EFFECT OF TEMPERATURE ON TIRE ROLLING RESISTANCE

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Abstract

Tire rolling resistance (RR) is closely related to overall vehicle fuel economy or range, and it's common that vehicle manufacturers require tire rolling resistance reduction to help optimize fuel economy/cruising range. Tire rolling resistance measurement requirements for use in consumer tire labeling laws are being released in some countries and districts. Threshold values for tires are being established to achieve energy savings, meet green initiatives, and reduce carbon emissions. Current conventional rolling resistance testing methods only focus on tire performance at an ambient temperature of 24°C or 25°C, but real-world applications span a much broader range of operation. This paper combines theoretical analysis and experimental methods to explore the rolling resistance of tires at other temperatures.

I. ROLLING RESISTANCE PRINCIPLES AND MATERIAL PROPERTIES

Modern research asserts that excluding factors such as road irregularities, impact, and energy loss due to slippage between the road surface and tire tread, tire rolling resistance is largely a result of energy dissipation within the volume of the tire. Hysteretic losses account for about 80-95% of the tire's total rolling resistance [1]. Thus, in the process of deformation to recovery, although most of the energy absorbed and stored in the rubber can be released, a small part of it is dissipated in the form of heat generation. In other words, the output power is less than the input power, which in most cases, can be viewed as a force opposite to the direction of travel. This force is called rolling resistance (RR or RRF). The ratio of rolling resistance force to applied load is the rolling resistance coefficient (RRc).

A tire's rolling resistance depends upon many factors including tire materials, construction, and design. Among all tire components, tread compounds have the largest contribution to rolling resistance accounting for 40-50% of passenger tire and 35-50% of truck tire rolling resistance [2]. The material property tangent delta (Tan δ), when measured at 60°C, is generally considered to be a good indicator of tire rolling resistance and is widely used as a reference to indicate "hysteresis characteristics" of tread compounds. Using Dynamic Mechanical Analysis (DMA), rubber compound samples are tested either in shear, compression, or extension. Tan δ is the ratio of loss modulus (G"/E") to the storage modulus (G'/E') in shear modulus (G) or compression/extension modulus (E).

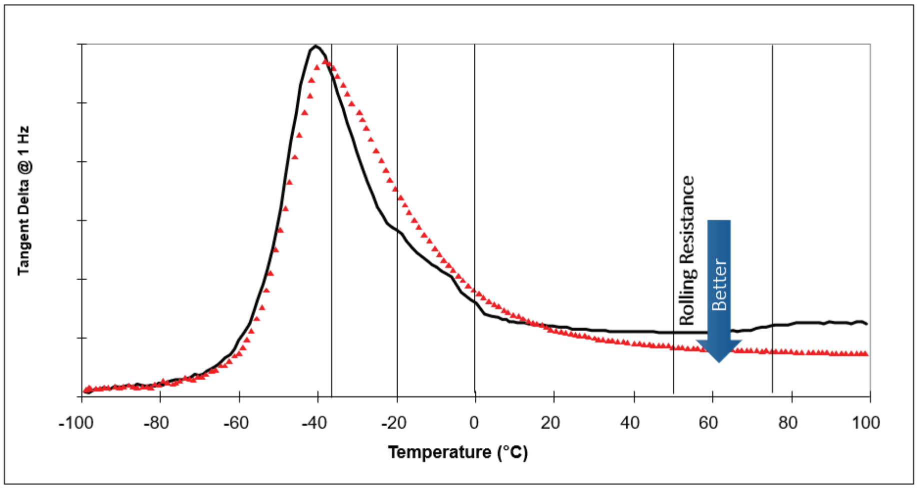

FIG.1, *DMA results for tire tread rubber over a temperature range of -100°C to 100°C*

II. RELATIONSHIP BETWEEN ROLLING RESISTANCE AND FUEL ECONOMY/ RANGE

It is well known that tire rolling resistance (RR) makes an important contribution to vehicle driving resistance force and significantly impacts fuel economy or driving range. Typically, tire rolling resistance contributes 4%-7% to the fuel consumption of internal combustion engine (ICE) vehicles. There are fewer studies on electric vehicles (EV), but on a percentage basis, the tire's contribution to the vehicle's driving resistance force is expected to be higher. This section discusses these differences and the multiple variables that can affect rolling resistance performance.

