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Analysis of the Characteristics of Hybrid Vehicles and Low-Viscosity Lubricating Oil Based on Real Road Tests in Four Extreme Environments

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Abstract

As countries around the world attach more importance to carbon emissions and more stringent requirements are put forward for vehicle emissions, hybrid vehicles, which can significantly reduce emissions compared with traditional fuel vehicles, as well as low-viscosity lubricating oil, have become significant trends in the industry.

In this article, a total of nine vehicles of 48 V mild-hybrid models and full-hybrid models are tested. Using three kinds of low-viscosity lubricating oil and driving a total of 120,000 km in environments with low temperature, high humidity, high temperature, or high altitude, the engines are then disassembled and scored. The effects of the four extreme environments on the engine starts–stops, ignition advance angle, engine power, state of charge (SOC), acceleration performance, and oil consumption characteristics of hybrid vehicles are studied; the oxidation characteristics and iron content change characteristics of low-viscosity lubricating oil are analyzed; and how lubricating oil protects the engine in durability tests are verified.

According to the test results, in the low-temperature environment, for full-hybrid models, the number of engine starts–stops and the running time are significantly increased, while the SOC is generally high. In the high-temperature environment, for full-hybrid models, the ignition advance angle of the engine is reduced, which inhibits the risk of pre-ignition; the characteristics of the SOC are similar to those in the high-humidity and standard-temperature WLTC working conditions; the oxidation rate of lubricating oil has almost no effect on full-hybrid models; for mild-hybrid models, oil is prone to oxidation and decay. In the high-humidity environment, the oil consumption rate deteriorates with the increase in relative humidity under the same load and engine speed, and the accumulation rate of iron content in oil increases compared with that in the high-temperature and high-altitude environments. In the high-altitude environment, with the increase in altitude, the engine power of full-hybrid models decreases at the same engine speed, resulting in a decrease in the engine's charging efficiency to the battery, so that the battery level could not be relatively stable. The acceleration performance of both hybrid models decreases significantly with an increase in altitude. After the engines are disassembled, it is found out that with the protection of low-viscosity lubricating oil, the wear of engine parts is very small, and the deposit control is good.

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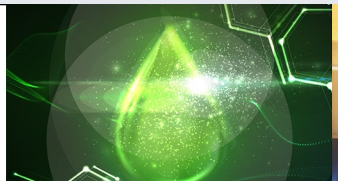
Hybrid vehicles, Low-viscosity lubricating oil, Real road tests, Extreme environments

Citation

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1. Background

Reducing greenhouse gas emissions such as CO_2 and slowing down the rise of global temperatures have become the common goals of all humankind. Europe's CO_2 emissions have begun to decline, and it has pledged to reduce its net CO_2 emissions by more than 55% by 2030 compared to 2020 and achieve carbon neutrality by 2050 [1]. In 2020, China also pledged to increase its nationally determined contributions, adopt stronger policies and measures, and strive to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060 [2].

According to the International Energy Agency, about 24% of the world's CO_2 emissions come from oil consumption in the transport sector, and about 75% of CO_2 emissions are generated by road transport [3]. In hybrid vehicles, batteries and internal combustion engines provide solutions for pollution-free ecosystems and effectively limit the extraction of natural assets [4], which fully leverage the advantages of electric and thermal systems and perform well in terms of power, energy efficiency, and emissions.

With the progress of automobile manufacturing technology, the processing technology of engine parts is improving, the fit clearance is getting smaller, and the viscosity of engine oil is expected to be lower. As synthetic oil technology develops, low-viscosity lubricating oil will be the trend. It has better fluidity, can quickly reach the surface of parts, fully lubricate the engine [5], reduce engine running resistance and oil consumption, and cut emissions [6]. Yet it faces the risk of component wear due to insufficient oil film thickness, as well as consuming more machine oil and the low adaptability at high engine speeds in long-term operation [7]. Therefore, the real performance of low-viscosity lubricating oil in hybrid vehicles and various test environments is very important.

Real road testing is of great significance in the R&D and manufacturing of automobiles and lubricating oil because researchers can understand the real performance of vehicles and oil in different environments. Compared with laboratory tests, real road tests can better simulate driving conditions, road surfaces, and climatic conditions [8]. They also meet the needs and expectations of consumers, since consumers can understand the performance and reliability of vehicles and oil on real roads in a straightforward manner [9].

In this article, nine vehicles (two hybrid models), using three types of low-viscosity lubricating oil, drive a total of 120,000 km in four environments. Data on hybrid vehicles and lubricating oil are collected for analysis. Afterward, engine wear and deposits in vehicles using low-viscosity lubricating oil are scored. The purpose is to analyze the effects of different environments on hybrid vehicles, low-viscosity lubricating oil, and the protection of low-viscosity lubricating oil on hybrid engines.

2. Test Method

2.1. Test Vehicles

Two types of hybrid vehicles are selected: 48 V mild hybrids and full hybrids. A total of nine vehicles are tested. See Table 1 for details. It is worth noting that the fully hybrid Toyota RAV4 is not a plug-in-hybrid (PHEV) model and cannot charge the battery.

2.2. Test Lubricating Oil

Three types of low-viscosity lubricating oil are selected. The lubricating oil used in each vehicle are shown in Table 2.

2.3. Test Environments

After running 2000 km in the preliminary stage, tests are done in four extreme environments (low-temperature, high-humidity, high-temperature, and high-altitude). The mileage of 30,000 km in each environment makes the total 120,000 km. See Figure 1 for locations and Table 3 for test conditions.

TABLE 1 Test vehicles.

Vehicle number	V1	V2	V3	V4	V5	V6	V7	V8	V9
Vehicle brands	Mercedes Benz C260L						Toyota RAV4		
Hybrid type	48-V mild hybrid						Full hybrid		
Engine displacement	1.5 L						2.5 L		
Air intake method	Turbocharged						Naturally aspirated		
Number of cylinders and arrangement	L4						L4		
Gearbox	9AT						E-CVT		
Maximum engine power	135 kW						131 kW		
Maximum motor power	—						88 kW		
Battery information	—						6.5 Ah (1.4 kWh)		

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TABLE 2 Test lubricating oil.

Vehicle number	V1	V2	V3	V4	V5	V6	V7	V8	V9
Oil name	A			B			C		
Oil viscosity	0 W-20			0 W-20			0 W-16		
API	SP			SN			SP		
Oil change interval	15,000 km			15,000 km	30,000 km		15,000 km		

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2.4. Road Test Design

About 20 vehicle driving data points are collected, such as vehicle speed, engine speed, engine oil temperature, etc. Besides, meteorological data equipment is installed on the roof of some vehicles to collect atmospheric temperature, atmospheric humidity, atmospheric pressure, oxygen content, and the like. In order to avoid the wear of a certain vehicle and the bias of the data due to the driver's driving habits, the drivers of the nine vehicles are rotated every 5000 km so that the driving conditions of the nine vehicles are basically similar.

