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The Challenges for the Brake System of Electric Vehicles

- Observations from a Huangshan Vehicle Test

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ABSTRACT: As there are more and more electric vehicles in the automotive market, the braking systems are facing some new challenges. There are many important functions in electric vehicles that impact the brake behavior, one of the key and unique features is the application of high-intensity regenerative braking. To study the challenges, a brake durability test for electric vehicles was specially designed and conducted in the famous Huangshan region of China. The back to back comparison testing was set up to understand the impact of different regen-brake level.In this paper, the Huangshan test that is popular in Chinese OEM for brake endurance and NVH will be initially introduced, then the tested electric vehicle and its features will be described, as well as the experimental settings. Later, in the analysis of test data, many changes of braking characteristics between vehicles with and without regenerative braking, including braking energy consumption, brake pressure, brake deceleration and brake temperature etc., would be revealed. These changes have generated a large impact on the brake NVH behavior and brake wear performance, related findings were demonstrated with comparison results and typical examples of the test. Finally, from an electric vehicle OEM point of view, the valuable experience and challenges of electric vehicle brake system will be summarized, and it is believed that the results will be very interesting and helpful for the brake community. The future work will be proposed as well, to improve the rig test procedure and Huangshan road test procedure for electric vehicles.

brake NVH, EVs brake wear

KEY WORDS: the challenges of the brake system, huangshan vehicle test, regenerative braking, EVs braking behavior, EVs

1. Introduction

In recent years, as various countries have paid more attention to environmental protection, energy security and energy conservation and emission reduction, the development of new energy vehicles, especially electric vehicles, has become the development direction for automotive industry. Compared with the fuel vehicles, the battery and high-power drive motor of electric vehicles replaced the original power systems: engines and transmissions, which caused many changes in the functions and characteristics of the vehicles. A key feature is that, many electric vehicles employ highly efficient regenerative braking, which allows converting kinetic energy into electrical energy, while simultaneously generating negative torque to driven wheels to slow down the vehicle[1]. This function would change the pattern of the energy input and energy consumption for braking system during vehicle deceleration, as a result, some braking behavior could be significantly affected. In addition, there are some other interesting features, such as quieter driving experience, and more powerful acceleration performance. Studying the impact of these differences will allow to clearly understand the challenges of electric vehicle braking systems.

2. Huangshan Brake Test

Because the braking behavior are profoundly affected by the complex operating environment and driving pattern of the vehicle, including vehicle speed, braking application sequence, traffics, environment, driving habits etc., for decades, extended mileage road tests have been one of the most realistic ways to examine the vehicle brake performances in auto industry. There are some well-known road testing programs in different regions of the world, such as LACT (Los Angeles City Traffic) in North America and Mojacar in Europe. The results obtained from these test procedures often have a significant or even decisive impact on the design and development of the braking system. In the Chinese auto market, Huangshan test is considered as one of the most effective procedures to evaluate and verify the brake attributes. Huangshan area, located in the mid-south of China, has a variety of geographical features. By driving in the severe mountain roads of Huangshan with typical driving traffic, many brake applications can be made in a short time securely, hence higher brake temperature can be achieved. In addition to mountain roads, there are also several road types of high grip and traffics of much diversity. Huangshan region has a maritime climate, and the temperature changes little in the four seasons. The annual average rainfall is large, resulting in high humidity. All of these conditions make Huangshan area an ideal place for brake endurance and NVH tests.

A similar driving test route in Huangshan area was normally employed by brake suppliers and auto makers, that was known as Huangshan Brake Experiment route (Can be abbreviated as HBE route). The durability circuit however also often be customized and adjusted according to test preference, such as mileage per lap, rest stops requirement etc. Since it was the first time that a pure electric vehicle was put into the brake endurance & NVH test in this region, some test settings were no longer applicable, especially test mileages in one cycle. Therefore, the author redesigned the route, taking into account the allowed driving range of electric vehicles and the convenience of power charging. Figure 2.1 shows the basic information of NIO HBE route. The roads and traffics in Huangshan area are very diverse, so the route combines country road, city traffic, mountain road, express way. More detailed map information of the route can be found in the Appendix A. The total mileage of each loop of NIO HBE route is around 170 kilometers, which generally takes 4 hours to complete. Normally two test loops were scheduled in a single day, so routine test mileage usually can reach about 340 kilometers. 9 stop points were set along the route for brake noise search as well as brake function check, and these areas were selected mainly considering the distribution of the braking temperature. Due to different road conditions, the braking temperature along the test route has a different distribution, and the highest braking temperature will exceed 200 degrees C. In general, more than 800 brake applications can be achieved in one single loop. In consequence, it is believed that the NIO HBE route is very suitable for brake durability to observe the brake NVH and brake wear performance of electric vehicles.

✧ Noise research points：9
① Work shop(cold condition)
② Meilin Avenue
③ Huizhou Garden（Groan search)
④ Demao Hall(hot condition)
⑤ Yang Village(recovery)
⑥ Fenghuang Source(hot condition)
⑦ Huangdi Source(recovery)
⑧ Shuanglin Tunnel(recovery)
⑨ Nantang Platform(warm up)

✧ Characteristics of HBE route
◆ Total mileages:168km
◆ Highest altitude:488.7m
◆ Cumulative climb:1294.4m
◆ Drive time: 3.49 hours
◆ Driver: 1 person/shift
◆ Brake numbers: approximately 800
◆ Average speed: >40km/h
◆ Max rotor temperature: >200° C

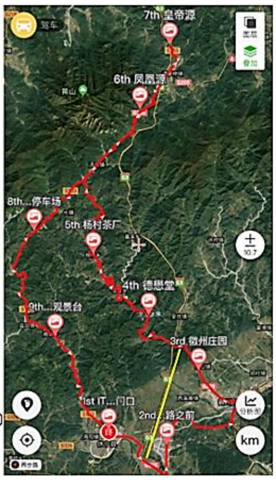


Figure 2.1 NIO Huangshan Brake Experiment Route

3. Test Vehicle and Experiment Setting

3.1. Test Vehicle

The vehicle used for testing was a high-performance four-wheel drive pure electric vehicle. It is equipped with two high-performance drive motors, which can reach 650 horsepower and accelerate from 0 km/h to 100 km/h in only 4.37 seconds. The vehicle packs a 70KWh battery that could reach 410 km NEDC driving range. The front brake corner is equipped with a fixed 4-piston caliper and low metal friction pads, while the rear brake corner is equipped with a floating single-cylinder caliper and NAO friction pads. Ventilated brake discs are used in both front and rear. Some other key parameters of the vehicle and its brake system are listed in Figure 3.1.

