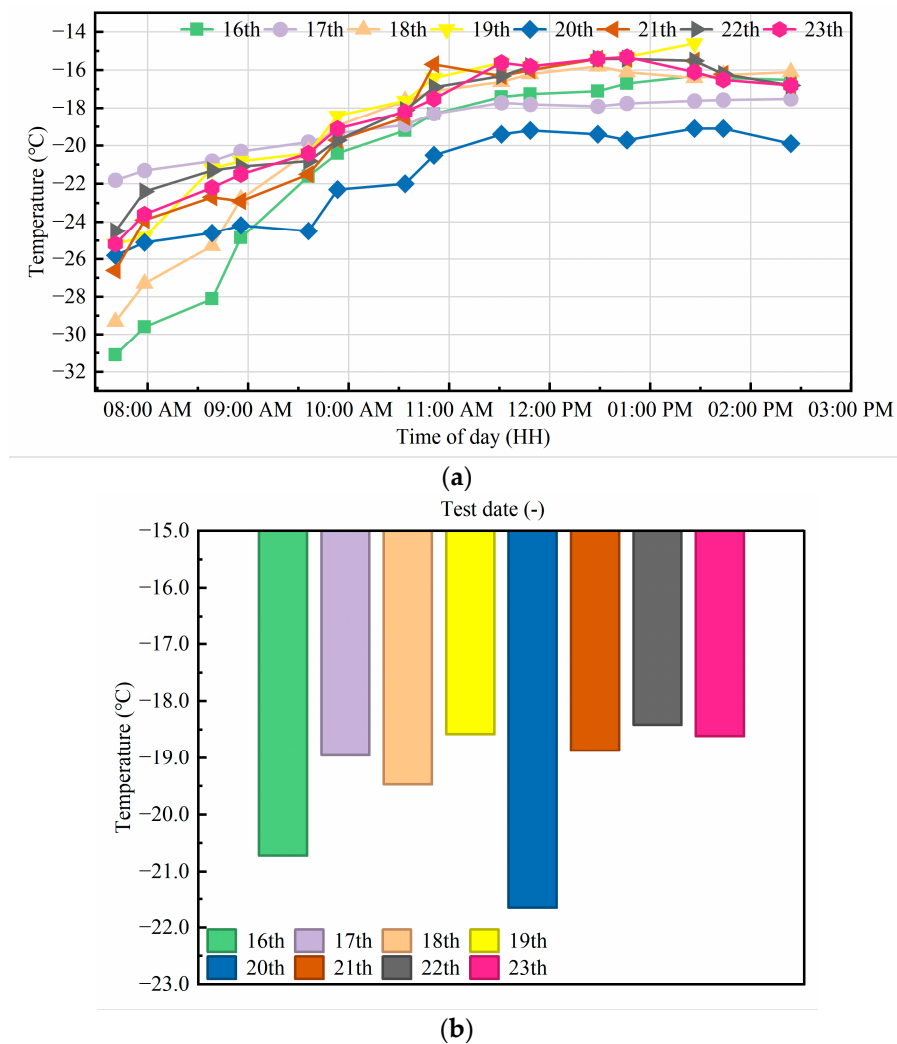


Figure 9. Environmental temperature consistency. (a) The distribution of ambient temperatures during the testing period from 16 December to 23 December. (b) The distribution of average ambient temperatures during the test period from 16 December to 23 December.

Figure 10 shows the overall framework of the method described in this paper. The flowchart presents the complete procedure from target speed input and simplified cycle construction to real-road speed tracking and multidimensional adaptability evaluation. First, the original WLTC target speed profile is used as the input, and the speed sequence is processed through 10-point moving average filtering, local minimum speed point identification, initial sub-motion segment generation, and sub-motion segment merging. Then, a simplified WLTC target speed profile suitable for real-world execution on frigid roads is obtained through low-speed steady-state reconstruction. Second, the target speed profile is imported into the portable driver assistance device, which provides visual or audible guidance to help the driver follow the target speed on real roads. During the test, the GPS device synchronously records the actual vehicle speed and time signals, and the consistency of speed following is evaluated using the ± 5 km/h speed tolerance band and the speed-tracking error. Finally, the measured data, including traction battery voltage/current, HVAC component power, ambient temperature, cabin temperature, charging time, and charging energy, are integrated to calculate the driving range degradation rate, charging time per 100 km, HVAC heating duration, and HVAC heating energy consumption per unit cabin volume.

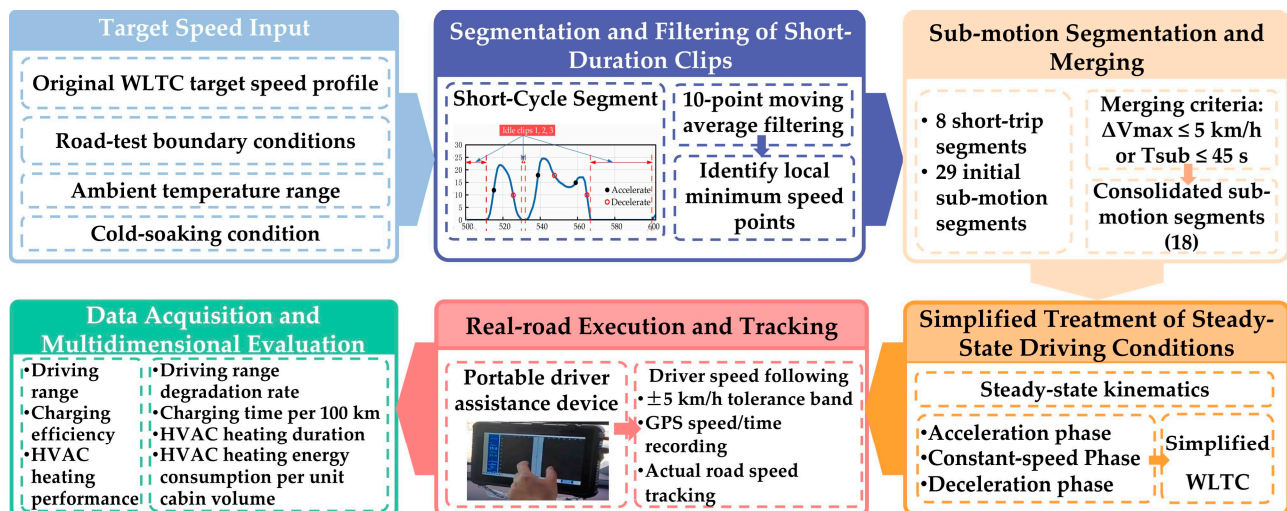


Figure 10. Overall framework for simplified WLTC construction, real-road speed tracking, and multidimensional BEV adaptability evaluation.