For traditional ICE vehicles, fossil fuels are burned producing energy that drives the pistons, crankshaft, gearbox, drive shaft, and ultimately the wheels and tires which propel the vehicle. A vehicle driving horizontally at a constant speed will use the available energy through the tires to overcome the driving resistance force. Under these conditions, driving resistance mainly consists of aerodynamic resistance and tire rolling resistance.

The relative impact of these two variables changes dramatically with different vehicle operating conditions. Aerodynamic resistance increases nearly exponentially with vehicle speed and is theoretically independent of the vehicle load according to Eq.1 [3].

$$F = \frac{1}{2} C \rho A_f V^2 \tag{1}$$

F is aerodynamic resistance force
C is the vehicle air drag coefficient
ρ is the air density
Af is the vehicle frontal area
V is velocity

Tire rolling resistance also increases with speed, but the rate of increase does not approach the exponential relationship between aerodynamic resistance and speed. The impact of speed on tire rolling resistance can be observed in the laboratory on a coast-down tire rolling resistance test. Fig. 2 shows data collected on an SAE J2452 test. As detailed in Table 1, each step of the test is run at a specified load and inflation. The test procedure calls for the tire speed to decrease from 115 kph to 15 kph during each step. Graphing rolling resistance versus the time of the speed decrease demonstrates the linear relationship between RR and speed.

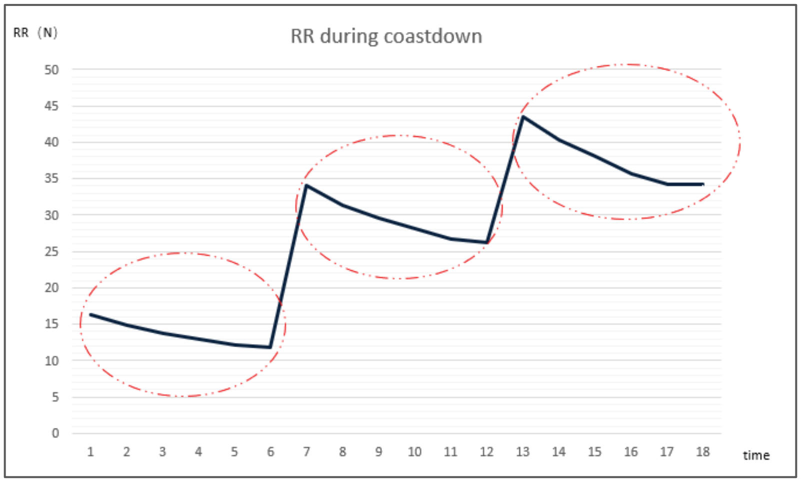

FIG.2, *Tire rolling resistance data collected from an SAE J2452 test*

Load and Inflation Test Matrix		
Step	Load (Kg)	Inflation (kPa)
1	195	260
2	390	210
3	585	310
4	585	210

Table. 1, *Combinations of tire pressure and load used in a PCR tire stepwise coast-down method test*

For illustrative purposes, an on-vehicle coast-down test was conducted on a level road measuring the combination of RR, vehicle inner resistance (energy loss during power transmission from the output end of the gearbox to the tires), and aerodynamic drag. After reaching a high speed the vehicle was shifted to neutral gear and allowed to decelerate. As illustrated in Fig. 3, the slope of the line representing coasting resistance and speed varies with speed. The coasting resistance of both the light truck (coasting down from 100 kph) and the sedan (costing down from 120 kph) decreased more rapidly at higher speeds than at lower speeds. As expected, the coasting resistance of the light truck, with a heavier weight and a larger frontal area, was significantly higher than that of the lighter and more streamlined sedan.