Basic information of vehicle and Brake		
Vehicle Category		Pure Electric Vehicle
Drive motor power		Dual: front 160KW+rear 160KW
Curb weight		2475kg
Wheelbase		2900mm
Max. velocity		200km/h
Tire type		255/50 R20
Booster		Electric booster
Master cylinder		Tandem 25.4mm²*21mm+25.4mm²*21mm
Pedal ratio		3.5
FA Brake	Fixed caliper	Piston size*effeive radius/P44mmX44mm*147mm
	Lining	type*mu*area*thickness/Low Metal*0.4*74.5cm² *9mm
	Vented disc	Diameter*thickness/355mm*32mm
RA Brake	Floating caliper	Piston diameter*effeive radius/44mm*159mm
	Lining	type*mu*area*thickness/NAO*0.38*36.5cm²*11mm
	Vented disc	Diameter*thickness/365mm*20mm

Figure 3.1 Test Vehicle Information

For an electric vehicle, one of the key and unique features is the regenerative braking function. The battery and the motor are a pair of energy conversion systems for electric vehicles. When the vehicle is running, the battery powers the motor, and when braking, the motor plays the role of the engine and powers the battery. The regenerative braking system absorbs the kinetic energy generated by vehicle deceleration, and converts it into electrical energy through the motor to charge the battery. The motor generates reverse torque to act on the drive shaft thus electric braking force is produced. At the current stage, the maximum vehicle deceleration that can be directly generated by the regenerative intensity of the vehicle motor can reach 0.2g (gravitational acceleration g=9.8 m/s^2). In this deceleration range, theoretically 100% energy recovery can be achieved, actual energy regeneration utilization rate is a little different due to the influence of battery status, vehicle stability control etc. For regenerative braking, two primary methodologies have been evolved in the industry and are defined as Category A and Category B regenerative braking according to Federal Regulations ECE R13H. [2] [3] , as shown in Figure 3.2. It should be noted that the test vehicle used regenerative braking of Category A, which is not part of the service brake and can only be controlled by the accelerator pedal or gear. The negative torque that was produced by regeneration mechanism in vehicle coasting phase would remain active when brake pedal was depressed [4].

5.2.18. Additional requirements for vehicles equipped with electric regenerative braking systems.

5.2.18.1. Vehicles fitted with an electric regenerative braking system of category A.

5.2.18.1.1. The electric regenerative braking shall only be activated by the accelerator control and/or the gear neutral position.

5.2.18.2. Vehicles fitted with an electric regenerative braking system of category B.

5.2.18.2.1. It shall not be possible to disconnect, partially or totally, one part of the service braking system other than by automatic means. This should not be construed as a departure from the requirements of paragraph 5.2.10. above;

Figure 3.2 Definition of Regenerative Braking Type in ECER13H

Considering the important role of regenerative braking, two electric vehicles were arranged for back-to-back comparison test to understand the impact of different brake regen level. To fulfill the mission, vehicles were set to different driving modes, one was tested in sports mode, and the other was tested in engineering mode. The Sports mode is an optional mode for customer drivers in daily driving. Its electric regenerative brake intensity was set to the low-level of 0.1g, which varies slightly with vehicle speed and battery status. Engineering mode is the manufacturer's debugging mode, so customer drivers cannot choose it in daily driving. The debugging mode for the test was to turn off the coasting torque based on the sports mode setting, that means, the vehicle in this mode does not have regenerative braking function. This setting can make the engineering mode test vehicle approximately represent a fuel vehicle, therefore, the comparison test results in this article can also tell the difference in the performance of the braking system between electric vehicles and fuel vehicles.

3.2. Experiment Setting

To complete the back-to-back comparison test, the variables of the test object, process and operator should be strictly controlled. To reduce the impact of environment and weather and make test consistent in the whole process, two vehicles were set to start at almost the same time every day and follow exactly the same scheduled route. Due to driving under natural traffic conditions, the two vehicles did not always follow each other. There will be time shifts during each loop, but the authors believe that it will not affect the results presented in this paper. In addition, multiple drivers were arranged to perform random shift driving to eliminate the influence of the driver's personal driving habits. For test parts directly related to brake system performance, including brake calipers, friction pads, and brake discs, used prototypes from the same batch for the two tested vehicles. Some other relevant vehicle parameters, such as vehicle weight and tire specifications, were set to the same state as much as possible. As a result, the driving resistance of the two vehicles, including wind resistance, rolling resistance and braking drag torque etc., can be controlled within a small difference.

Obtaining test results for the brake NVH performance is one of the main goals for the automaker to set up the Huangshan durability test. Currently, in vehicle instrumentation is commonly used to get objective evaluation of noise performance. Figure 3.3 shows a typical data acquisition device and a microphone inside the cabin; some necessary sensors are listed as well. These devices can identify the brake noise and provide detailed occurrence information, such as brake pressure, temperature, speed etc. The in-vehicle system was quite effective in recognizing squealing brake, which is a significant cause of annoyance and of high warranty cost for auto industry. Nevertheless, the subjective evaluation method is still applicable and acts as an important way for test engineers to evaluate the severity of some abnormal noise and vibration, such as groan, brake judder. In the NIO HBE procedure, the driver was required to perform one or two subjective evaluations in one test loop for groan. As for brake judder evaluation, a section of highway in the test area (as shown by the yellow line on the route diagram in Figure1.1) was selected for testing. The conditions and sequences in the Table 3.1 were used to check vehicle sensibility to the vibration situation of steering wheel, vehicle body, brake pedal. After each evaluation, the disc run out on vehicle and disc thickness variation were measured.