The simplified WLTC described in this study is used in conjunction with a portable driver assistance system to form a human-in-the-loop road speed following method. During testing, the target speed curve is input into the portable driver assistance system. The system guides the driver through visual or audible prompts to control the accelerator and brake pedals, maintaining the vehicle's actual speed as closely as possible within a tolerance band of ± 5 km/h relative to the target speed. This reduces the impact of driver style variations on test results and improves the consistency of road testing across multiple vehicle models. In practical applications, the data acquisition system and GPS logging system used in this study met the sampling requirements for the simplified WLTC road test. Since the simplified WLTC is based on two-level vehicle speed tracking, the actual sampling rate was sufficient to capture changes in vehicle speed, time information, ambient temperature, and the energy consumption data required by the proposed evaluation method. During data processing, checks were performed for outlier data points, short-term signal fluctuations, and potential transient GPS signal losses to minimize the impact of telemetry noise on distance integration. Additionally, prior to testing, externally mounted sensors and wiring harnesses were mechanically secured and electrically insulated to withstand icy, low-temperature, and locally uneven winter road conditions. No significant signal interruptions or equipment malfunctions due to insufficient sensor durability were observed during testing. The display delay of the portable driver assistance unit was relatively small compared to the Level 2 speed update interval of the simplified WLTC; therefore, a speed tolerance band of ± 5 km/h was adopted to minimize the impact of short-term display delays and driver reaction times on the consistency of speed tracking. This method utilizes an external portable driver assistance display, requiring no modifications to the vehicle's original control systems or access to the electronic control unit (ECU), making it more suitable for standardized comparative testing across different vehicle models.

The tests described in this study refer to the basic requirements regarding road test conditions and vehicle preparation specified in GB/T 12534-1990 [27], "Motor vehicles--General rules of road test method." The test process was conducted while avoiding periods of strong crosswinds, significant snow accumulation, and traffic interference as much as possible. To minimize the systematic impact of road gradients and wind direction on energy consumption results, a round-trip driving method was adopted during testing, allowing unidirectional gradients and local wind direction disturbances to be partially offset over the course of the entire test. It should be noted that this study involved field testing on

actual high-altitude, cold-weather roads; active control of crosswinds and gradients under closed-course test conditions was not implemented. Consequently, crosswind and gradient disturbances remain sources of uncertainty in road testing.

2.4. Sensor Installation Plan for Tested Vehicles

To accurately record the energy consumption of the tested vehicle during high-cold environment testing, voltage and current sensors were installed at the output terminals of the power battery busbar for the tested BEV. Voltage and current sensors were also installed at the output terminals of the HVAC compressor, HVAC blower, passenger compartment positive temperature coefficient (PTC) heater, and battery PTC heater. A power analyzer was used to integrate and record the electrical energy consumption. To capture the temperature variation characteristics during the cabin HVAC heating process, the head temperature measurement point was arranged at the front passenger seat in accordance with Annex F.2 of the Chinese national standard GB/T 18386.1-2021 [28]. In addition, the foot temperature measurement point was arranged at the front passenger seat with reference to Annex B of the Chinese automotive industry standard QC/T 658-2009 [29]. The specific locations of the temperature measurement points are shown in Figure 11. GB/T 18386.1-2021 is mainly used to specify vehicle preparation, test conditions, HVAC system settings, and temperature measurement point arrangements for energy consumption and driving-range tests of light-duty electric vehicles, whereas QC/T 658-2009 is mainly used to specify road-test conditions and temperature measurement point arrangements for automotive air-conditioning systems. During on-road testing with the actual vehicle, a portable driver assistance display provided the driver with simplified WLTC target speed information in real time to guide the driver in maintaining speed in accordance with the preset operating conditions. At the same time, the global positioning system (GPS) was used to continuously record the vehicle's actual speed and time signals during operation, and the actual distance traveled was calculated by integrating the speed-time data. To ensure the power battery's energy is solely consumed for driving during testing, all externally connected sensors and testing equipment—including the onboard voltage sensor, current sensor, temperature sensors at measurement points, GPS, and portable driver assistance device—are powered by separate mobile power supplies, as shown in Figure 12. The external mobile power supplies did not draw electricity from the tested vehicle's traction battery; therefore, their electrical loads were not included in the vehicle driving energy consumption or HVAC heating energy consumption. The purpose of using external power supplies was to isolate the power consumption of the measurement devices and avoid affecting the energy consumption calculation of the tested vehicle.

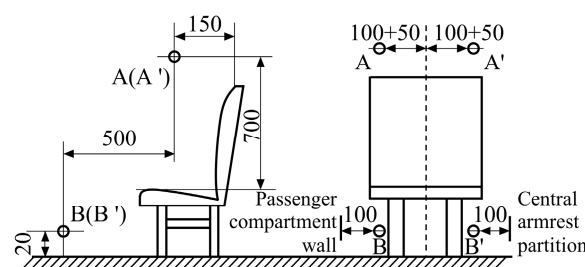


Figure 11. Head and foot temperature measurement points for the passenger seat. All dimensions are in mm. A, A'—Passenger head temperature measurement points; B, B'—Passenger foot temperature measurement points.

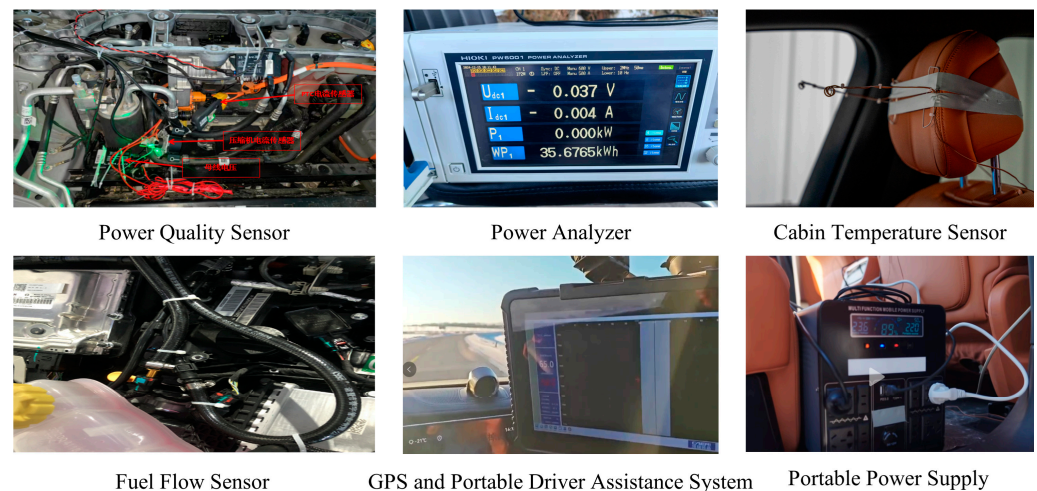


Figure 12. Vehicle Sensor and Equipment Installation.