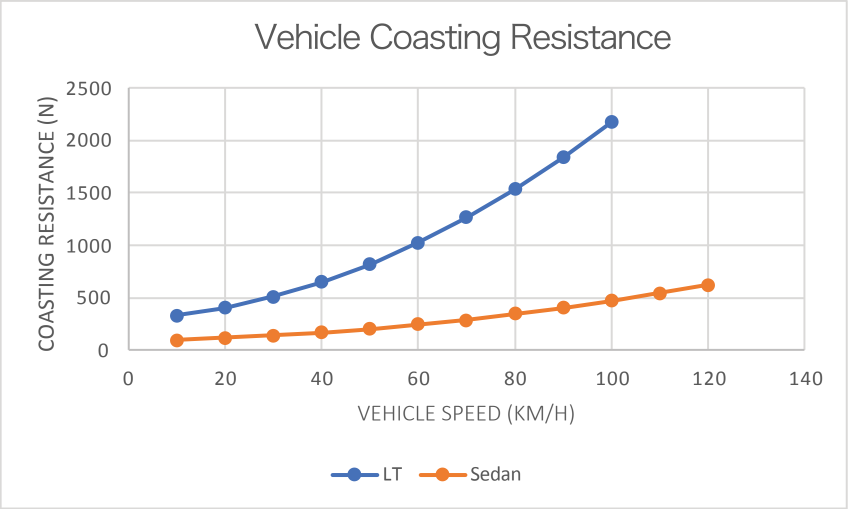

FIG.3, *Coasting resistance measured for a light truck and a sedan coasting horizontally at neutral gear*

In summary, the contribution of rolling resistance to the vehicle's energy consumption varies when the operating conditions change. The contribution of rolling resistance is diluted by the higher percentage of aerodynamic resistance at high speeds but also magnified at low speeds and heavy loads. However, there is no doubt about the importance of rolling resistance. Taking the combined operating conditions (55% urban + 45% highway) used by the EPA to calculate fuel consumption for passenger cars and light vehicles as an example, a 7.3% reduction in rolling resistance brings about a 1% reduction in fuel consumption. For heavy vehicles, a 3.6% reduction in rolling resistance brings about a 1% reduction in fuel consumption [4]. At the same time, the theoretical upper limit of the contribution of tire rolling resistance to fuel consumption under EPA calculations (where RRc=0) is about 14% for passenger cars and light-duty vehicles and up to 28% for heavy-duty vehicles [1].

It's important to note that due to the existence of frictional resistance in the transmission system, the energy output of the engine is not fully transferred to the wheels and tires as the transmission, drive shaft, and other components produce energy losses. Therefore, for ICE vehicles, mechanical transmission losses are an important contribution to fuel consumption. In the case of electric vehicles, the engines and the gearbox have been removed and the motors are usually mounted close to the wheels, therefore, the power transmission path is greatly shortened and mechanical transmission losses are greatly reduced. However, EVs are negatively impacted by battery weight, meaning that, even with the same tires, tire rolling resistance will increase due to the increased load.

Take a hypothetical example that compares a compact SUV in both ICE and EV configurations. The mass of the ICE version is 1400kg. When it drives at a constant speed of 80kph, assuming that the tire rolling resistance is 100N, the aerodynamic resistance is 525N and the efficiency of the transmission system is 0.85; thus the total resistance is 625N. In order to maintain a constant speed, the power source (engine) needs to provide a driving force of 625/0.85 ≈ 735N, and the tire rolling resistance contribution accounts for 100/735≈13.6%. The electric version has a mass of 1700kg; 300kg heavier than the ICE version. Assuming the tire rolling resistance coefficient and the air resistance remain unchanged, and the efficiency of the transmission system rises to 0.93, rolling resistance will increase to 120N and the total resistance is 645N. In order to maintain a constant speed, the driving power source (the electric motor) needs to provide a driving force of 645/0.93 ≈ 694N. The tire RR contribution increases to 120/694≈17.3%, 27% higher than the ICE version (17.3% vs 13.6%). This example highlights the increased significance of tire rolling resistance in EVs.

	ICE	EV
Mass (Kg)	1400	1700
Rolling Resistance coefficient	0.071	0.071
Rolling resistance (N)	100	120
Aero resistance (N)	525	525
Efficiency of the transmission system	0.85	0.93
Total resistance (N)	625	645
Driving force needed	735	694
Tire rolling resistance contribution to driving force	13.6%	17.3%

Table. 2, *Comparison of energy-related parameters between a hypothetical compact SUV in ICE and EV configurations*

III. RELATIONSHIP BETWEEN ROLLING RESISTANCE AND TEMPERATURE

There is also a complex relationship between tire rolling resistance and temperature. Two tires with similar rolling resistance performance at room temperature may exhibit different rolling resistance coefficients (RRc) relative to each other at higher or lower temperatures. This can create challenges when optimizing for fuel consumption or range performance over the full set of environmental conditions. This is a more critical consideration for EVs, especially in low-temperature operating conditions when the combination of decreased battery efficiency and increased tire RR contributes to a decline in vehicle range. Fig. 4 shows the measured driving range for the 14 best-selling Battery Electric Vehicles (BEVs) in the Chinese market when tested at “winter” conditions (-15°C to -20°C) vs “summer” conditions. In this testing, the “summer” conditions were measured between 18°C to 28°C in accordance with the New European Driving Cycle (NEDC). The average drop in vehicle driving range from “summer” to winter” temperatures was measured at 52% for these 14 BEVs.