To make it as real as possible in the 30,000 km endurance test in each environment, we refer to the ratio of low-speed and medium-speed sections to high-speed and ultra-high-speed sections in the WLTC working conditions and make the ratio between urban roads and expressways 3:7. Efforts are also made to keep the road conditions similar in each region. The average speed of urban road conditions is 30 km/h, and the average speed of expressways conditions is 80 km/h.

2.5. Accelerated Power Test Method

To test the power performance of the vehicles, 0–100 km/h acceleration power tests are carried out in different

FIGURE 1 Test locations.



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TABLE 3 Conditions in four extreme environments.

Extreme environment	Alpine	High humidity	High temperature	High altitude
Average temperature (°C)	−21	30	35	6
Average absolute humidity (g/m^3)	0.8	20.9	8.1	3.6
Average altitude (m)	573	13	120	3035
Extreme temperature (°C)	−38	—	48	—
Extreme absolute humidity (g/m^3)	0.1	24.7	—	—
Extreme altitude (m)	—	—	−88	4731

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altitude environments before and after the oil drain interval. The test process follows the national standard "Test Method of Power Performance in Hybrid Vehicles," as shown in Figure 2. Straight, no-slope paved asphalt roads with sufficient acceleration and braking distance are selected. The test vehicles have the same oil temperature and battery level in each region. The weather is good, and the wind speed is less than 3 m/s. The test is repeated five times with a standard deviation of less than 0.2 s.

2.6. Engine Noise and Vibration Test Method

After leaving V1 and V4 in the low-temperature environment (−19°C and −40°C) for 12 h, a cold-start engine vibration and noise test is carried out. During the test time of 80 s, from cold start to idling, the near-field engine noise, in-car noise, and engine vibration are tested.

2.7. Engine Disassembly Method

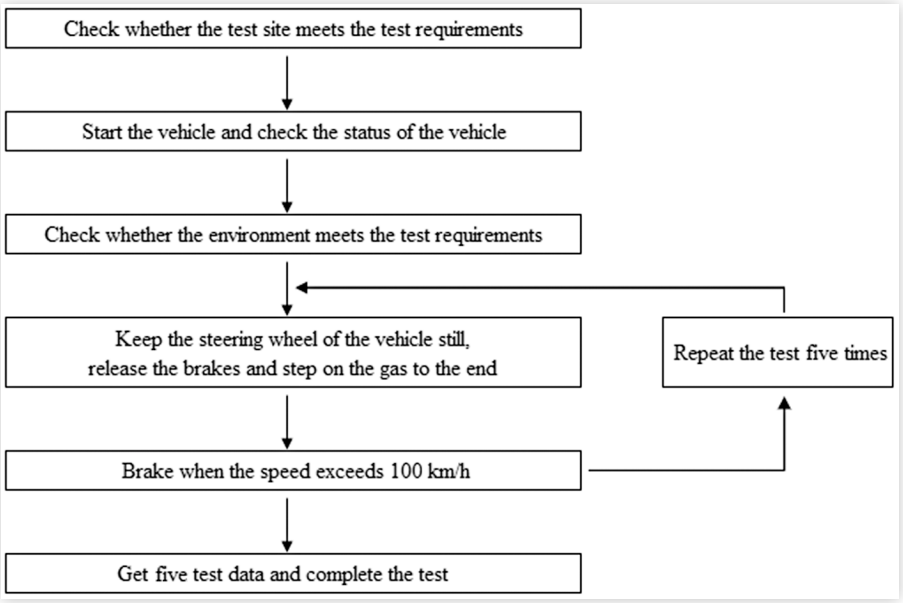
After the completion of the endurance test of 120,000 km in the four extreme environments, the engines of V1, V4, and V7 are disassembled. The dismantling and scoring work invited colleagues who participated in the ASTM International Certification program. He participated in the ASTM/TMC light-duty rating workshop and obtained a certificate. He used methods such as visual observation and contrasting color cards to score the wear status of the main components and the accumulation of deposits. Based on the scoring results of engine parts, the durability test results are finally evaluated to verify the protection of low-viscosity lubricants for hybrid vehicle engines in four extreme environments.

3. Analysis

3.1. Characteristics of Engine Starts–Stops and Ignition Advance Angle of Full-Hybrid Models

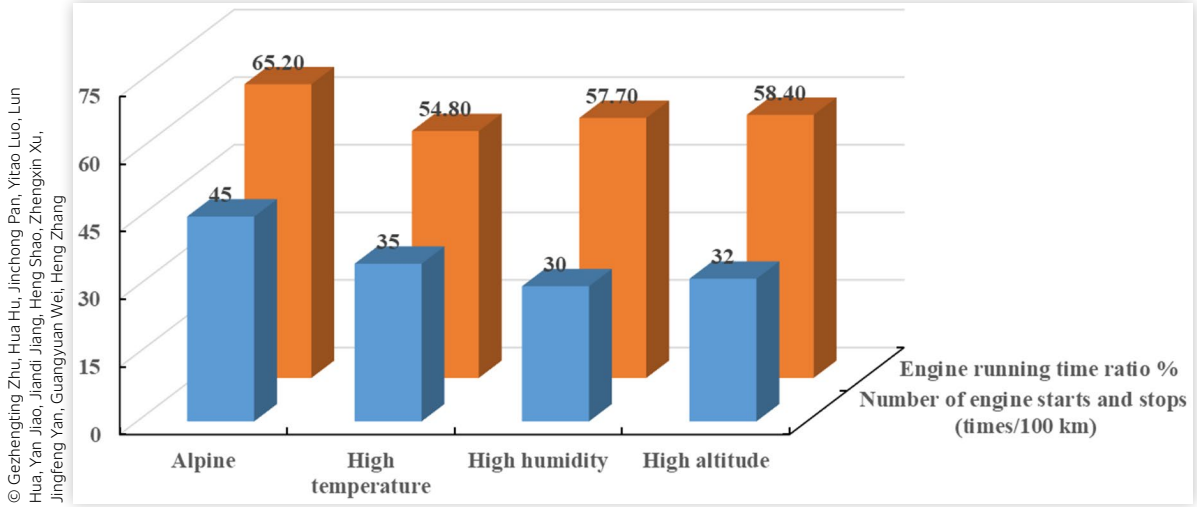
The number of engine starts–stops and the ratio of running time of full-hybrid models in the four extreme

FIGURE 2 Workflow of the accelerated power tests.



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FIGURE 3 The number of engine starts–stops and the ratio of running time of full-hybrid models.