Meanwhile, to reduce possible secondary thermal effects introduced by the external mobile power supplies, the external power supplies and data acquisition devices were fixed at positions away from the head/foot temperature measurement points, HVAC outlets, and return-air inlets. During the tests, the cabin temperature was controlled around 21 °C, with an allowable fluctuation range of approximately ± 2 °C. The localized heat generated by the external power supplies was small relative to the overall HVAC heating load and therefore did not dominate the cabin temperature response. Regarding mass distribution, all external test devices and mobile power supplies were included in the vehicle test mass and were arranged and fixed according to the vehicle test mass requirements of GB 18352.6-2016. The placement of external devices was kept consistent across the tested vehicles to reduce the influence of additional mass and mass distribution differences on rolling resistance and driving energy consumption calculations.

3. Testing and Evaluation Methods

This study develops driving range tests, rapid charging tests, and HVAC heating tests for extremely cold environments based on real-world winter driving scenarios, simulating actual user driving and charging conditions. Prior to testing, the vehicle under test is first fully charged and then left to acclimate outdoors in a low-temperature environment starting at approximately 7:00 p.m. the night before the test until approximately 7:00 a.m. the following day, for a total duration of 12 h. During the acclimation period, the ambient temperature remains below -20 °C.

3.1. Drive Range Testing Methodology

To evaluate the driving range adaptability of BEVs in frigid environments, this study conducted real-world on-road driving range tests on a flat, straight road at ambient temperatures ranging from $(-25$ to $-15)$ °C. Prior to testing, the tested vehicle was fully charged and cold-soaked for 12 h with all windows and doors closed to ensure that the thermal states of the traction battery, passenger compartment, and the vehicle as a whole reached thermal equilibrium with the ambient temperature. The primary vehicle operating mode was configured in accordance with Annex C of GB/T 18386.1-2021. After starting the vehicle, it was operated according to the simplified WLTC shown in Figure 6.

During the test, the HVAC system was configured in accordance with Annex A.2.4 of GB/T 18386.1-2021 to maintain the front-seat head temperature measurement point within the range of 20–22 °C. Guided by the portable driver assistance display, the vehicle was operated to follow the simplified WLTC target speed curve, with an instantaneous speed tolerance band of ± 5 km/h relative to the target speed. When the vehicle under test could no longer maintain the instantaneous speed tolerance requirement relative to the cycle curve, the driving-range test was deemed to have reached its termination condition. Thereafter, the driver released both the accelerator and brake pedals, allowing the vehicle to coast to a low speed of approximately 5 km/h, and then gently applied the brake pedal to bring the vehicle to a smooth stop.

During vehicle operation, the ambient temperature was recorded once per minute, and the average ambient temperature T_{avg} [°C] over the entire driving range test was calculated. To quantify the degree of driving-range degradation of the tested vehicle in a frigid environment relative to the manufacturer-certified driving range, this study defines the frigid-environment driving range degradation rate N_{frigid} [%], as shown in Equation (6):

$$N_{\text{frigid}} = \frac{D_{\text{cert}} - D_{\text{frigid}}}{D_{\text{cert}}} \times 100\%, \quad (6)$$

where N_{frigid} [%] represents the range decline rate in extreme cold environments, D_{cert} [km] denotes the manufacturer's rated range, and D_{frigid} [km] indicates the range achieved under the WLTC simplified test cycle in extreme cold conditions. After completing the range test, a 7 kW alternating-current charging station was used to charge the tested vehicle until the traction battery indicator showed a full charge, and the electrical energy drawn from the grid during the charging process was recorded. Based on the electrical energy input during charging and the actual driving range measured in the cold environment, the energy consumption per 100 km of the tested vehicle in the cold environment was calculated, as shown in Equation (7):

$$C_{\text{frigid}} = 100 \times \frac{E_{\text{grid}}}{D_{\text{frigid}}}, \quad (7)$$

where C_{frigid} [kWh/100 km] denotes the energy consumption per 100 km in frigid conditions, and E_{grid} [kWh] represents the energy drawn from the grid during charging after the range test concludes.

3.2. Charging Efficiency Testing Methodology

To evaluate the energy replenishment efficiency of BEVs in frigid environments, this study conducted low-temperature fast-charging tests and used the charging time per 100 km as an indicator of charging efficiency. This indicator characterizes the time required for a vehicle to replenish the energy needed to travel 100 km in a frigid environment and reflects the combined effects of the traction battery's charge acceptance under low-temperature conditions, the vehicle thermal management strategy, and the actual fast-charging process on energy replenishment efficiency.

The tests were conducted on a flat, straight road at ambient temperatures ranging from (−25 to −15) °C. Prior to testing, the tested vehicle was fully charged and cold-soaked for 12 h with all windows and the doors closed to ensure that the thermal states of the traction battery, passenger compartment, and the vehicle as a whole reached thermal equilibrium with the ambient temperature. After the low-temperature cold-soaking period, the tested vehicle underwent a road discharge test following the simplified WLTC shown in Figure 6. During the test, the HVAC system was used to maintain the front-seat head temperature measurement point within the range of 20–22 °C to simulate the vehicle's

energy-consumption state when users operate HVAC heating in frigid environments. When the traction battery indicator reached 30% SOC, the discharge process was terminated, and this state was used as the initial SOC for the fast-charging test in the frigid environment.

Subsequently, in accordance with the vehicle manufacturer's recommended shortest-time charging strategy, the tested vehicle was charged using a public fast-charging station with a rated power of no less than 120 kW until the traction battery indicator reached 80% SOC. During charging, the charging time n [min] was recorded from the moment the charging station began outputting current until the traction battery indicator reached 80% SOC. Simultaneously, a power analyzer was used to record the electrical energy $E_{n,\min}$ [Wh] drawn from the grid during the charging process. It should be noted that the fast-charging test described in this study did not assume that public charging facilities could provide an ideal, constant power output; the recorded charging time and energy input were both measured results from the actual charging process. Therefore, the test results reflect the combined effects of fluctuations in the output power of public charging stations, the vehicle's battery thermal management strategy at low temperatures, and the traction battery's charge acceptance under low-temperature conditions.