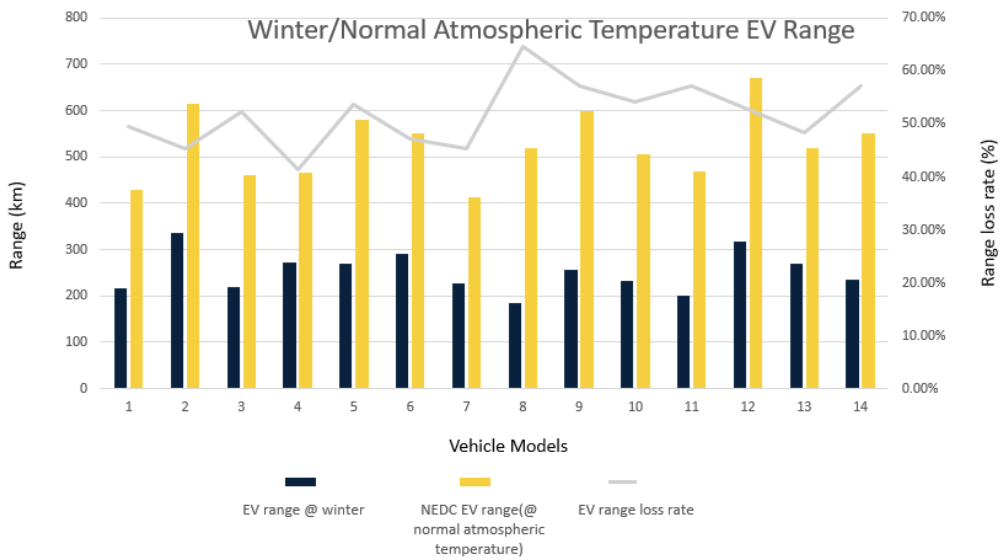

FIG.4, *Winter cruising range test report of 14 best-selling BEVs in China market (media report, https://mp.weixin.qq.com/s/SrwKUCI5OwrgLwPR_Ssufg)*

Therefore, in conjunction with the worldwide trend of vehicle electrification, testing the rolling resistance of tires at a wider temperature range, especially at low temperatures, has become an area of interest for many OEMs.

It has been understood for many years that tire rolling resistance and temperature are highly correlated, whether it is measured across an ambient temperature difference or across the difference in the temperature of the tire itself (e.g. tire temperatures prior to running and after a specified period of time) [5]. To account for this tire temperature change, most rolling resistance test methods require that the tires are conditioned at the test environment temperature for a specified period of time before the test begins. Also, tires must be warmed up sufficiently to ensure that the tire temperature and rolling resistance measurements are stable before data is collected.

The ultimate purpose of rolling resistance testing is to characterize how the tire could perform on a given vehicle to optimize fuel consumption/range. The real-world driving environment is made up of a variety of factors that could affect tire rolling resistance. Excluding road factors, the load, speed, tire pressure, temperature, and other conditions are also changing. However, current rolling resistance test methods cover very limited operating conditions.

The single-point method represented by ISO 28580 only tests rolling resistance under a single combination of temperature, load, speed, and tire pressure. The stepwise coast-down method represented by SAE J2452, while taking different loads, speed, and tire pressure into consideration, still tests at a room temperature environment only.

IV. USE OF DMA TESTING TO UNDERSTAND TEMPERATURE EFFECTS

As it relates to temperature variance, some theoretical inferences on rolling resistance performance can be made from DMA test results. The conventional DMA testing method is to conduct a temperature sweep (e.g., -80℃~80℃) at a certain change rate when applying a specific frequency of cyclic strain (e.g., 15% strain 1 Hz frequency) to the rubber sample. Therefore, the variation of rubber hysteresis characteristics with the variation of temperature can be seen from the results of a DMA test. In general, the hysteresis characteristics of tire tread compounds are much higher in the lower temperature range than in the normal temperature range, which deteriorates rolling resistance performance. Both carbon black-filled and silica-filled compounds have a relatively similar curve as it relates to temperature. Tan δ peaks at low temperatures (e.g. around -40°C) and decreases significantly as the temperature rises, as clearly illustrated in Fig. 5.