The standard metrics for subjective evaluation and objective evaluation follow the methods proposed in the literature [2], and are summarized in the Table 3.2, where the noise weighting factor is given by the test driver in accordance with the SAE N45 method shown in the Table 3.3.

Equipments and sensors	Functions or Signals
Thermocouple	Rotor temperature
Vbox and its accessories	Vehicle speed and brake deceleartion
Vibration acceleration sensor	Caliper vibration data
Microphone in the middle of cabin	Noise data
humidity sensor	Ambient temperature and humidity
LINK4000 & Head BrakeObserver	Data acquisition and analysis
Micrometer	Wear thickness

Figure3.3 Test Instrument Setup

Table 3.1 Brake Judder Evaluation

Judder Evaluation Record							
Driver		Date:		mileages		Time	
vehicle speed (km/h)	deceleration (g)	Disc temperature (° C)	Brake pedal	steering wheel (Tangential)	steering whee (Normal)	Body	Remark
120~80	0.1~0.3	<100					
120~80	0.1~0.3	100~250					
120~80	0.1~0.3	>250					

Table 3.2 Definition of ONI and SNI

SNI definition:		
	$SNI = \frac{\sum(noisy\ stops) * (noise\ weighting\ factor)}{Total\ stops}$	
	N45 Noise rating	noise weighting factor
	10	1
	9	2
	8	5
	7	10
	6	30
	5	100
	4	300
	<3	1000
Acceptance Criteria:	Excellent	SNI<1.2
	Fulfil requirements	1.2<=SNI<=1.75
	Critical state	1.75<=SNI<=5
	Disqualified	SNI>5

ONI definition:		
	$ONI = \frac{\sum(noisy\ stops) * (noise\ intensity\ factor\ I)}{Total\ stops}$	
	Decibel value	noise intensity factor
	<50dB	0
	50dB<=I<=60dB	1
	60dB<=I<=70dB	3
	70dB<=I<=80dB	10
	80dB<=I<=90dB	30
	>=90dB	100
Acceptance Criteria:	Excellent	ONI<0.4
	Fulfil requirements	0.04<=ONI<=1.2
	Disqualified	ONI>1.2

Table 3.3 The SAE N45 Subjective Rating

N45 Subjective Evaluation Standard									
1	2	3	4	5	6	7	8	9	10
Very bad		Bad		Critical state		Acceptable		Very good	
Very loud Continuous Severe vibration of suspension and body		Grade according to the noise decibel, duration, vibration of suspension and body				Slight/obvious short No vibration of suspension and body		No noise/imperceptible	

4. Test Data and Analysis

According to the scheduled NIO HBE route and procedures, two electric vehicles conducted the long-term road test. With the help of a brake trigger mounted on the brake pedal, and the devices mentioned above, the data related with brake events were recorded, including vehicle speed, brake pressure, brake temperature, deceleration, humidity and brake noise related frequency, dB etc. Table 4.1 listes a brief test results summary. The statistics tell that a total of 37 repeated loops of testing were carried out finally, with a cumulative test mileage of more than 6200 kilometers and a test duration of more than 25 days. The test data will be discussed and analyzed in detail in the following sections.

Table 4.1 Brief Result Data Summary

Data Summary for Engineering Mode				
	LF	RF	LR	RR
Max Temperature(C)	/	321.59	/	277.11
Mean Temperature(C)	/	124.54	/	109.62
Max Pressure(bar)	65.66			
Mean Pressure(bar)	8.21			
Max Deceleration(g)	0.71	Mean Deceleration(g)		0.11
Max Speed(kph)	114.33	Mean Speed(kph)		33.00
Test loops(-)	37.00	Test Distance(km)		6216.00
Energy(MJ)	1496.10	Record brake events(-)		32218.00

Data Summary for Sport Mode				
	LF	RF	LR	RR
Max Temperature(C)	/	207.23	/	98.88
Mean Temperature(C)	/	51.76	/	43.37
Max Pressure(bar)	52.39			
Mean Pressure(bar)	6.52			
Max Deceleration(g)	0.61	Mean Deceleration(g)		0.17
Max Speed(kph)	133.48	Mean Speed(kph)		29.54
Test loops(-)	37.00	Test Distance(km)		6271.00
Energy(MJ)	782.28	Record brake events(-)		17760.00

4.1. Brake Energy Consumption

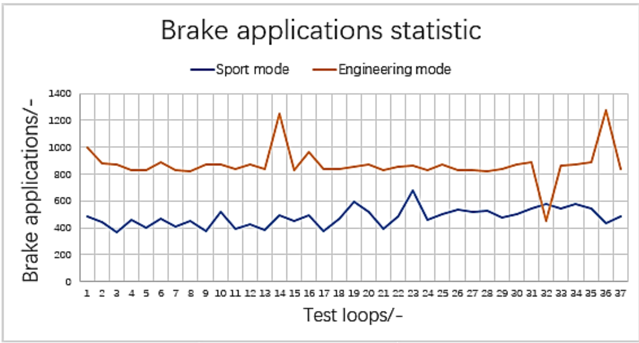
The vehicle deceleration process follows the kinetic energy theory, which defines that the work done by external force is equal to the change of the kinetic energy of the object. For each braking application, the amount of kinetic energy dissipation is as equation (1), where m is the vehicle mass, and Vt, Vo are the initial and final vehicle velocity during vehicle braking.

$$W = \frac{1}{2}mv_t^{\,2} - \frac{1}{2}mv_0^{\,2} \qquad (1)$$

$$\sum W = W_1 + W_2 + W_3 + \cdots + W_n \qquad (2)$$

According to the formula (2), the sum of the kinetic energy changes generated in all braking processes were calculated and shown in the Figure 4.1, which shows that sports mode (1068 MJ) has 28% less energy input to braking system than engineering mode (1496 MJ) during whole test period. This result is based on the premise that two vehicles have similar driving resistance. Because the differences in test routes, driving behavior, environment, and traffic were strictly controlled, the test loads of the two test cars can be considered to be basically comparable, which means that the total energy consumption of the vehicles during vehicle deceleration was similar.[4] Therefore, in the sports mode, in addition to the hydraulic braking force and driving resistance, the regenerative braking also afforded a portion of the kinetic energy consumption, and its amount is less than the engineering mode to a first approximation (Δ ≈1496 MJ-1068 MJ = 428MJ). The absorbed energy was then converted into battery power, which adds about 10-15% of the driving range to the vehicle during each testing loop. In summary, the regenerative braking system shares only about a quarter of the workload of the braking system and significantly improves the vehicle's energy efficiency.