Based on the energy consumption per 100 km in a frigid environment C_{frigid} obtained in Section 3.1, the charging time n recorded during the fast-charging process, and the electrical energy input from the grid $E_{n,\min}$, this study defines the charging time per 100 km in a frigid environment $T_{100 \text{ km}}$ [min], as shown in Equation (8):

$$T_{100 \text{ km}} = \frac{100 \times C_{\text{frigid}}}{\frac{1}{n} \times E_{n, \min}}, \quad (8)$$

where $T_{100 \text{ km}}$ [min] represents the fast-charging time required to drive 100 km, n [min] denotes the charging duration from the point when current flows from the charging station to the end of charging when the power battery reaches 80% SOC, and $E_{n, \min}$ [kWh] indicates the energy drawn from the grid during charging as recorded by the power analyzer.

3.3. HVAC Heating Test Method

On a flat, straight road at an ambient temperature of $(-25 \text{ to } -15)^\circ\text{C}$, fully charge the test vehicle and immerse it for 12 h with all windows, hood, and doors closed to ensure the vehicle's temperature aligns with the ambient temperature. Set the vehicle's primary operating mode according to Appendix C of GB/T 18386.1-2021. After starting the vehicle, operate it according to the simplified WLTC, as shown in Figure 6. Simultaneously, set the HVAC system in accordance with Appendix A.2.4 of GB/T 18386.1-2021. Continue running the vehicle under the simplified WLTC for 1 h after the average temperature at the passenger footwell temperature measurement point reaches 21°C . This procedure allows both the maximum and sustained heating capacities of the HVAC system to be evaluated throughout the entire heating process. Record the current and voltage of the HVAC compressor, HVAC blower, passenger compartment PTC heater, and battery PTC heater during the test. The HVAC heating energy consumption is evaluated using the heating energy consumption per unit cabin volume in a high-cold environment using the heating power consumption per unit volume of the passenger compartment. Combine this with the temperature constraint at the foot temperature measurement point and the time constraint for the first point at which 21°C is reached to reflect the maximum heating capacity, average heating power consumption, and a weighted evaluation of thermal comfort during the heating process, as shown in Equation (9):

$$\varepsilon_h = \frac{\int_{t_0}^t (P_1 + P_2 + P_3) dt}{3600V_0}, \quad (9)$$

where ε_h [kWh/m³] is the heating energy consumption per unit volume of the passenger compartment, P_1 [kW] is the discharge power of the HVAC compressor, P_2 [kW] is the discharge power of the blower assembly, P_3 [kW] is the discharge power of the passenger compartment PTC and the power battery PTC, t_0 [s] is the time at which the HVAC system is activated, t [s] is the time when the test ends, and V_0 [m³] is the passenger compartment volume, provided by the vehicle manufacturer.

3.4. The Development of an Evaluation System for the Adaptability of BEVs in Cold Environments

Based on the three evaluation aspects outlined in Sections 3.1–3.3, this study establishes an evaluation system for assessing the cold-weather adaptability of BEVs. This system encompasses three dimensions—driving range, charging efficiency, and HVAC heating performance—and four evaluation indicators, as shown in Table 3.

Table 3. This table represents the evaluation system for assessing the cold-weather adaptability of BEVs.

No.	Test Dimension	Evaluation Indicator
1	Driving range	Driving range decline rate in cold environments
2	Charging efficiency	Charging time per 100 km
3	HVAC heating	Heating duration
4		Heating energy consumption per unit volume of the passenger compartment

4. Evaluation Results and Discussion

To evaluate the assessment system for the adaptability of BEVs in extremely cold environments proposed in this study and to study vehicle performance under real-world road conditions, this study selected 10 mainstream BEVs launched in the Chinese market between 2023 and 2024 as test subjects. From 16 to 23 December 2024, in Heihe City, Heilongjiang Province, China, all 10 BEVs were tested according to a testing protocol covering three dimensions: driving range, charging efficiency, and HVAC heating performance. Figure 9 shows the distribution of ambient temperatures during the testing period, and data analysis and evaluation were conducted based on the test results.

To facilitate the analysis of performance differences among the various vehicles, this study assigns anonymous codes ranging from 1 to 10 to the 10 vehicles under test. The curb weight, test weight, payload capacity, battery capacity, and battery type of the vehicles under test are shown in Table 4. From the perspective of battery chemistry, the 10 BEVs tested were equipped with lithium iron phosphate (LFP) batteries and ternary lithium-ion batteries. Low-temperature environments cause the viscosity of lithium-ion battery electrolytes to increase, ionic diffusion to decrease, polarization-induced internal resistance to rise, and available capacity to decline, thereby affecting vehicle range and fast-charging performance. Different battery chemistries exhibit varying sensitivities to local temperature changes; specifically, the rate capability and available capacity of LFP batteries at low temperatures are typically more susceptible to temperature fluctuations, while ternary lithium-ion batteries also experience increased internal resistance and reduced charge acceptance at low temperatures. At the same time, the battery pack's thermal insulation structure, thermal management strategies, preheating logic, and sensor placement at the vehicle level can alter the local temperature distribution of the battery cells, thereby further affecting low-temperature performance. Therefore, this study interprets the differences in range degradation rates and low-temperature fast-charging performance among various vehicles as the result of the combined effects of battery chemistry, battery pack thermal

management, vehicle-level energy management, and HVAC strategies, rather than the result of a single battery material factor.

Table 4. Key specifications of 10 test vehicles.

Vehicle No.	Curb Weight (kg)	Test Mass (kg)	Payload Mass (kg)	Battery Capacity (kWh)	Battery Type (-)
1	2150	2291	141	75	Lithium Iron Phosphate
2	2130	2300	170	75	Lithium Iron Phosphate
3	2355	2501	146	100	Ternary Lithium-Ion Batteries
4	2122	2277	155	84.8	Ternary Lithium-Ion Batteries
5	1911	2057	146	60	Lithium Iron Phosphate
6	2210	2361	151	71.4	Lithium Iron Phosphate
7	2090	2243	153	94.3	Lithium Iron Phosphate
8	2230	2383	153	78.2	Lithium Iron Phosphate
9	2224	2396	172	79.05	Ternary Lithium-Ion Batteries
10	2379	2542	163	100	Ternary Lithium-Ion Batteries

4.1. Driving Range Evaluation

Figure 13 shows the range degradation rates of 10 BEVs in a frigid environment. Combined with the data in Figure 9, it can be observed that the average temperature throughout the testing period was $-20.4\text{ }^{\circ}\text{C}$, meeting the environmental temperature boundary conditions designed in this study. The range degradation rates of the 10 BEVs in the frigid environment ranged from 55% to 67%, with an average of 60.7%.