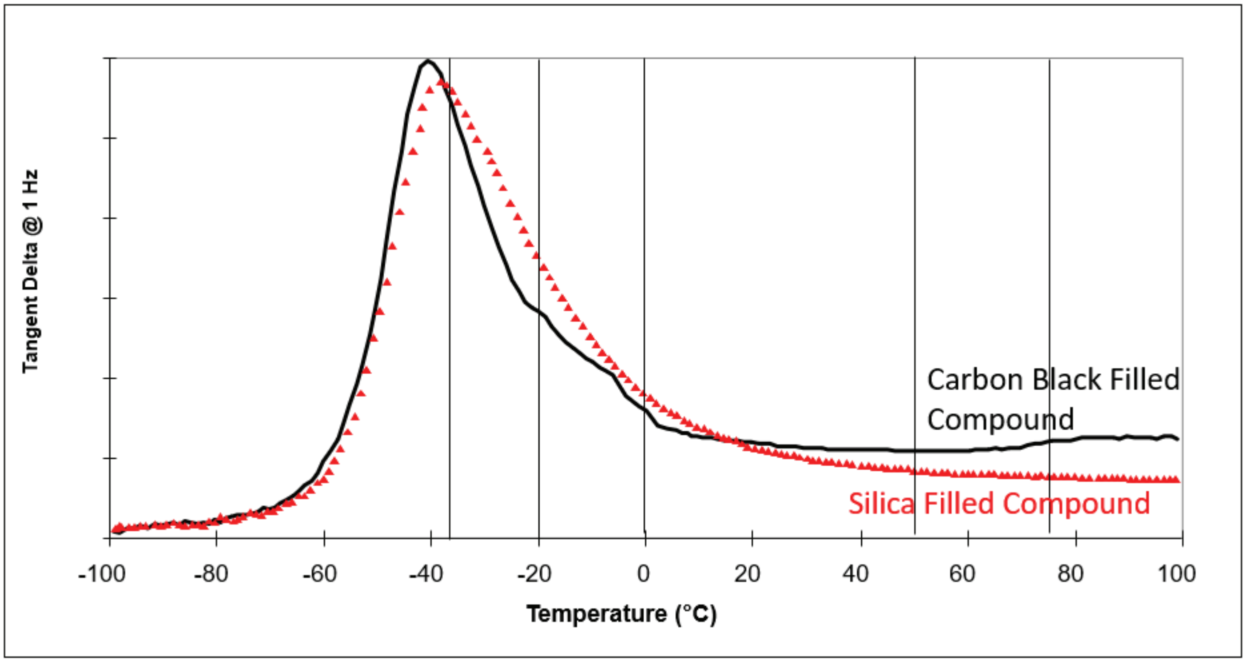

FIG.5, *DMA results for tire tread samples with carbon black filled compound and silica filled compound respectively with a temperature range of -100*°C *to 100*°C

It should be clear, however, that predicting tire rolling resistance directly from DMA results is difficult and not advisable for two main reasons.

1. DMA testing has limitations. Due to cost efficiency and the difficulty of sampling, in most cases, only the samples from tread and sidewall areas are tested for DMA. In addition, as mentioned above, DMA is often measured at a fixed frequency and strain, but the actual tire driving conditions vary widely. Therefore, the DMA results cannot be generalized to all conditions.
2. Ambient temperature is not equal to the tire rubber operating temperature. When the tire is driven to the state at which the rolling resistance is stabilized, it reaches a state of thermal equilibrium. Heat generation and dissipation become balanced, and the temperature is subsequently stabilized around a certain value. However, it is also clear from the DMA results that the hysteresis characteristics of the rubber vary considerably with temperature (Fig. 6), and slight fluctuations may substantially change the position of the final equilibrium point.