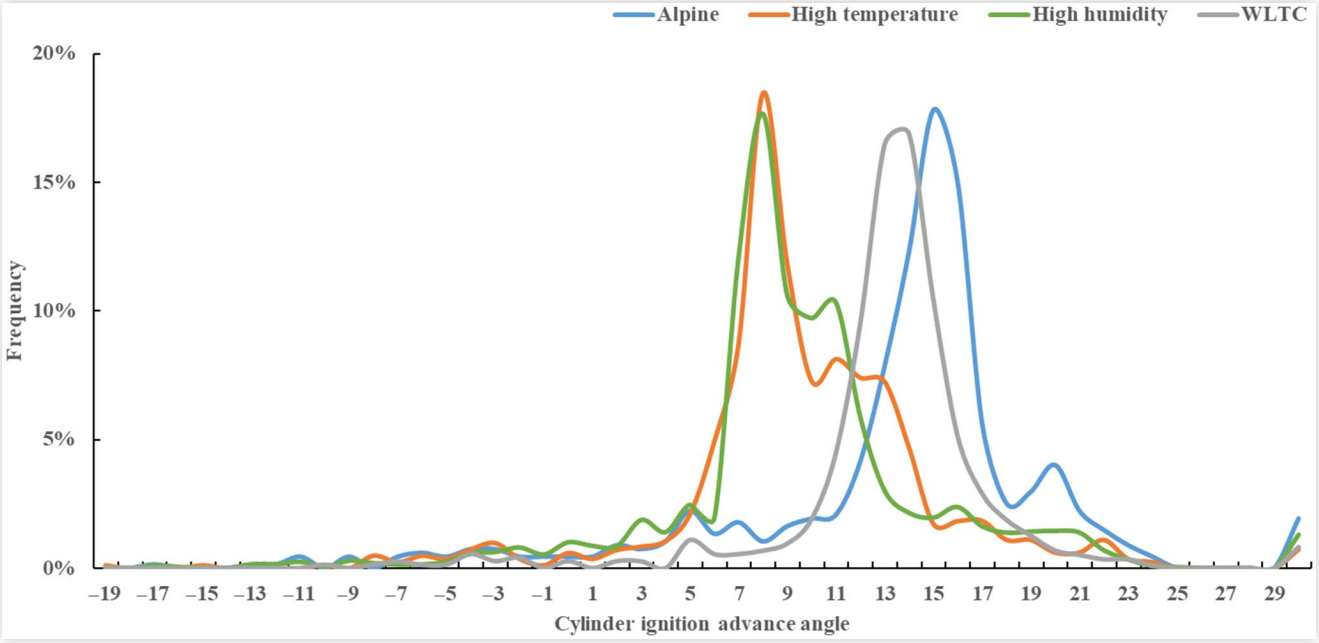


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environments are shown in Figure 3. The engine starts more frequently in the low-temperature environment. Compared with the other three environments, the average number of engine starts increases by 40.6%, and the engine running time increases by 8.2% on average.

In the case of low-temperature, high-humidity, high-temperature, and standard-temperature WLTC working conditions, when the speed of the full-hybrid models is 10–30 km/h, increasing the engine speed to over 2000 rpm will result in the frequency distribution of the ignition advance angle as shown in Figure 4, in which the data of five repeated tests are used for the standard-temperature WLTC working condition. The average temperature of a high-temperature and high-humidity environment is 33°C, and the ignition advance angle is reduced by 7° on average compared with that of a low-temperature environment and by 5° compared with that of a standard-temperature environment. The adjustment of the engine ignition advance angle strategy may be due to the fact that the vehicle is prone to knocks caused by pre-ignition in low-speed and high-load conditions. Although the hybrid vehicle has an electric motor to assist, it faces this risk. When the ambient temperature and intake air temperature increase, the engine tends to

FIGURE 4 The frequency distribution of the ignition advance angle of full-hybrid engines.



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pre-ignite, and the ignition advance angle can be adjusted to suppress pre-ignition so that the engine can work normally within a safe range.

3.2. Engine Power and State of Charge Characteristics of Full-Hybrid Models

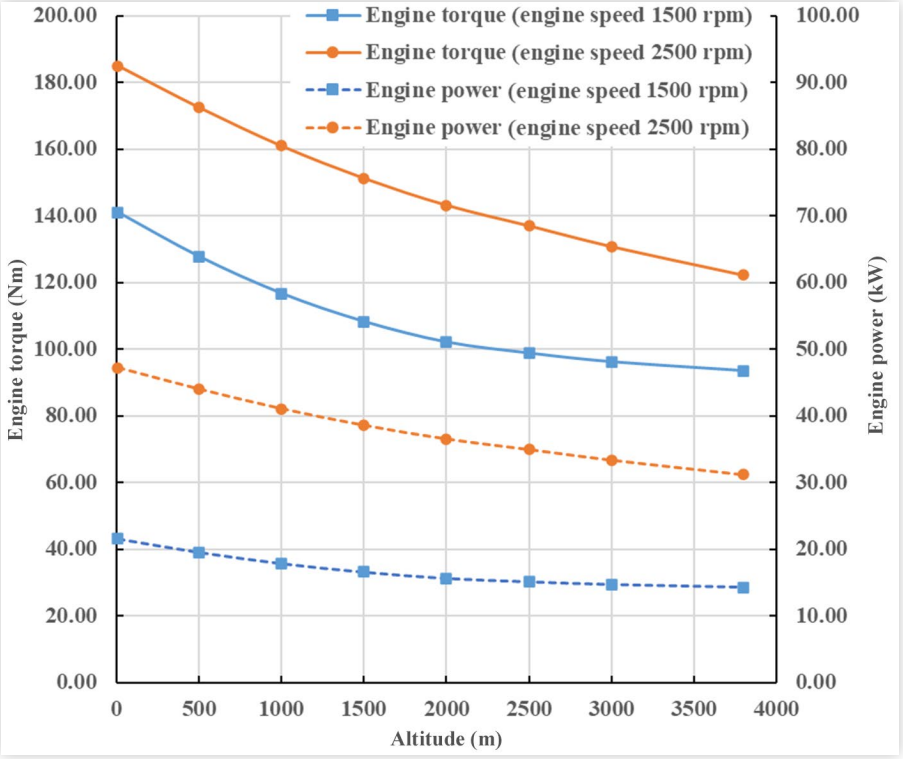
For full-hybrid models, when driving at high speed in stable conditions, set the engine speed at 1500 and 2500 rpm, respectively, to get the engine torque and power at different altitudes, as shown in Figure 5. With the increase in altitude, the engine intake pressure decreases, and the engine power decreases at the same engine speed. The engine power drops by 10% on average as the altitude increases every 1000 m. For the 48 V mild-hybrid models, turbochargers make the torque and power almost unchanged at different altitudes.

The state of charge (SOC) frequency distribution of full-hybrid models in four extreme environments and WLTC working conditions (temperature: 23°C, humidity: 50%, atmospheric pressure: 101 kPa) is shown in Figure 6. In the high-temperature and high-humidity environments, the SOC frequency curve is similar to the curve in WLTC working conditions, and the battery level is generally maintained at about 45%–47%. The charging and discharging characteristics of the battery are similar to those in high-temperature, high-humidity environments and standard-temperature WLTC working conditions. In the low-temperature environment, the battery discharges quickly and charges frequently; in this case, the charging and discharging strategy of the full-hybrid models keeps the battery at a high level, about 68%. In the high-altitude environment, with the increase in altitude, the engine power decreases at the same engine speed, resulting in a decrease in the charging efficiency of the engine of the full-hybrid models, so there is no obvious peak in the SOC frequency curve in the high-altitude environment, and the battery level cannot be relatively stable.