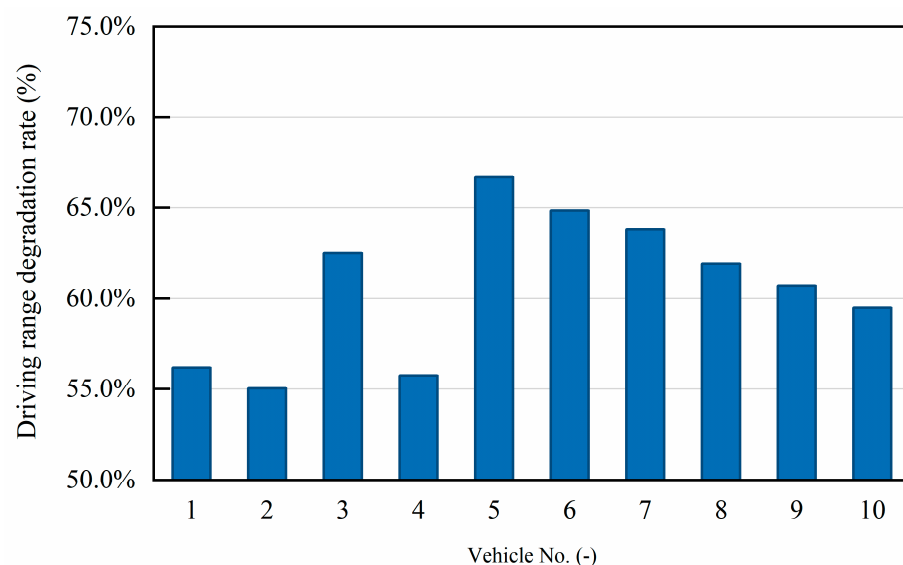


Figure 13. Driving range degradation rates of 10 BEVs.

Figure 14 compares the range degradation rates in extreme cold conditions measured on roads with those from the rotating drum environmental chamber laboratory. Comparing road and laboratory data reveals an average range degradation rate of 40% at $-7\text{ }^{\circ}\text{C}$. This indicates that at $-20\text{ }^{\circ}\text{C}$, despite a 17% increase in air resistance relative to ambient temperatures and significantly higher internal resistance and heating demands compared to $-7\text{ }^{\circ}\text{C}$ conditions, current BEVs demonstrate relatively favorable range decay performance.

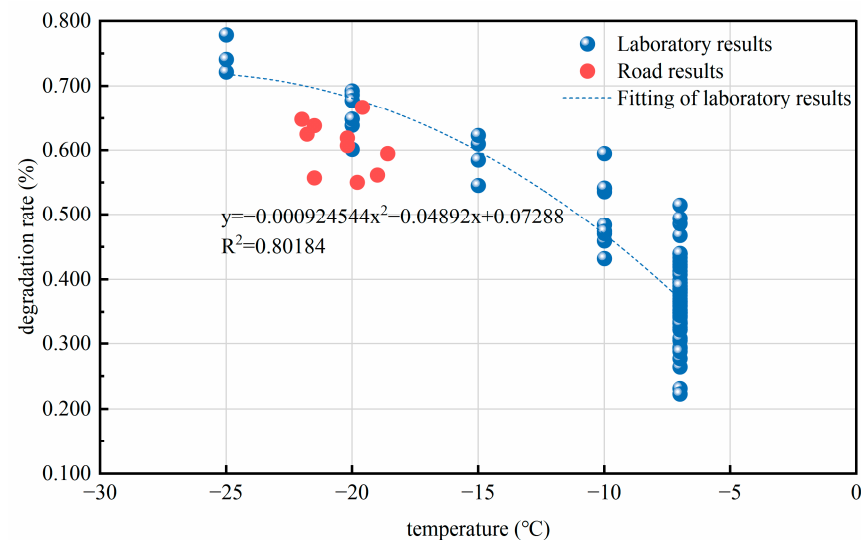


Figure 14. Comparison of range decay rates between road and laboratory conditions.

It is worth noting that Figure 15 shows the relative proportions of energy consumption by the HVAC heating system and non-HVAC systems throughout the entire driving range test. The HVAC heating energy share of the 10 vehicles ranged from 17% to 51%, indicating significant differences among the models in terms of cabin heating requirements, HVAC system configurations, and thermal management strategies.

It should be noted that the HVAC heating energy consumption is a relative metric and is not equivalent to the absolute HVAC heating energy consumption. A higher HVAC heating energy share may result either from greater HVAC heating energy consumption or from relatively lower energy consumption by the propulsion system and other non-HVAC systems. Therefore, there is no simple one-to-one correlation between the proportion of heating energy consumption and the range degradation rate.

All other things being equal, an increase in heating energy consumption reduces the amount of electrical energy available for vehicle propulsion, which may exacerbate range degradation; however, when comparing different vehicle models, the heating energy consumption percentage alone is insufficient to draw a single-factor causal conclusion regarding the range degradation rate.

4.2. Charging Efficiency Evaluation

Figure 16 shows the converted charging time per 100 km. It reveals that the charging times for the 10 models range from 20 to 170 min, exhibiting significant variation. However, 60% of the vehicles have a charging time per 100 km of less than 30 min, which is a relatively good performance. Figure 17 illustrates the charging power per unit time, reflecting the charging rate. The average charging rate for the 10 models is 1.03 kWh/min, with some models exceeding 1.6 kWh/min. Figures 13 and 14 reveal that after 12 h of immersion in a $-20\text{ }^{\circ}\text{C}$ to $-30\text{ }^{\circ}\text{C}$ extreme cold environment, influenced by battery insulation and heating strategies, some vehicles exhibited lower initial charging power requests, limiting their charging rate potential. This indicates that users in frigid climates should avoid immediately charging vehicles after they have frozen outdoors during actual usage.