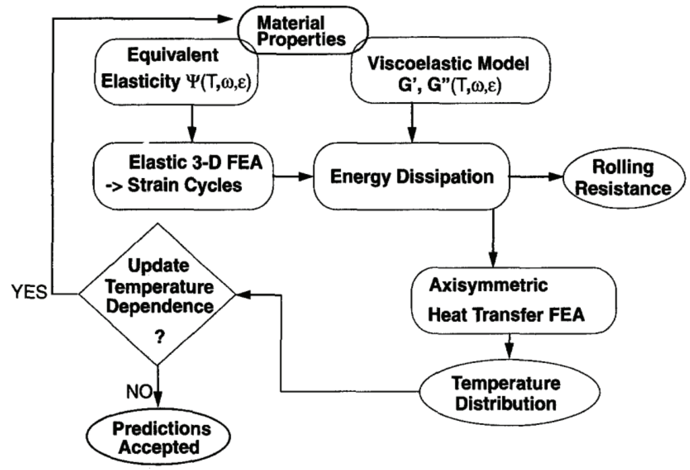

FIG.6, *Thermal-mechanical process for a finite element analysis-based rolling resistance and temperature distribution prediction*

As illustrated in Fig.6, temperature changes impact tire material characteristics because the stress-strain distribution and hysteresis characteristics of the tire are altered [6]. The total amount of heat generation and the heat transfer characteristics change, leading to more temperature fluctuation. Starting the cycle again, the new temperature drives changes in material properties, and this cyclic loop continues until equilibrium is reached.

It is important to recognize that equilibrium does not mean a uniform temperature for all parts of a tire. Fig. 7 and 8 are provided as simple examples of how temperature varies at different points on a tire being tested. A thermal image of a tire being run on a rolling resistance test is shown in Fig 7. It highlights the temperature variation seen across the tread area. Fig. 8 shows the results from a study on predicted tire temperature from finite element analysis versus actual temperature measurements on a test tire. Temperatures varied by 23°C across various points of the tested tire, with a temperature of 56°C measured for the inner liner at the crown and only 33°C measured in the outer bead.

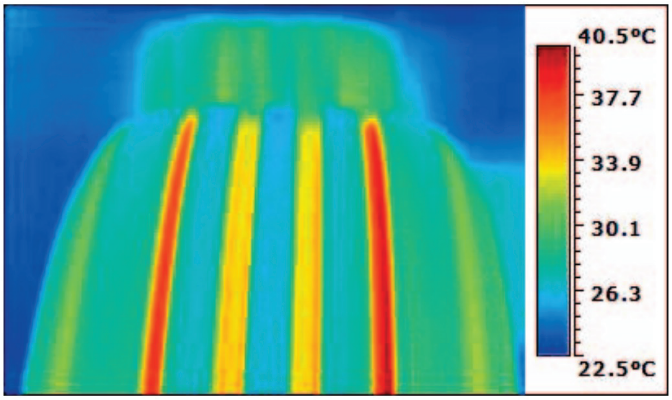

FIG.7, *Thermal camera image of a tire subjected to rolling resistance test*

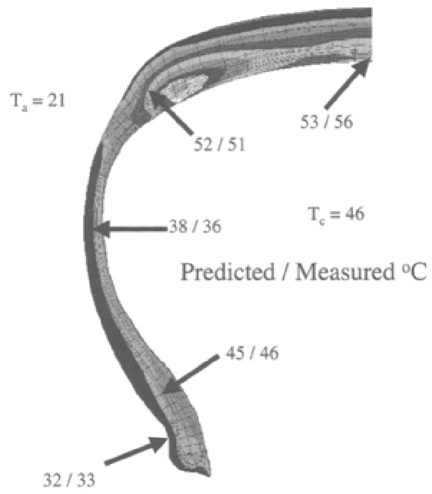

FIG.8, *Comparison of predicted and measured surface and internal temperature for a P195/75R14 tire*

In summary, the material-based approach to understanding rolling resistance at low temperatures provides some theoretical suggestions that low temperatures could adversely affect rolling resistance performance. This suggests that laboratory-based tire rolling resistance testing at low temperatures is critical to understanding true vehicle fuel efficiency/range effects in various real-world conditions.

V. LABORATORY-BASED ROLLING RESISTANCE TEST MEASUREMENT AT HIGH/LOW AMBIENT TEMPERATURES

In an attempt to understand temperature-based effects and support the automotive industry, Smithers introduced a new high- and low-temperature rolling resistance testing machine (as shown in Fig. 9) at its tire and wheel testing laboratory in Suzhou, China in August 2022. A series of initial tests have been conducted to better understand the effects of multiple temperatures on rolling resistance performance.