3.3. Vehicle Acceleration Performance and Fuel Consumption Characteristics

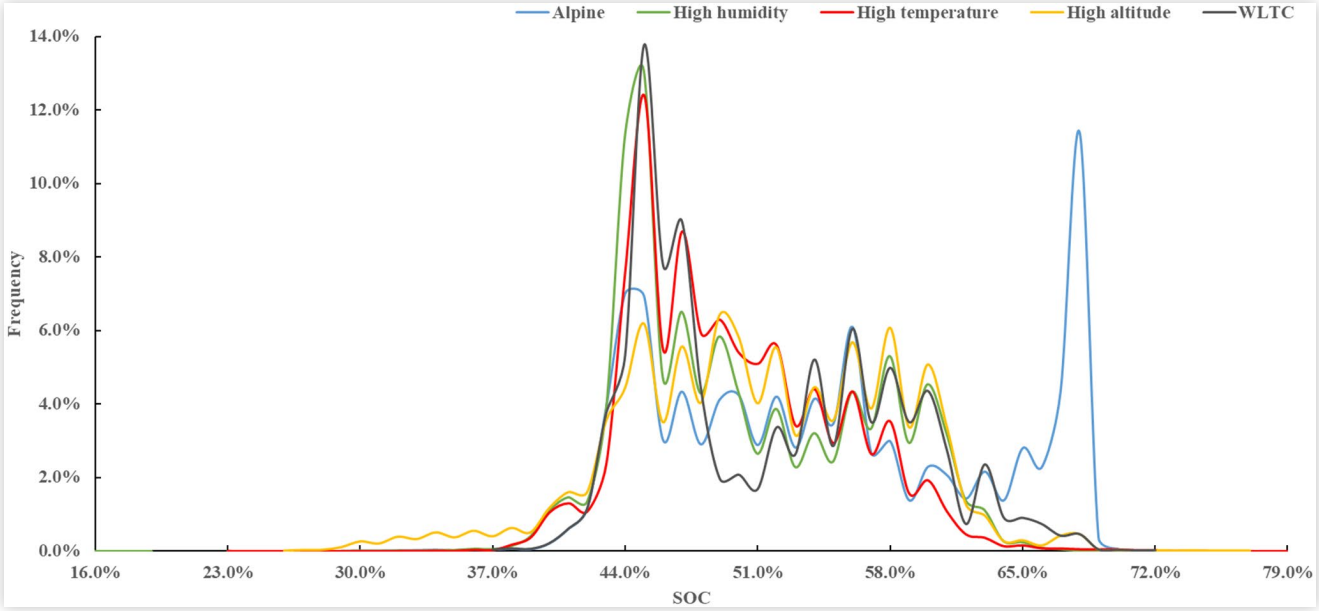
The 0–100 km/h acceleration test results of V1, V3, and V5 at different altitudes are shown in Figure 7. For the same vehicle, the test results of the fresh oil before 15,000 km and the used oil after 15,000 km are similar, indicating that the used oil has almost no effect on the acceleration performance of the vehicle. The acceleration performance of the full-hybrid models and the 48 V mild-hybrid models is similar at the five altitudes, which decreases as altitude increases. The acceleration

FIGURE 5 The relationship between engine torque, power, and altitude in full-hybrid models.



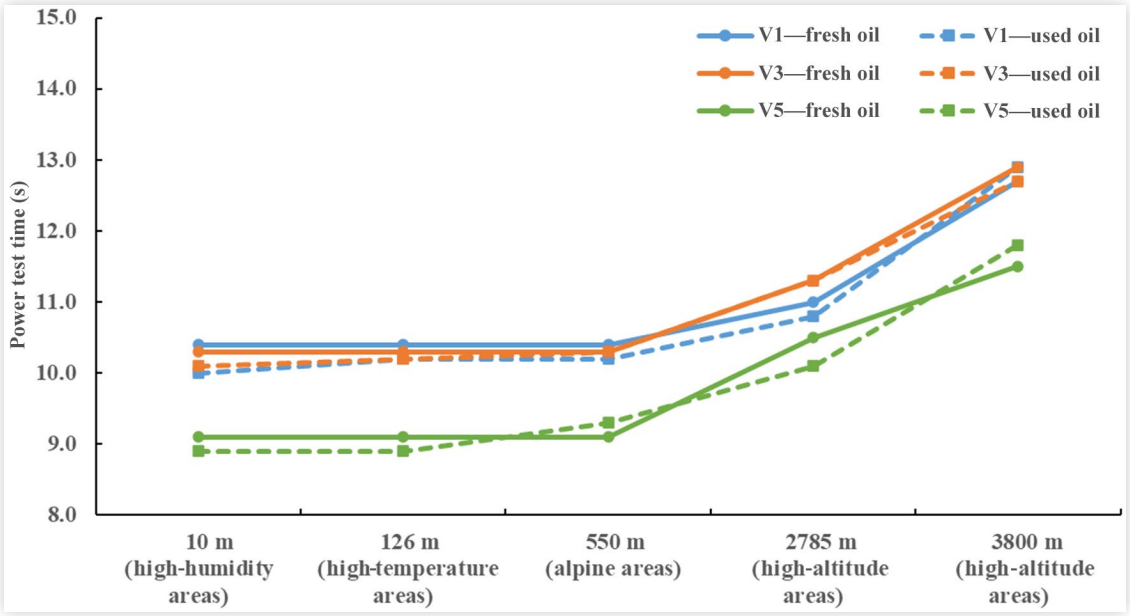
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FIGURE 6 SOC frequency distribution of full-hybrid models.



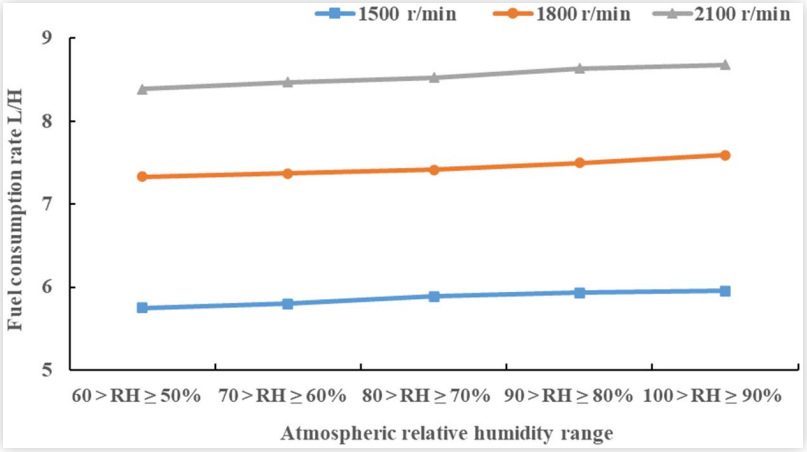
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FIGURE 7 Test results of 0–100 km/h acceleration.



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FIGURE 8 Relationship between fuel consumption rate and relative humidity.