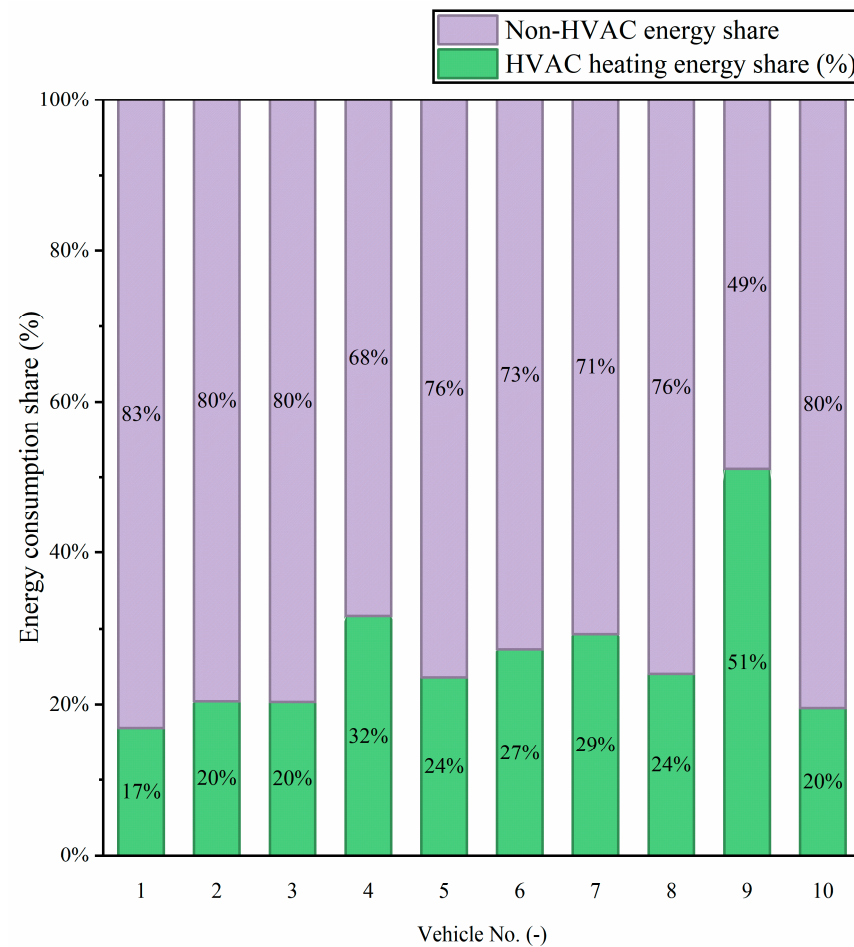


Figure 15. Energy consumption shares of the HVAC heating system and non-HVAC systems over the complete driving range tests of the 10 BEVs.

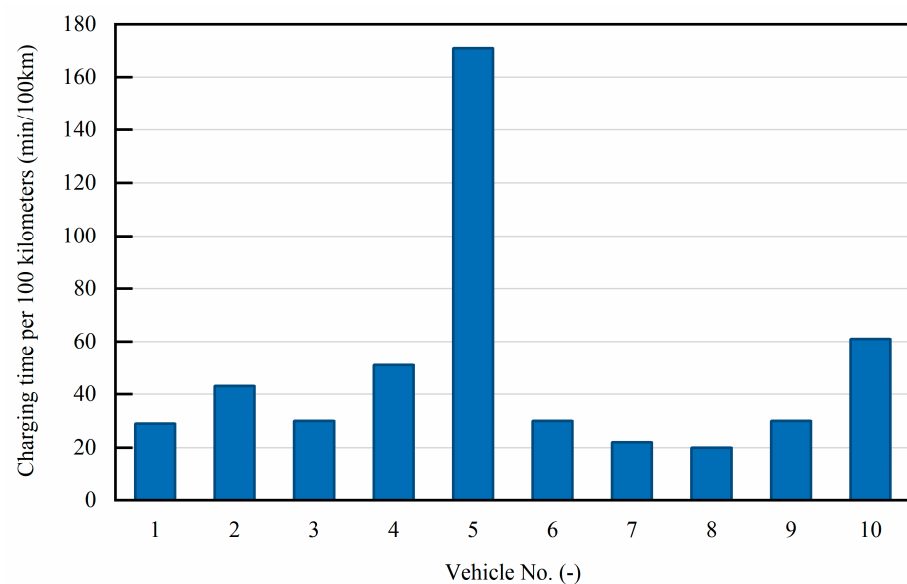


Figure 16. Charging time per 100 km of 10 BEVs.

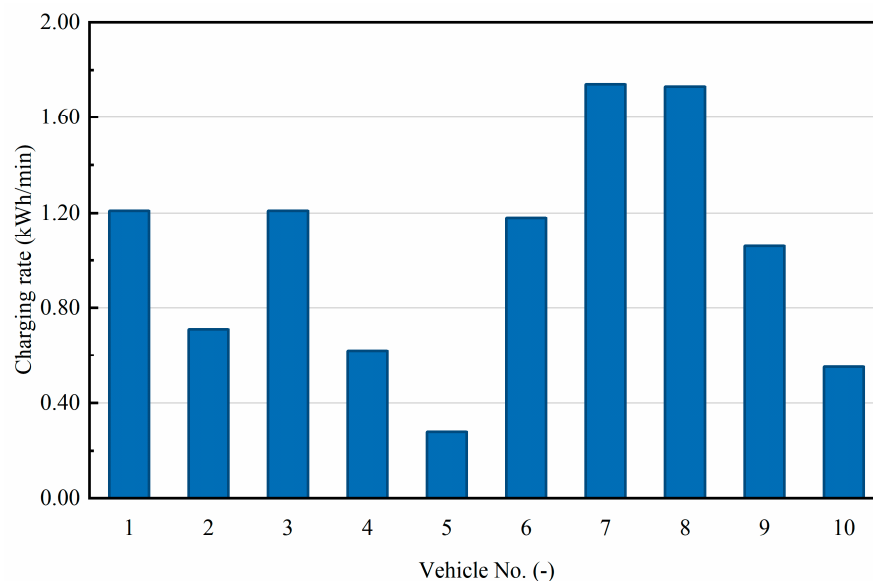


Figure 17. Charging power per unit time of 10 BEVs.

4.3. HVAC Evaluation

Figure 18 shows the time from the start of the HVAC heating test until the average temperature at the foot measurement point first reaches 21 °C for 10 vehicle models. This duration characterizes the maximum heating capability of the HVAC system. It can be seen that the time taken for the foot measurement point to reach 21 °C ranges from 21 to 72 min, with an average of 34 min. This indicates that the HVAC heating rate of current BEVs remains relatively slow in the harsh cold environment of −20 °C.