One of the important reasons for the reduction in energy input to the braking system in sports mode was the decrease in the number of braking events. The Figure 4.1 lists the number of braking events that were triggered. Throughout the test, vehicle in engineering mode had a total of 32218 hydraulic braking events, with an average of 871 times for one loop, while the vehicle in sports mode had only 17760 hydraulic braking events, with an average of 480 times each loop. Thanks to the application of regenerative braking, a 45% reduction in the brake event numbers was achieved. It can be explained by that, that regenerative braking enables larger deceleration during the coasting phase, thus increasing coasting events and reducing hydraulic braking events. According to test driver's feedback, under some moderate or light braking conditions, such as typical conditions-when passing through small curves on mountain roads, or short-term light braking when driving on highways etc., the acceleration and deceleration of the vehicle can be basically controlled by the single accelerator pedal, and hardly needs the utilization of the brake pedal. Therefore, the deceleration events using hydraulic brakes was dramatically decreased.



	Sport mode	Engineering mode
Total brake applications	17760	32218
Ave applications per loop	480	871

Figure 4.1 Statistics of Brake applications

4.2. Brake Deceleration Activities

Figure 4.2 and Figure 4.3 present the distribution of brake deceleration intensity and hydraulic brake pressure.Overall, compared with the engineering mode, the sports mode has a relatively higher brake deceleration distribution, but the brake pressure distribution is not quite similar. On the contrary, the test vehicle in the sports mode has more brake pressure distribution in the low pressure area.It can be explained by that, for each braking event, the regenerative braking torque generated in the coasting phase would remain active in the braking phase and be overlaid to the hydraulic braking torque, which would increase the intensity of the vehicle deceleration in many brake conditions, especially under the condition of high braking intensity and fast braking (The high intensity mentioned here is relatively speaking, and it can be considered mostly above 0.2g, because the results in both engineering mode and sports mode show that more than 96% of braking occurs below 0.3g). However, for some low braking intensity conditions, the driver may often first use the regenerative braking torque to control the vehicle deceleration, and then step on the brake pedal to use the friction brake to assist in slowing down or stopping the vehicle, which will reduce the hydraulic braking intensity and thus reduce the brake pressure.

It needs to be emphasized that the regenerative braking intensity of the sports mode is the weakest among all selectable modes for the test vehicle. If switching to comfort mode or economy mode, the deceleration contributed by the regeneration will reach higher intensity of 0.18g ~ 0.2g. This will allow a wider range of vehicle deceleration that can be modulated by single pedal control, and will lead to a further reduction in the number of braking events, higher braking deceleration distribution and more proportion of low brake pressure for brake deceleration activities.

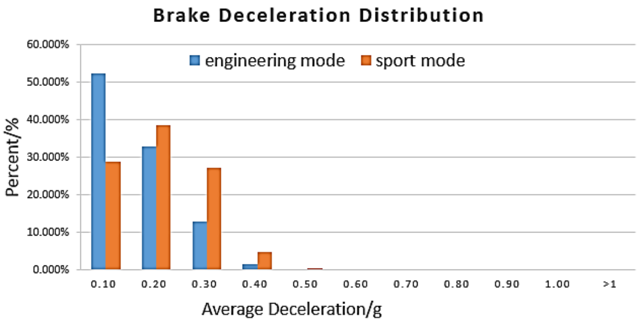


Figure 4.2 Statistics of Brake Deceleration Distribution

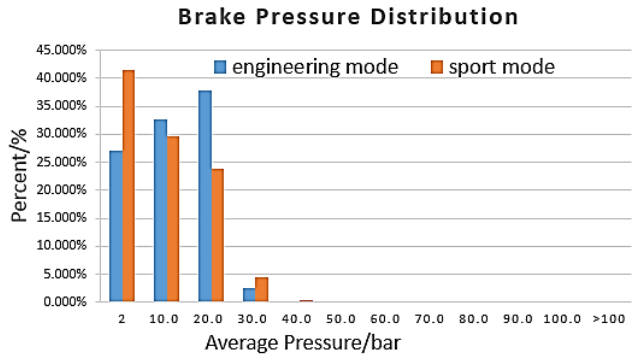


Figure 4.3 Statistics of Brake Pressure Distribution

4.3. Brake Temperature Distributions

Figure 4.4 shows the temperature distribution of the vehicles for all test loops. Obviously, the brake temperature in engineering mode was always higher than that in sports mode. In engineering mode, the braking temperature of many braking events was between 100 degrees C and 250 degrees C, the highest can reach more than 300 degrees C. However, in sports mode, most braking temperatures were distributed below 100 degrees C. According to statistics, more than 99% of brake applications were made at brake temperatures below 80 degrees C. The distributions of two randomly selected cycles are shown in Figure 4.5, to have a clear display for temperature changes during each loop, and also to illustrate that the temperature difference between the two test modes was consistent in long-term road test.