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performance at an altitude of 2785 m is about 10% lower than that at lower altitudes, and the acceleration performance at an altitude of 3800 m is about 15% lower than that at 2785 m and about 26% lower than that at lower altitudes.

There are many influencing factors on fuel consumption in the four test locations, such as air-conditioning settings, road conditions, and the like. The high-humidity environment is analyzed. Taking 48 V mild-hybrid models as an example, when driving at high speed under stable conditions, if the load is the same, the fuel consumption rate changes with humidity at three different engine speeds, as shown in Figure 8. The average ambient temperature is 30°C. With the increase in relative humidity, the fuel consumption rate deteriorates at the same engine speed. If the humidity increases from 50% to more than 90%, the fuel consumption rate of the three engine speeds increases by about 3.5%. The fuel consumption increases by 0.87% at the same load and the same engine speed for every 10% increase in humidity. The deterioration of fuel consumption may be due to the fact that the amount of dry air entering the engine is affected by the water vapor in the intake air, which has an impact on the combustion of the mixture in the cylinder.

3.4. Cold-Start Engine Vibration and Noise Test

Cold start V1 at −19°C and −40°C, the time domain and spectrum of the near-field engine noise are shown in Figure 9, the time domain and spectrum of the in-car noise are shown in Figure 10, and the time domain and spectrum of engine vibration (X and Y directions) are shown in Figure 11. The test results of V4 are similar to those of V1. The first 30 s are generally for the cold start, and the last 50 s are for warming up, where the engine runs relatively steadily. Vehicles successfully start with low-viscosity lubricating oil in the two low-temperature environments. When the engine is cold-started at a low temperature of −40°C, there is a fluctuation in the speed, which causes the vibration of the rotating parts of the engine, and a small amount of fluctuation occurs in the spectrum of the near-field engine noise, the in-car noise, and the engine vibration, which is a normal situation. There is no abnormality in the near-field engine noise or in-car noise. There is no obvious abnormality in the time domain or spectrum. There is no transient broadband knocking or other characteristics in the vibration spectrum.

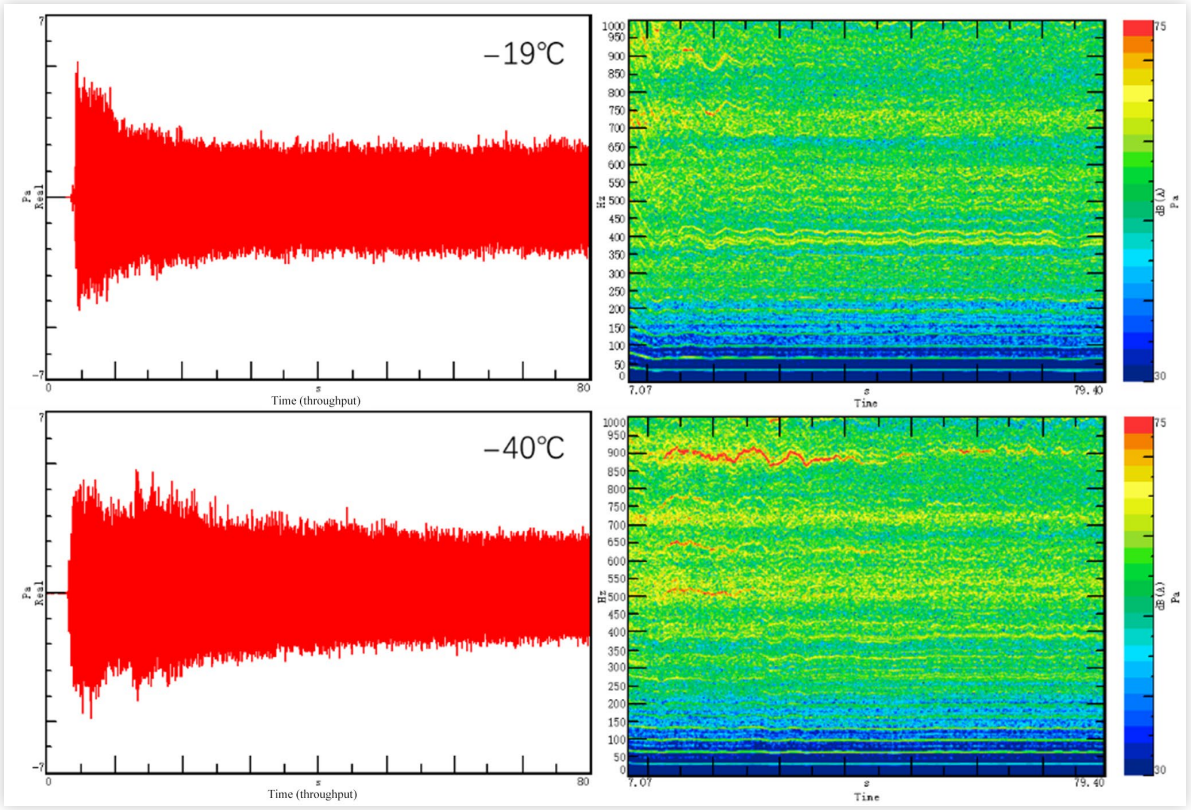
For V1 at −19°C and −40°C, the near-field engine noise and the in-car noise are shown in Figures 12 and 13. The near-field engine noise at −40°C is 87.47 dB, about 4 dB higher than that at −19°C, which is normal in low-temperature starting conditions. The in-car noise at −40°C is 56.41 dB, about 5 dB higher than at −19°C, which is a normal response of the structure as the engine is started at a low temperature, and there is no obvious correlation with low-viscosity lubricating oil.

3.5. Characteristics of Oxidation and Iron Content Change in Low-Viscosity Lubricating Oil

In the low- and high-temperature environments, as the endurance mileage increases, the lubricating oil (A, B, and C) are oxidized, as shown in Figure 14. The oxidation value of lubricating oil was tested by ASTM E2412-18 *Standard Practice for Condition Monitoring of In-Service Lubricants by Trend Analysis Using Fourier Transform Infrared (FT-IR) Spectrometry*.