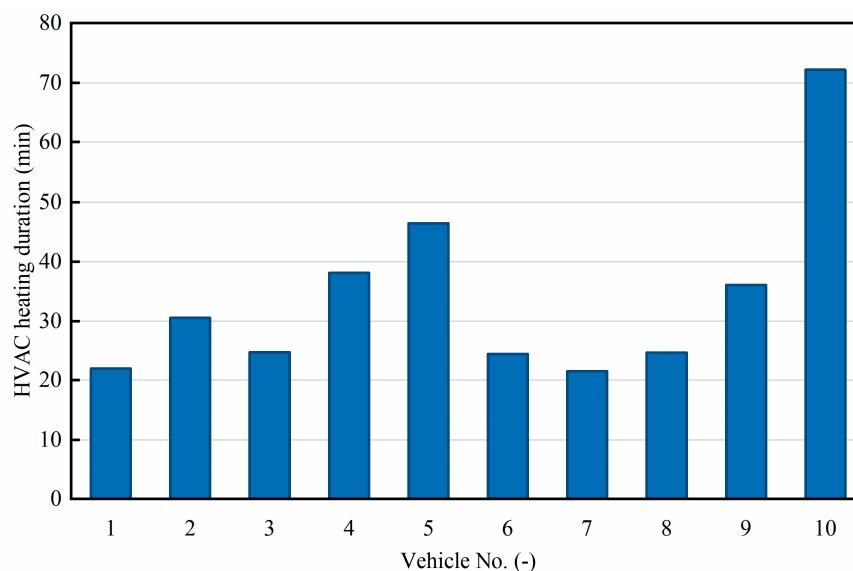


Figure 18. HVAC heating durations of the 10 BEVs.

Figure 19 shows the HVAC heating energy consumption of the 10 BEVs. The total electrical energy consumed by the HVAC system ranges from 5.4 kWh to 18 kWh, with an average of 9.2 kWh. This value represents approximately 10% to 25% of the power battery capacity, highlighting the substantial HVAC heating energy demand of BEVs in winter. The average energy consumption per unit volume of the passenger compartment is 2.6 kWh/m³.

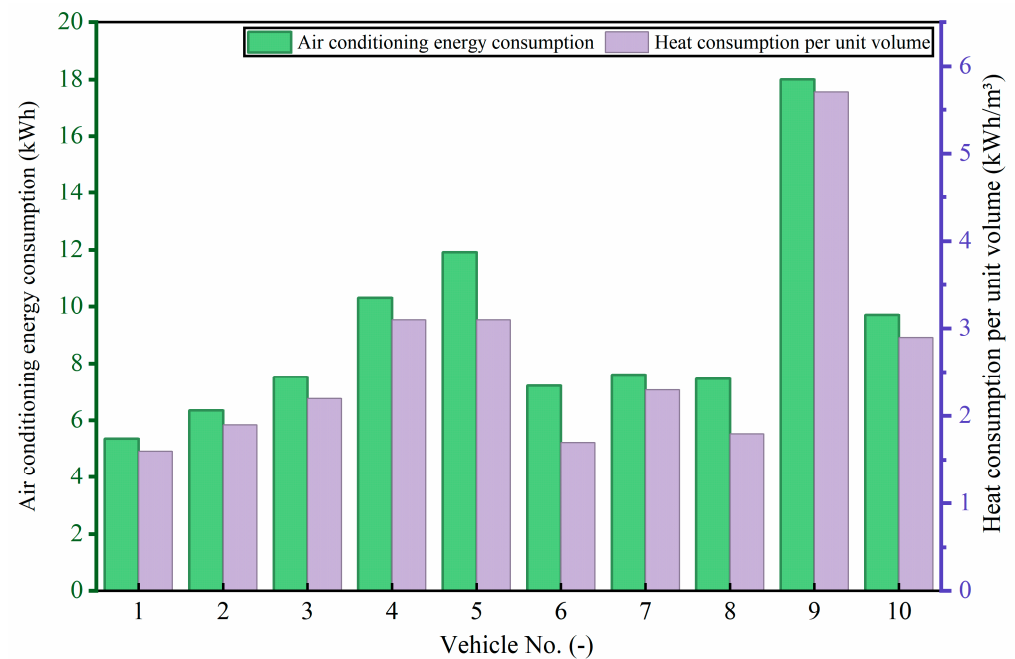


Figure 19. HVAC heating power consumption of the 10 BEVs.

Figure 20 presents the energy flow distribution during the HVAC heating process. The passenger compartment PTC heater accounts for the largest share of energy consumption, indicating that cabin HVAC heating is prioritized over battery heating. Additionally, Model 5's energy consumption performance indicates that heat pump HVAC systems exhibit limited heating performance in extreme cold environments below $-20\text{ }^{\circ}\text{C}$. Among the 10 models tested, the mainstream HVAC configurations remain PTC heating and combined PTC–heat pump systems.

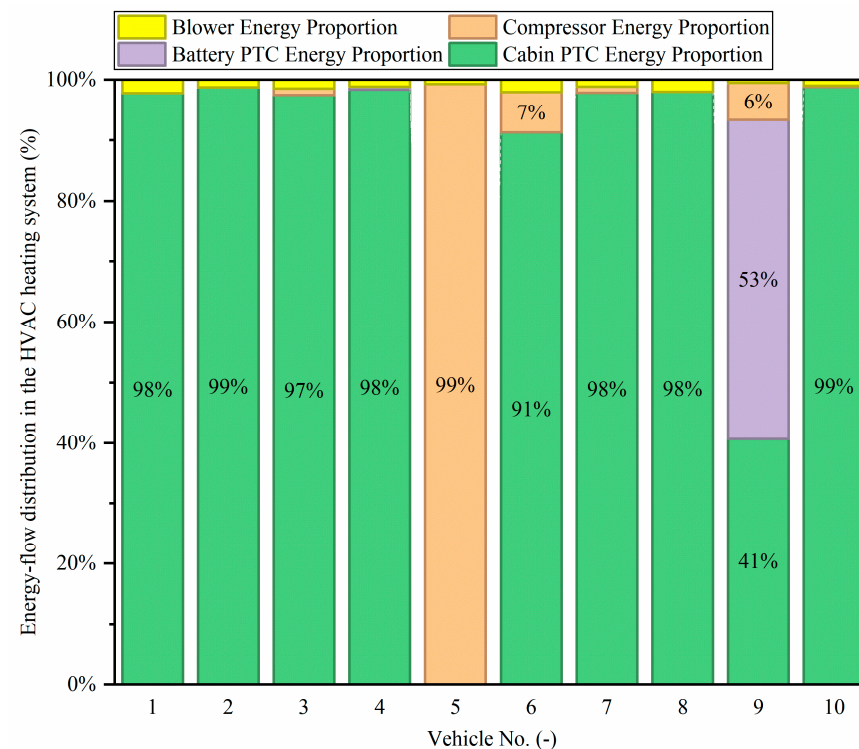


Figure 20. Energy flow distribution during the HVAC heating process of the 10 BEVs.