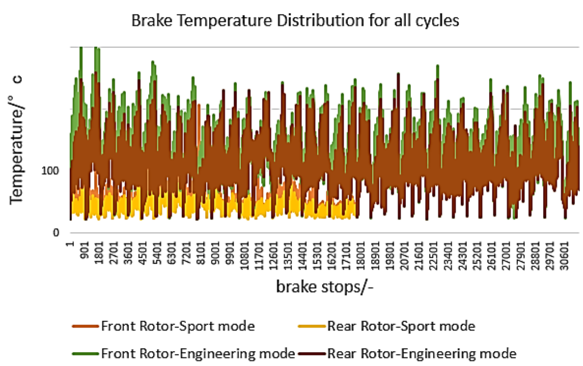


Figure 4.4 Brake Disc Temperature Distribution for Whole Test Loops

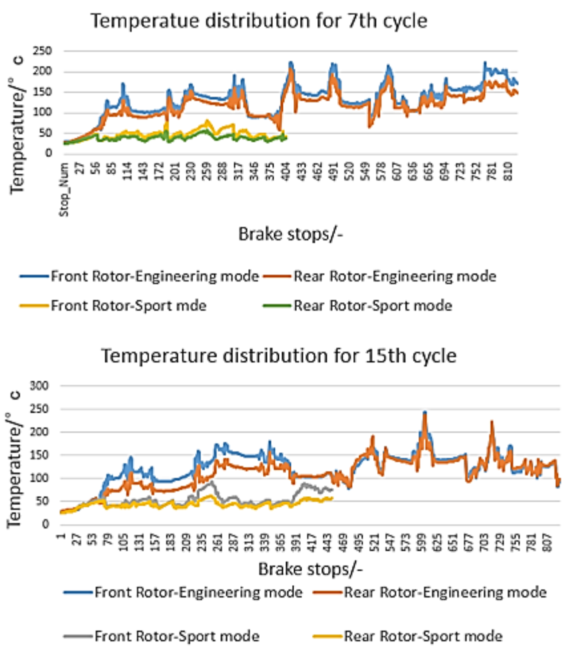


Figure 4.5 Brake Disc Temperature Distribution for Two Typical Loops

The brake parts, especially the brake discs and friction linings, are components that directly generate friction and dissipate heat. The variation and transmission of frictional thermal energy directly affects the change of friction coefficient during braking, the deformation of materials, the aging and durability of brake parts. Therefore temperature would have a strong impact on braking behavior.

Overall , characteristics of brake energy, brake application numbers, braking deceleration, braking pressure, braking temperature etc., basically, constitute the brake durability profile of the NIO HBE route. This helps to have a clear understanding of the load profile of electric vehicle braking systems. It is also a rather important reference to know the distribution of vehicle braking behavior that would happen in the daily driving by electric vehicle consumers. Brake designers should reconsider the establishment of a set of brake working conditions that is used for design reference.

5. The Observations of Braking Performance

5.1. Brake NVH Behavior

Changes in braking characteristics, especially the brake temperature, have made a big difference on the braking noise behavior. A typical example will be presented for demonstration. It was a kind of noise known as chirp noise, which was found as the dominant noise of rear brake in the initial dyno and was verified according to standard rig procedure SAE J2521.The typical occurring conditions were: the brake discs and linings were at high temperature conditions or have experienced high temperature fading (temperature higher than 100 degrees C), with low vehicle speed, as shown in Figure 5.1 and Figure 5.2. Many chirp noises exceed 60 decibels, which is easy to cause discomfort. however, they can't be killed even after multiple rounds of optimization tests, including the tuning of the shims, underlays of lining, and the different chamfers.