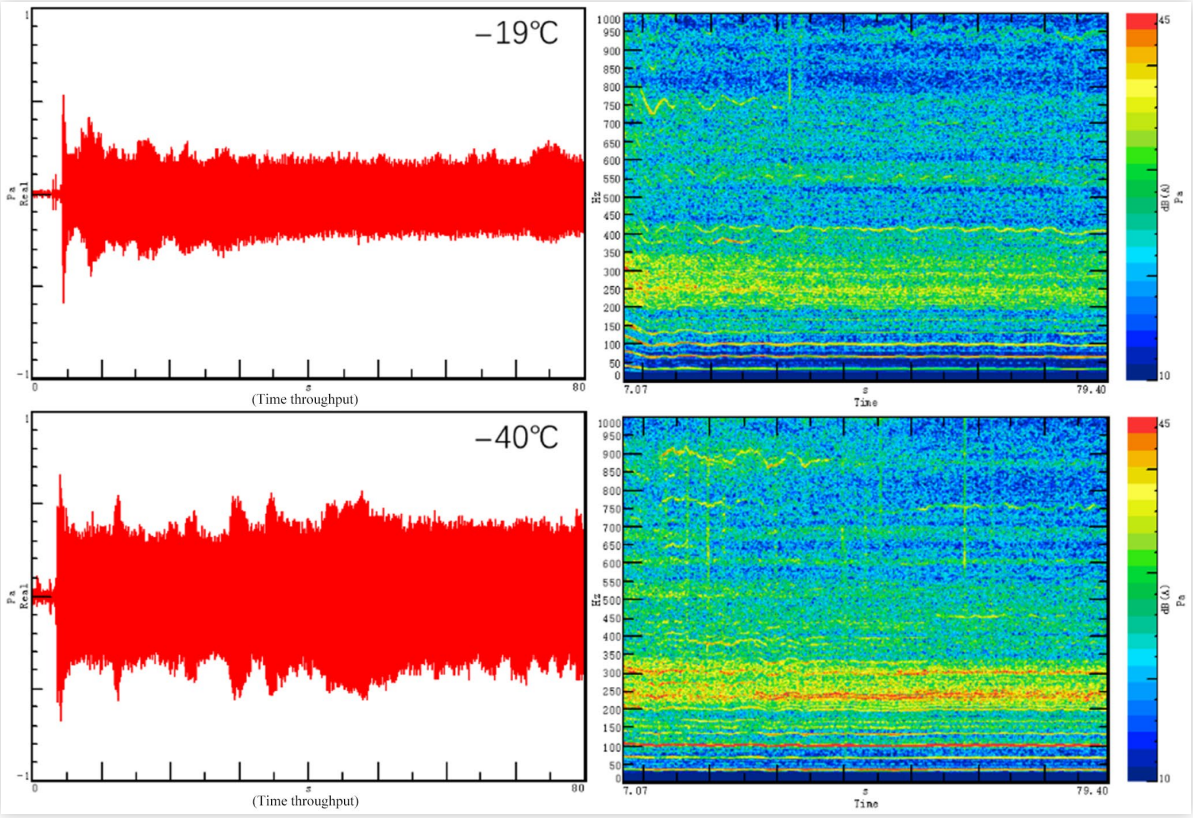
Compared with a low-temperature environment, the average oil temperature of A and B in the high-temperature environment is 11°C higher, and the oxidation rate of the oil is about 57% faster. B has a long oil drain interval (LODI), and its oxidation rate is similar to that of the short oil drain interval, indicating that the ambient temperature

FIGURE 9 Time domain and spectrum of the near-field engine noise.



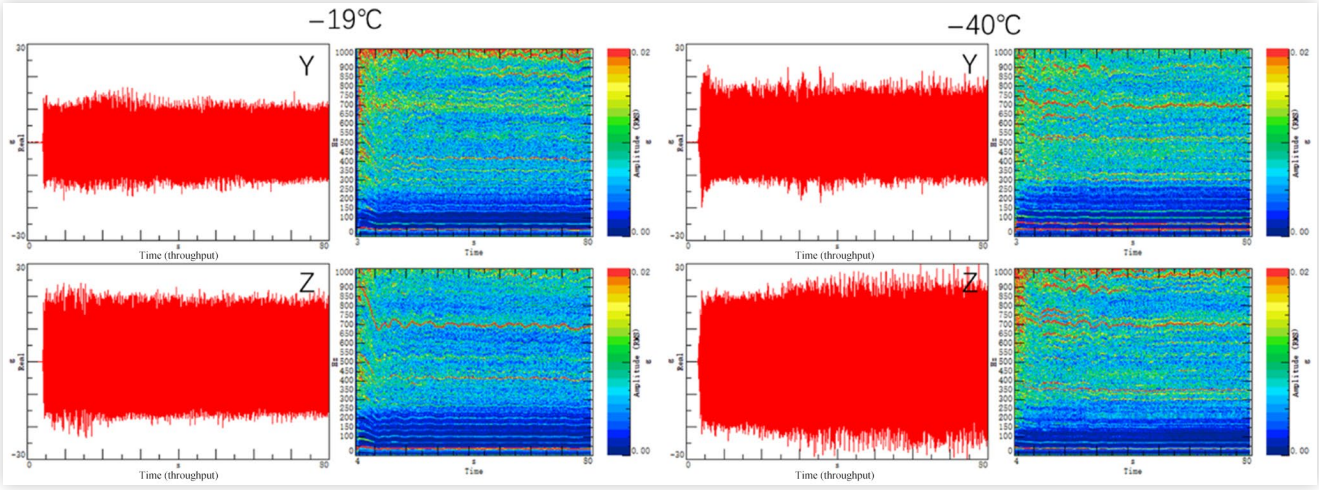
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FIGURE 10 Time domain and spectrum of the in-car noise.



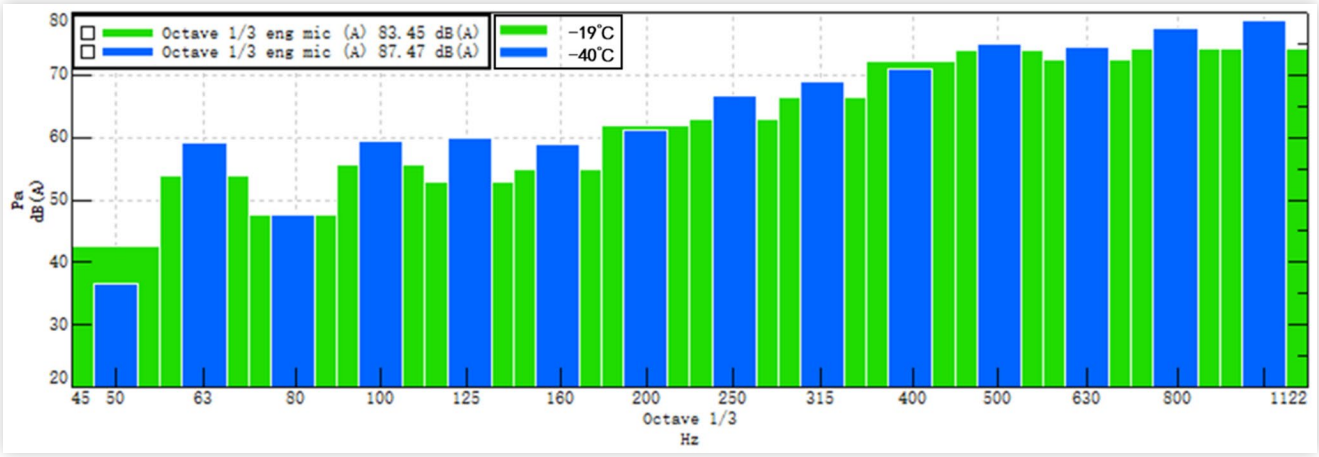
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FIGURE 11 Time domain and spectrum of the engine vibration.