It is worth noting that, as shown in Figure 21, the temperature rise curves at the left and right foot temperature measurement points differ significantly for some vehicle models. This discrepancy will further lower the average temperature at the foot measurement points, increasing the HVAC heating load and the associated energy consumption. Additionally, the inconsistency in foot temperature measurement points will significantly impact occupant thermal comfort.

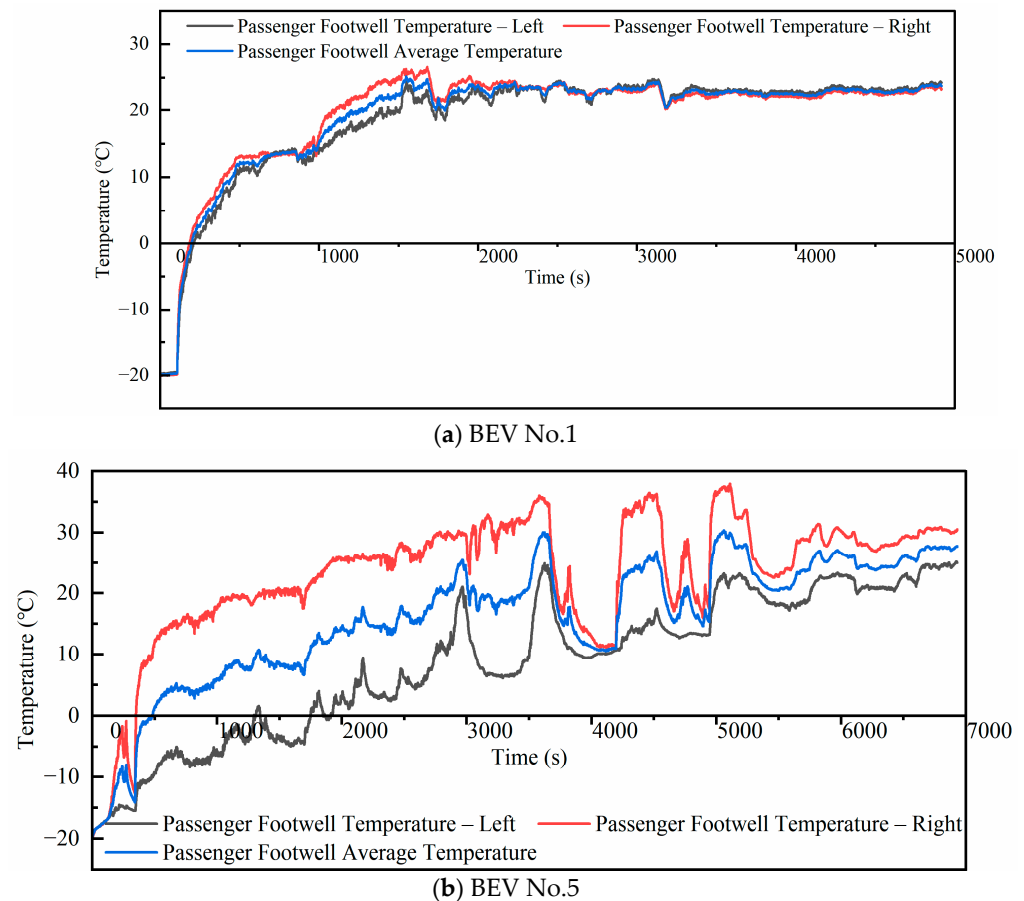


Figure 21. The Consistency of Foot Temperature Measurement Points During the Heating Process. (a) The consistency of the foot temperature measurement points for BEV No. 1 during the heating process. (b) Significant variations in the foot temperature measurement points for BEV No. 5 during the heating process.

5. Conclusions and Outlook

This study conducts a real-road test evaluation study on the cold-weather adaptability of BEVs, defining environmental temperature, driving conditions, and road test consistency assurance criteria for road testing. A testing and evaluation framework was developed with three dimensions—driving range, charging efficiency, and HVAC heating performance—and four metrics: range degradation rate, charging time per 100 km, HVAC heating duration, and HVAC heating energy consumption per unit cabin volume. This plan simulates real-world driving and energy replenishment scenarios. The feasibility of the cold-weather evaluation plan was validated through testing on 10 vehicle models in Heihe City, providing a baseline understanding of current vehicle performance in extreme cold conditions.

The evaluation results indicate that range performance and charging efficiency in extreme cold environments remain relatively strong, reflecting domestic manufacturers' recent efforts to address "range anxiety," "charging anxiety," and environmental resilience. However, for BEVs currently operating in $-20\text{ }^{\circ}\text{C}$ environments, PTC heating systems remain necessary. Single-heat-pump HVAC systems still have significant room for improvement in heating time, efficiency, and thermal comfort under such extreme conditions.

The uniformity of cabin temperature distribution warrants attention, particularly in areas such as air vent placement, duct flow direction, and cabin airflow design. Industry focus on these aspects is essential to ensure consistent foot temperature on both sides and enhance thermal comfort in the footwell.

This study still has certain limitations, and future research will further strengthen quantitative comparisons with existing standard protocols, established testing methods, and results from the literature. On the one hand, the real-world road test results from this study can be compared with low-temperature testing methods specified in standards such as GB/T 18386.1-2021 to analyze differences in driving range, energy consumption, and HVAC heating performance between real-world road conditions and standard test conditions. On the other hand, by integrating results from chassis dynamometer environmental chamber tests, we can further compare the effects of test bench and real-world road testing on test results in terms of rolling resistance, road adhesion conditions, changes in aerodynamic drag, and driving follow-up errors. Furthermore, future work could expand the number of vehicle models tested, include samples with different temperature gradients and thermal management system configurations, and conduct systematic comparisons with the existing literature on low-temperature range, low-temperature fast charging, and HVAC heating energy consumption results. This would further validate the universality, applicability limits, and engineering value of the evaluation system presented in this study.

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Conflicts of Interest: Authors Peng Wang, Xiaona He, Ming Liu, Guoqiang Tang, Qianlu Zhou and Zaiqiang Meng were employed by the China Automotive Engineering Research Institute Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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