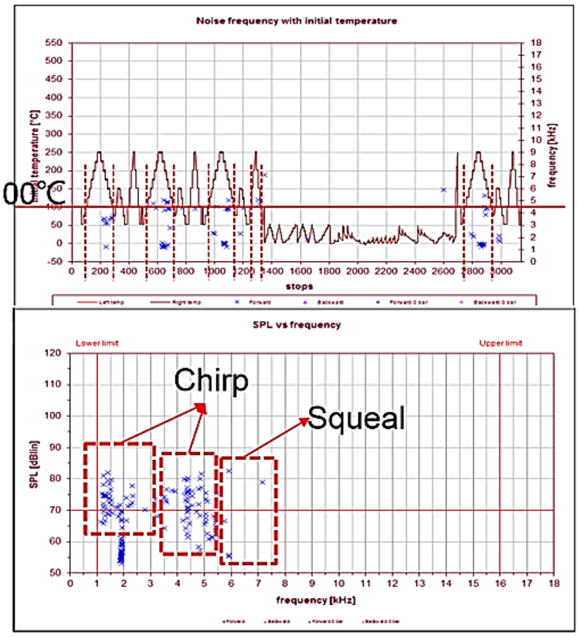


Figure 5.1 Dyno Test Results of Rear Brake

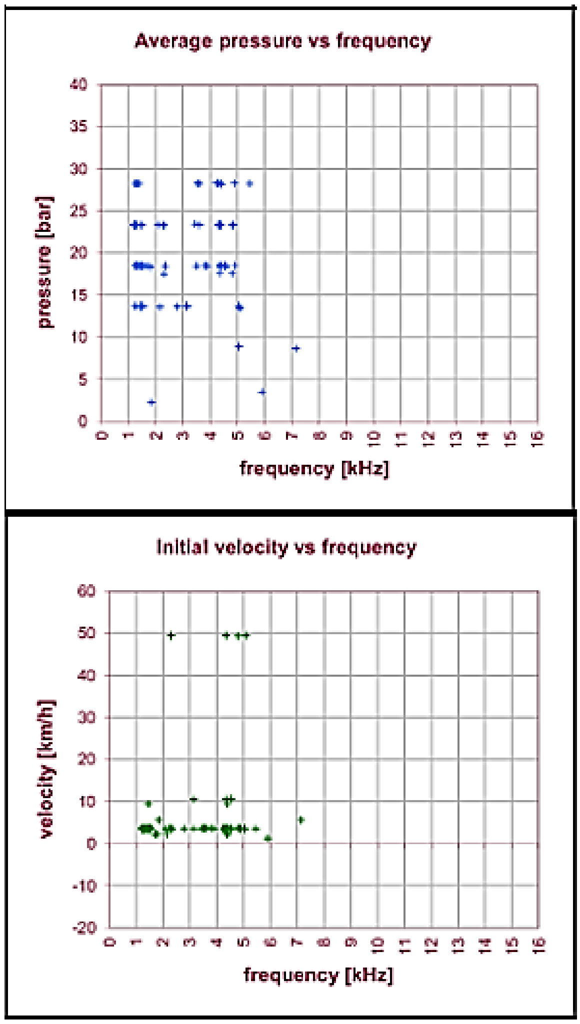


Figure 5.2 Distribution of Brake Pressure and Vehicle Speed vs Noise Frequency

Significant changes of chirp noise behavior were found in the Huangshan vehicle road test. Figure 5.3 and Figure 5.4 describe the noise occurrence of test vehicles in engineering mode and sports mode. They provide information on noise frequency and braking conditions including temperature, pressure and vehicle speed. The green and red dots in the figure represent the noise from the left and right brakes, respectively, which was determined by objective collection and analysis with the in-vehicle equipment. The yellow dots were marked by the test driver when noise was subjectively noticed during the test. It is easy to observe that the chirp noise was reproduced on the vehicle in the engineering mode and had the same occurrence conditions as on the bench, while the vehicle in the sports mode however can hardly find it. This obviously can be explained by the different distribution of thermal conditions. Substantial reduction of hot conditions will inevitably cause the decrease of “hot noise”. Therefore, in the future, the braking noise challenge for electric vehicles will mainly focus on cold noise and should occur under conditions of low braking pressure. Moreover, this phenomenon simultaneously revealed that the standard rig test program such as SAE J2521 cannot systematically represent the typical working conditions of electric vehicles, resulting in its poor correlation with the actual road test program. For automobile manufacturers, an initial dyno test is a very important and economical method that has been widely used in the brake industry for decades, hence some modifications may be necessary to be considered for the standard rig procedures to adapt the new changes for electric vehicles.

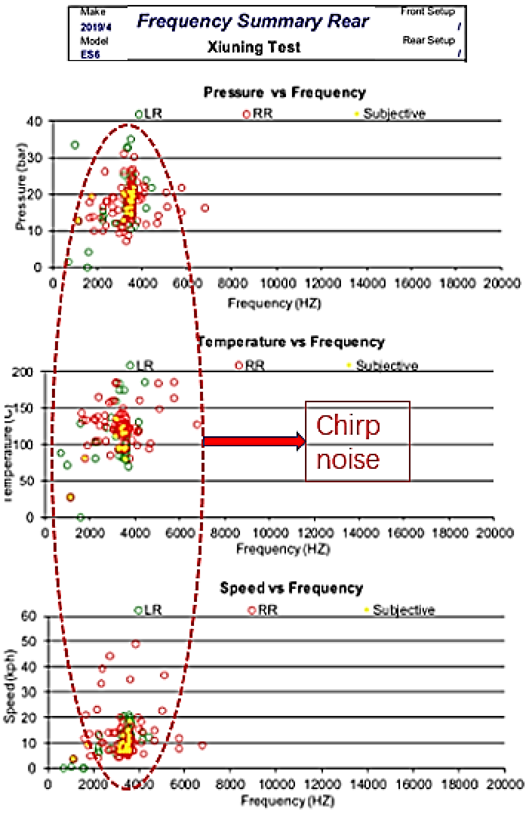


Figure 5.3 Huangshan Vehicle Road Test Result of Rear Brake in Engineering Mode

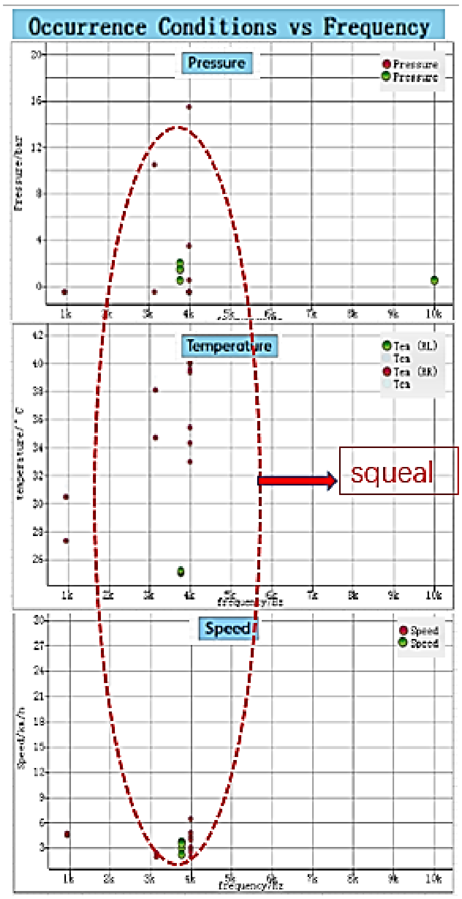


Figure 5.4 Huangshan Vehicle Road Test Results of Rear Brake in Sport Mode

Another interesting phenomenon found in the test is about groan behavior. Electric vehicles become very quiet at low speeds or when stationary, which makes braking noise and vibration more critical. A record of the evaluation for groan performance during Huangshan test proves the new situation facing electric vehicles, as shown in Table 5.1. It was found that the groan performance of the front brakes was rather poor, and the score was in an unacceptable and critical state. This behavior generally occurs on friction materials with high friction coefficients, and is basically caused by the physical phenomenon of stick-slip motion during dynamic and static conversion. The quieter interior of electric vehicle makes the groan noise even more sensitive, especially when the vehicle is changing from static to dynamic at low speed. The tester's feedback was that the absence of engine sound in the front compartment made the groan noise and vibration coming from the front brakes extremely harsh, which deteriorated subjective acceptance. With the increasing popularity of automatic transmission models, the groan and the accompanying abnormal noises of brakes are increasingly complained by vehicle consumers. The reason is that with the rapid growth of vehicle ownership and the intensification of traffic congestion in large and medium-sized cities, vehicles repeatedly start at low speeds and brakes frequently, which greatly increases the probability of brake groan. Therefore, when the braking system of electric vehicles needs to use friction materials with higher braking efficiency to achieve stronger braking performance, groan performance will become an important challenge.