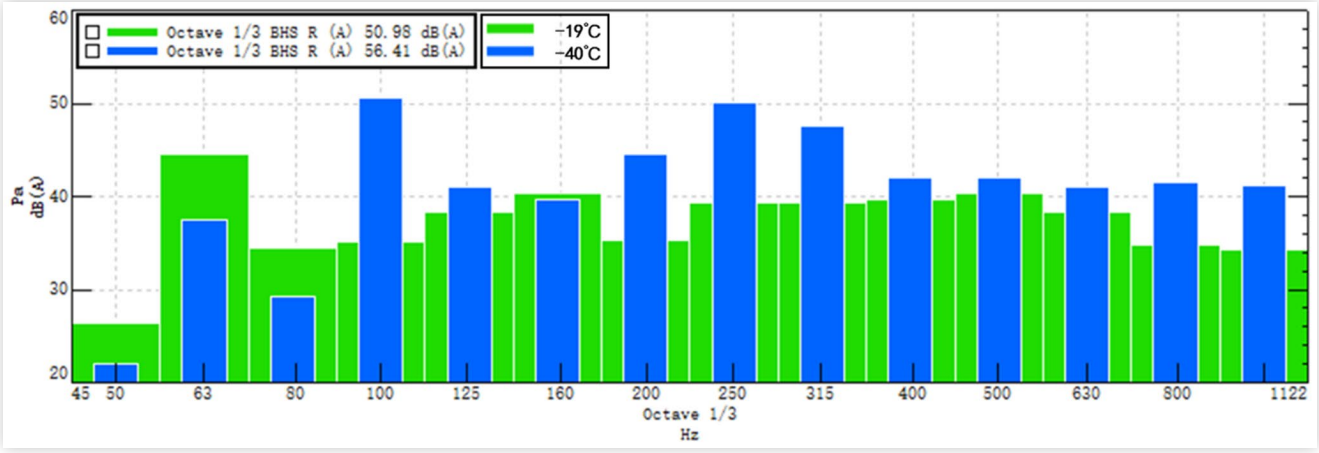
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FIGURE 12 Near-field engine noise.



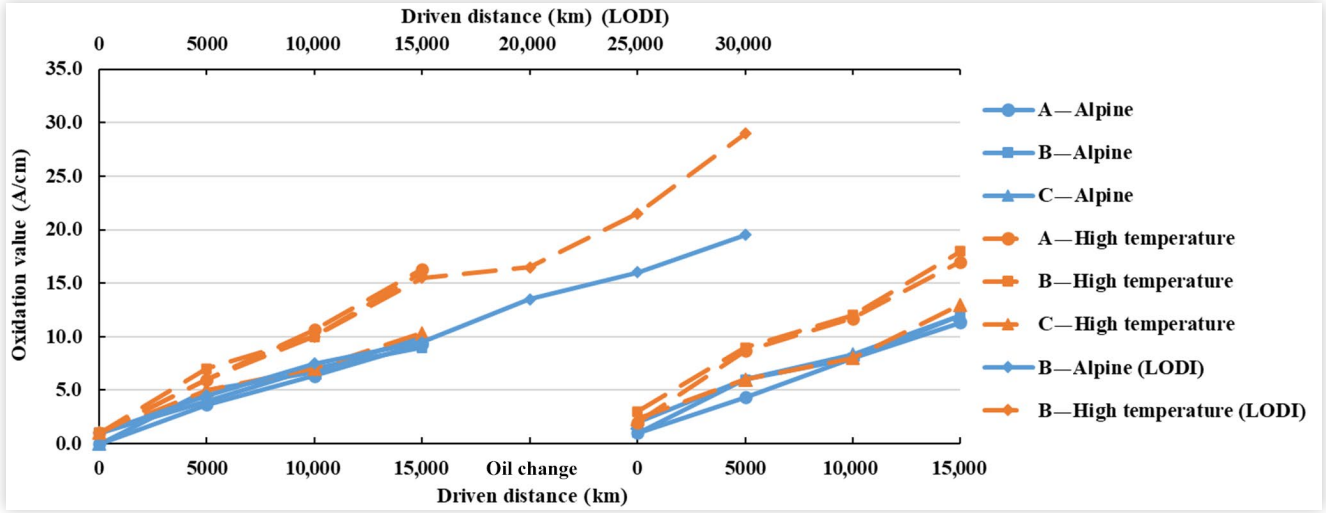
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FIGURE 13 In-car noise.



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FIGURE 14 Test results of the oxidation value of lubricating oil.



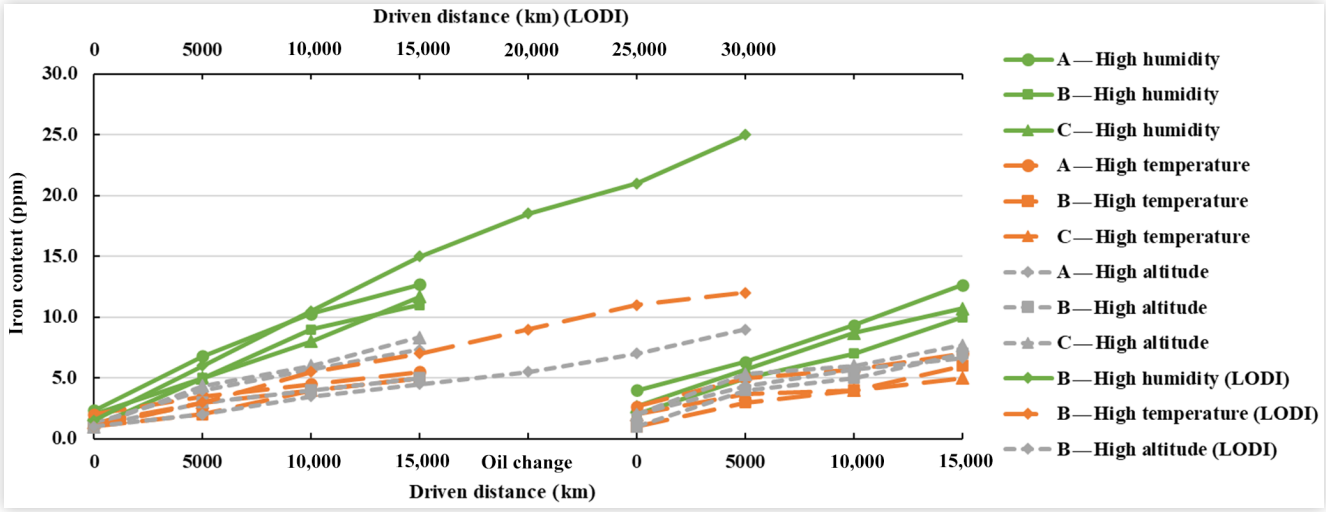
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is still the main factor affecting the oxidation rate of the oil, and the oxidation rate is challenged in the high-temperature environment. The oxidation curve of C in the high-temperature environment almost overlaps with the curve in the low-temperature environment, which may be due to the frequent engine starts of full-hybrid models in the low-temperature environment, and the oxidation rate is similar to that in the high-temperature environment.