FIG.9, *Test equipment: high/low temperature rolling resistance test machine at Smithers lab in Suzhou, China*

A. SINGLE POINT TEST METHOD（FIG.10 WITH TEST METHOD ISO 28580）

Four different brands of 235/55R17 All-season tires were tested according to ISO 28580. This method is used by vehicle OEMs and tire manufacturers to evaluate tires, often in support of tire labeling requirements. Tires are normally run only at 25°C (room temperature). During this test, the tires were tested at 25°C, but also at 35°C, - 10°C, and -°20C. to better understand performance at both high and very low temperatures.

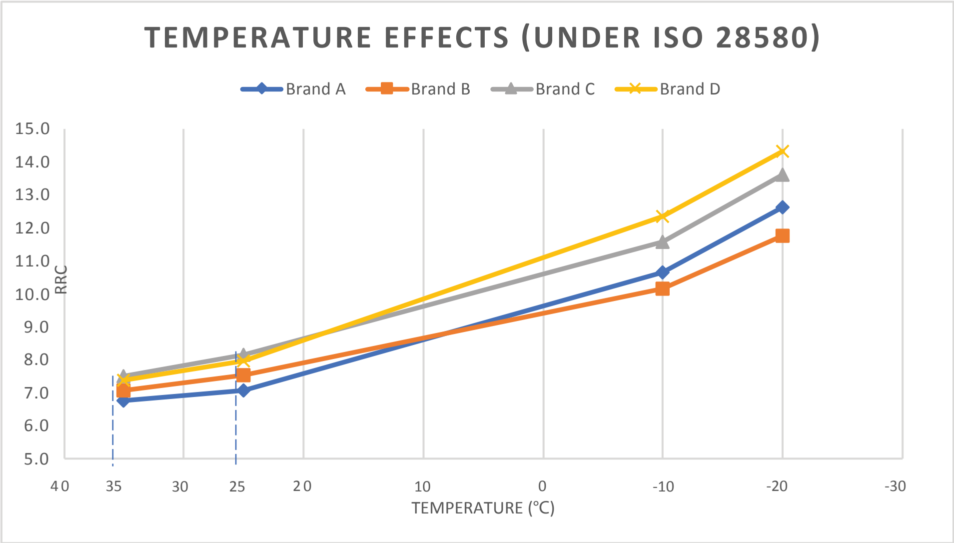

FIG.10, *Temperature effects on tire rolling resistance of tires from 4 brands under test method*: *ISO 28580*

Summary:
The rolling resistance coefficient (RRc) increased with a decrease in temperature. Tires were more sensitive at low temperatures than at high temperatures.

1. RRc at 25°C vs 35°C:
    a. RRc of all tires decreased with increasing temperature
    b. RRc increase ranged from 4.6% to 7.7%, with an average of 6.1%
2. RRc at 25° vs -10°C:
    a. RRc of all tires increased with decreasing temperature
    b. RRc decrease ranged from 35% to 55%, with an average of 45%
3. RRc 25°C vs -20°C:
    a. RRc of all tires increased with decreasing temperature
    b. RRc increase ranged from 56% to 80%, with an average of 75%
4. RRc sensitivity to a 10°C temperature change when measured at “high” vs “low” temperatures
    a. For the same 10°C delta: RRc variation between -10°C / -20°C was much greater than 25°C / 35°C, and the slope of the curve increased as the temperature decreased. In other words, tires are more sensitive relative to RRc at a lower temperature range compared to a higher temperature range.
5. Brand A vs Brand B:
    a. Brand A had lower RRc than Brand B at high temperatures
        i. 6% lower at 25°C, and 5% lower at 35°C.
    b. Brand A had a higher RRc than Brand B at lower temperatures
        i. 5% lower than Brand A at -10°C, and 7% lower at -20°C.
6. Brand C vs Brand D:
    a. Brand C and D had similar RRc at high temperatures (35°C & 25°C)
    b. Brand C had lower RRc than Brand D at low temperatures,
        i. 7% lower than D at -20°C, with a 9% delta

B. COAST-DOWN METHOD（FIG.11 WITH TEST METHOD: SAE J2452）

Two different brands of 235/55R17 All-season tires were tested according to SAE J2452. As described earlier, this method uses various loads and inflation pressures and uses a coast-down period to understand rolling resistance measurements as the speed decreases. Tires were studied at room temperature (as indicated in the standard) as well as at -10℃ and -20℃.