Table 5.1 Groan Evaluation Record

NIO ES6 Groan Evaluation Result					Update: [illegible]
Date	Time	Shifts	FA	RA	Humidity
2019.6.29	上午	59	7	8	82%
	下午	60	7	9	71%
2019.6.30	上午	61	6	9	99%
	下午	62	7	8	41%
2019.7.1	上午	63	7	9	83%
	下午	64	6	9	47%
2019.7.2	上午	65	7	8	75%
	下午	66	7	9	55%
2019.7.3	上午	67	6	9	77%
	下午	68	7	8	51%
2019.7.4	上午	69	6	9	85%
	下午	Vehicle status check			
2019.7.5	上午	70	6	9	98%
	下午	71	7	8	97%
2019.7.6	上午	72	6	9	84%
	下午	73	6	9	76%
2019.7.8	上午	74	7	8	70%
	下午	75	6	9	71%
2019.7.9	上午	76	6	9	90%
	下午	77	7	9	99%
2019.7.10	上午	78	6	9	99%
	下午	79	6	9	98%
2019.7.11	上午	80	7	9	85%
	下午	81	6	9	61%
2019.7.12	上午	82	6	9	84%
	下午	83	7	8	83%
2019.7.14	上午	Vehicle status check			
	下午	84	6	9	99%
2019.7.15	上午	85	6	9	88%
	下午	86	7	9	83%
2019.7.16	上午	87	6	9	97%
	下午	88	7	9	58%
2019.7.17	上午	89	7	9	99%
	下午	Vehicle status check			
2019.7.18	上午	90	7	9	85%
	下午	Vehicle status check			

5.2. Brake Wear Analysis

The friction pads and brake discs were disassembled and measured after the test was completed. Statistics of corresponding wear data are shown in Table 5.2. The prediction of average life is based on when the lining was completely worn out and only 2 mm underlayer material was left for the friction material, and when the wear of brake discs reaches 2 mm. It can be observed from the chart that the brake wear in sports mode is much lower than in engineering mode. Average expected service life of the front and rear lining in sports mode is at least 2.2 times and 4.2 times longer than that in the engineering mode, respectively. Average expected service life of the discs is approximately 1.2 to 1.3 times longer than that in the engineering mode. Under the premise that the engineering mode vehicle can be approximately regarded as a fuel vehicle, the test wear results can prove that the brake wear of the electric vehicle utilizing the regenerative braking will be substantially reduced compared to the fuel vehicle.

Table 5.2 Wear and Life Prediction for Linings and Discs of Huangshan Test Vehicles

Engineering mode									
Items		FA				RA			
		FL		FR		RL		RR	
		outer	inner	inner	outer	outer	inner	inner	outer
Pad	Average wear(mm)	2.27	2.03	1.52	2.22	1.26	1.46	1.35	1.31
	Life until 2mm rest(km)	21062	23522	31466	21543	48629	41949	45392	46705
Rotor	Disc wear(mm)	0.39		0.33		0.03		0.03	
	Disc life time(km)	34997		41146		443577		505185	

Sport mode									
Items		FA				RA			
		FL		FR		RL		RR	
		outer	inner	inner	outer	outer	inner	inner	outer
Pad	Average wear(mm)	0.65	0.45	0.4	0.51	0.2	0.2	0.17	0.15
	Life until 2mm rest(km)	68730	99180	111258	88536	257272	257083	294364	330674
Rotor	Disc wear(mm)	0.154		0.125		0.02		0.02	
	Disc life time(km)	81441		100336		627100		627101	

From historical experience, the braking intensity under the Huangshan test was generally 2 to 3 times more intensive than that of the end user under normal driving conditions. According to the rough calculation, the average expected service life of the friction linings and brake discs in the sports mode are close to the vehicle general designed life of 200,000 kilometers. In other driving modes, because of higher regenerative intensity, a longer life could be expected accordingly. In fact, according to the statistics from after sales, among the tens of thousands of vehicles already sold, the proportion of driving modes selected by the end users is: 93% in normal mode, 5% in economy mode, 2% in sports mode. Apparently, users quickly adapt to high-intensity regenerative braking and are willing to use it in daily driving. This is of great significance for the brake wear, which will greatly increase the possibility that most vehicles will not be replaced with brake discs and friction pads during the service life of the vehicle. This result will likely benefit electric vehicle buyers by saving on replacement brake components, but it will require automakers to adjust their brake after-sales operation strategies.

To confirm that the above conclusions are representative beyond Huangshan test, the brake wear test data of simulating normal customer driving patterns was selected for comparison. Reliability tests that were designed to represent the real daily usage scenario of general end customers, were conducted with the same series models in different regions of China. Those vehicles were set in normal driving modes, which meant that they all had different levels of regenerative braking. The statistical data for brake lining wear are shown as Table 5.3. Similarly, the calculated minimum service life of the lining predicted by the measurement basically exceeds the designed service life of the vehicle, which is consistent with the basic facts reflected by Huangshan test.

Table 5.3 Lining Wear of Normal Driving Test Vehicles

Vehicle	Measured site	Mileage (km)	Leftover Thickness Ori. Thickness Front:7mm Rear:9mm				Max wear percentage		Front Estimate pad life(km)	Rear Estimate pad life(km)
			FL	FR	RL	RR	Front	Rear		
8VB3RE 01	Shanghai	200252	5	4	7	8.1	66%	40%	304731	500630
8VB3RE 02	Shanghai	181043	5	5	7	7.7	64%	43%	281622	417792
MP2-4	Guangde	88827	8	7	8	8.4	27%	31%	327257	285515
MP2-20	Shanghai	79242	8	8	10	9.6	21%	17%	369796	475452
MP2-21	Shanghai	83393	8	8	10	9.5	16%	17%	530683	500358
MP2-15	Heihe	91145	7	7	9	9.5	36%	22%	255206	410153
MP2-6	Heihe	92577	7	7	9	9.5	27%	23%	341073	396759
MP2-12	Heihe	93624	8	7	10	9.8	29%	17%	327684	561744
MP2-1	Heihe	93227	8	8	9	9.8	16%	22%	593263	419522
								Aver	370146	440881
								Min	255206	285515
								Max	593263	561744