In the high-humidity, high-temperature, or high-altitude environment, the iron content in the lubricating oil (A, B, and C) changes as the endurance mileage changes, as shown in Figure 15. The iron content of the lubricating oil was tested by ASTM D5185-18 *Standard Test Method for Multielement Determination of Used and Unused Lubricating Oils and Base Oils by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES)*.

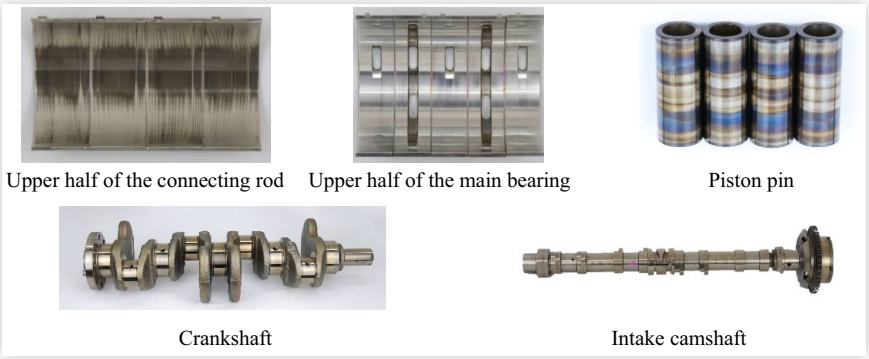
The increase in iron content in the high-humidity environment is faster than that in the high-temperature and high-altitude environments. At the same time, in long oil drain intervals, the increase in mileage does not change the rate of iron content increase in the oil, and the ambient humidity is still the main reason for the higher rate of iron content accumulation, indicating that the high relative humidity of the atmosphere may affect the wear of engine parts and rust prevention. Combined with the engine disassembly, it is found that the accumulation of iron content in A, B, and C in the high-humidity

FIGURE 15 Test results of iron content in lubricating oil.



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FIGURE 16 Wear on the V1 engine parts.



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environment does not cause wear to the engine. Even when B is used in long oil drain intervals in the 30,000-km enderance test, the oxidation value and iron content are still within the acceptable range, and there is no impact on the engine or vehicle performance.

3.6. Engine Wear and Deposit Analysis

After a total of 120,000 km of real road tests in the four extreme environments, the engines of V1, V4, and V7 are disassembled, and the wear and deposits of engine parts are analyzed and scored. The total score is 10, and it is graded at a 0.5 interval. The score of 0 is extremely poor, which means the engine parts are in a non-normal working condition. The score of 10 is excellent, which means the engine parts are brand new.

Figure 16 shows the wear of some V1 engine parts. It can be seen that the wear is very small; the overall score is 9. There is a small amount of wear on the upper half of the connecting rod and the upper half of the main bearing. The wear of the V4 and V7 engines is similar to that of the V1 engine.

Figure 17 shows the deposits in some V1 engine parts. It can be seen that the deposit control is very good, and the overall score is 9.

Among them, the piston deposits are mainly in the second ring belt and the lower part of the top belt. The turbocharger deposits are mainly between the exhaust end oil seal and the floating bearing. There is almost no heavy-component oil sludge residue on the inner surface of the engine. There is a small amount of carbon deposits on the outer edge of the oil ring spring and the bottom surface of the second ring. The deposits in V4 are similar to those in V1. The deposits in V7, which have no turbocharger, are similar to those in V1 and V4.

To sum up, the subjective overall scores for the disassembled V1, V4, and V7 engines are all 9. It demonstrates that after using three low-viscosity lubricating oil (A, B, and C) on the hybrid vehicles in 120,000 km of endurance testing under four extreme environments,

FIGURE 17 Deposits in the V1 engine parts.



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the wear of engine parts is very small and the deposit control is good, thanks to the protection provided by the lubricating oil.

4. Conclusions

In this study, nine vehicles (two hybrid models), using three types of low-viscosity lubricating oil, are tested for a total of 120,000 km on real roads in four extreme conditions. Afterward, some engines are disassembled and analyzed. Here are the conclusions:

1. In the low-temperature environment, for full-hybrid models, the number of engine starts–stops increases by 40.6% on average, compared with the high-temperature, high-humidity, and high-altitude environments; the engine running time increases by 8.2% on average, resulting in frequent battery charging and rapid discharging, so that the battery level stays relatively high, about 68%. V1 and V4, using low-viscosity lubricating oil, have successfully cold-started at −19°C and −40°C. There is no abnormality in the near-field engine noise or in-car noise. There is no obvious abnormality in the time domain or spectrum. There is no transient broadband knocking or other characteristics in the vibration spectrum. Compared with at −19°C, the near-field engine noise at −40°C is about 4 dB higher and the in-car noise is about 5 dB higher, which is a normal response of the structure as the engine is started at a low temperature, and there is no obvious correlation with low-viscosity lubricating oil.
2. In the high-temperature environment, when the full-hybrid models are running at low speed and the engine is at high speed, the ignition advance angle is 7° lower than that in the low-temperature environment and 5° lower than that in the standard-temperature environment, so as to reduce the risk of pre-ignition. SOC is generally around 45%–47%, which is close to the charge–discharge characteristics of the battery in the standard-temperature WLTC working condition. The oxidation rate of oil has almost no effect on full-hybrid models, while the oil in mild-hybrid models is easy to oxidize and decay, and the oxidation rate is 57% faster than that in the low-temperature environment. After the endurance test in the high-temperature environment, the oxidation value and other physical and chemical values of the oil are still within the acceptable range, and there is no impact on the engine or vehicle performance.
3. In the high-humidity environment, the charge–discharge characteristics of batteries in the full-hybrid models are close to those of the high-temperature and standard-temperature WLTC working conditions. The oil consumption rate deteriorates with the increase in relative humidity, and the oil consumption increases by 0.87% on average at the same load and the same engine speed for every 10% increase in humidity. The accumulation rate of iron content in oil is faster than that in high-temperature and high-altitude environments, and such a rate does not change as mileage changes. After the endurance test in the high-humidity environment, the oil still maintains excellent anti-rust and anti-wear properties, and the iron content is well below the 70 ppm limit required by the national standard.
4. In the high-altitude environment, for full-hybrid models, the engine power decreases with the increase in altitude at the same engine speed, and the engine power decreases by 10% on average for every 1000 m of increase in altitude. This also leads to a decrease in the charging efficiency of the engine in the full-hybrid model. There is no obvious peak in the SOC frequency curve, and the battery level cannot be relatively stable. At the same time, with the increase in altitude, the acceleration performance of both hybrid models decreases significantly. Compared to low altitudes, acceleration performance decreases by 10% and 26%, respectively, at altitudes of 2785 and 3800 m.
5. After the two hybrid models, using three types of low-viscosity lubricating oil and driving a total of 120,000 km on real roads in four extreme conditions, the engine disassembly demonstrates that the wear of engine parts is minimal and the deposit control is good, thanks to the protection provided by low-viscosity lubricating oil. For the two hybrid models, the low-viscosity lubricating oil easily copes with long oil drain intervals in the 15,000 and 30,000-km endurance tests in four extreme conditions.

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