The significant reduction in brake wear would bring many effects on the braking system of electric vehicle. On the one hand, it will allow development engineers to make some improvements. For example, reducing the thickness of the lining or disc to get a caliper structure of better stiffness and lighter weight. Another example, eliminating the friction pad wear indicator that is used to remind the driver when the friction pad needs to be replaced to get a cost reduction. On the other hand, it will also bring some challenges. First, the design life and durability of some brake parts need to be improved. As the service life increases and approaches 200,000 kilometers, the durability of the friction pad-related parts including the corrosion resistance of the back plate, the adhesion strength between the back plate and the shim, and the harness life of the electric pad wear indicator etc., will withstand a huge test. It might need to improve the design standards for these parts to avoid potential durability failures. Secondly, the drastic reduction in wear will extend the bedding period between the friction lining and the brake disc. From industry experience, the friction linings need to run in for a certain mileage to make the braking performance stable. Therefore, the extension of the bedding period will also extend the duration of the potentially unstable braking problems that may occur during this period. At last, potential degradation of rust removal ability. When the brake discs are rusted, or dirty, hydraulic brakes can clean them by removing them through friction between lining and disc. However, an electric vehicle, it might be driven under frictionless braking or very low-intensity braking frequently, which could degrade the rust removal performance of linings, and may increase DTV growth of the disc.

6. Conclusions & Future Work

Through the observations and discussions of Huangshan test, it can be seen that the new features and functions of electric vehicles have a comprehensive impact on the braking system in many aspects. The following conclusions can be drawn to point out the challenges facing braking system of electric vehicles. Future work is proposed to improve the correlation between experimental procedures and actual performance of electric vehicles.

6.1. Changes in Brake Characteristics

For the applications of regenerative braking, an electric vehicle has less hydraulic brake events and less brake energy consumptions than traditional fuel vehicle. The brake pressure will be more distributed in the low pressure area, and the brake temperature will be greatly reduced. Changes in these characteristics have redefined the brake endurance profile for electric vehicles. Brake designers should reconsider the establishment of a set of brake working condition profiles used for reference of brake design and test.

6.2. New Challenges in Braking NVH Behavior

Changes with braking energy, heat, etc., have a significant impact on the brake NVH behavior. Firstly, as braking temperatures decrease, more attention needs to be paid to cold noise. Secondly, the electric vehicle's motor drive makes the vehicle interior much quieter, but it may worsen the subjective acceptance of some brake noise and vibration, such as groan. These potential issues may cause new complaints. Finally, the standard rig procedures that are commonly used for brake noise development for conventional fuel vehicle, need to be reviewed and modified to adapt to the new situation of electric vehicles.

6.3. Significant Reduction in Brake Wear

Due to the reduction of the friction brake workload, the braking wear was drastically reduced, which greatly extends the life of the friction linings and discs even closer to the vehicle design life. It gives some benefits for brake design, but it also brings some new challenges. The efforts on improving the durability performance of the friction pad-related parts must be made. The bedding period between the linings and disc will be extended, which may cause potential complaints in this period.

6.4. Future Work.

Research on continuous improvement of the standard brake rig noise procedures to pay more attention on cold condition noise for electric vehicles.

Improve the correlation between Huangshan braking experiments and actual vehicle performance of electric vehicles. As an accelerated wear test, it is necessary to reflect the wear change of the friction lining during the life cycle in the limited test mileage, to investigate the effect of the wear change on the braking performance. The possible method is to switch the setting of brake regen level during different experiment mileage stages of a test vehicle.

References

[1] Guoqing Xu, Weimin Li, Kun Xu, and Zhibin Song, An Intelligent Regenerative Braking Strategy for Electric Vehicles, Energies 2011,4,1461-1477

[2] Kiran Krishnapur and Jim Luo, TRW Automotive, “Brake Squeal Rig and LACT Vehicle Test Correlation Improvements -Focus on Thermal Conditionings” SAE TECHNICAL PAPER SERIES, 2004-01-2791

[3] Regulation ECR R13, Uniform provisions concerning the approval of vehicle categories M, N and O with regard to braking

[4] Thomas J. Hall Faraday & Future Inc. A Comparison of Braking Behavior between an IC Engine and Pure Electric Vehicle in Los Angeles City Driving

Conditions, SAE Technical Paper 2017-01-2518, 2017, doi:10.4271/2017-01-2518.

[5] “Noise Dynamometer and Vehicle Test Correlation” Jim Luo and Aaron Lock, Chapter 12 of “Disc Brake Squeal (Mechanism, Simulation, Test and Prevention), Editor: F. Chen, C. A. Tan and R. L. Quaglia” SAE Book, 2005

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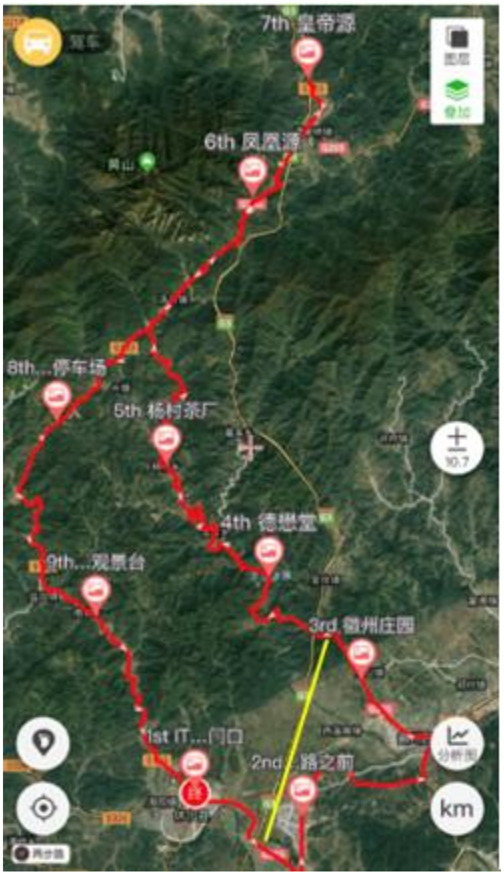
Appendix

A: NIO HBE Route



B: Status of Brake Discs and Brake Linings after 6000 km Test