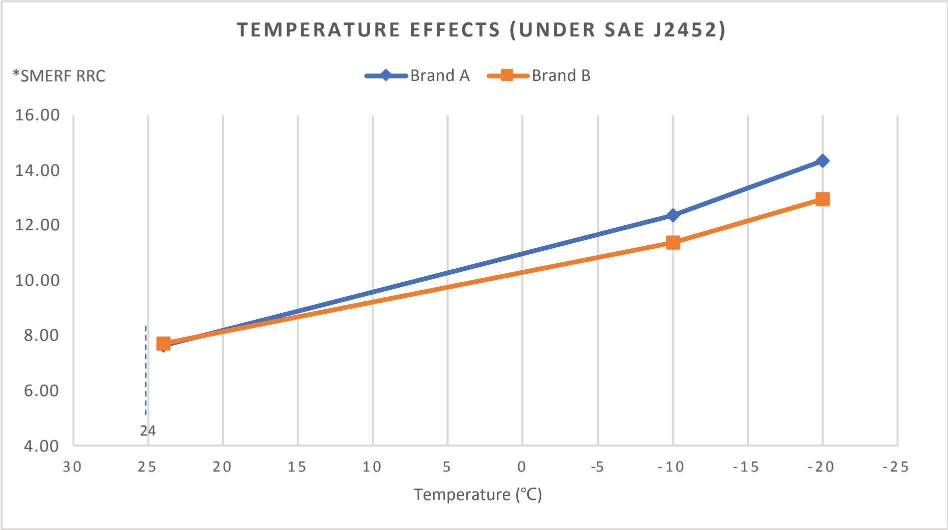

FIG.11, *Temperature effects on tire rolling resistance of tires from 2 brands under test method*: *SAE J2452*

**Note: SMERF (standard mean equivalent rolling force) is the combined weighting of the average rolling resistance of a tire, at a given load/inflation condition, over a driving cycle with a specified speed-time profile, calculated using the standard EPA urban and highway driving cycles [7]. Specifically, this weighting is 55% for the EPA Urban Federal Test Procedure (FTP) Cycle and 45% for the EPA Highway Fuel Economy Cycle.*

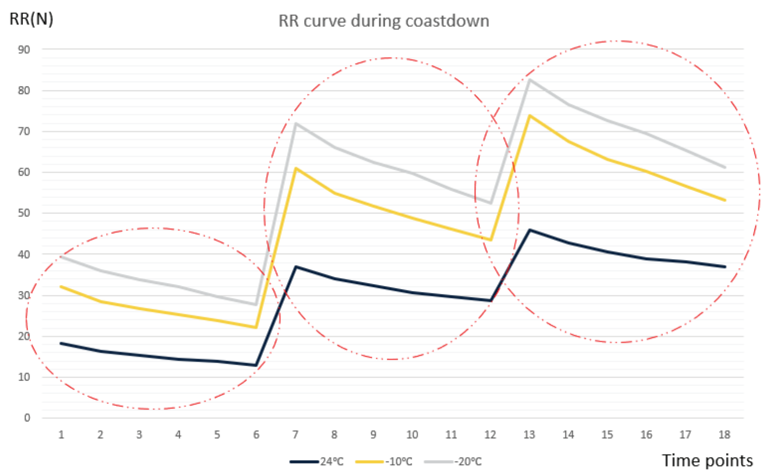

FIG.12, *Rolling resistance of the same PCR tire measured at different temperatures*

As in Fig. 2, each downward slope in Fig. 12 shows that the tire coasted down from 115kph to 15kph at a specific combination of inflation/load. Curves in the same oval shared the same combination.

Summary:
Similar to the single-point method, RRc increased with a reduction in temperature.

1. *Brand A vs Brand B:* Two tires showed similar SMERF RRc at 24°C, Brand A was only 1.1% lower than B. But a difference is seen when the temperature dropped below zero, where Brand A was measured at 8% higher than B at -10°C (9% delta compared to 24°C) and at 10% higher than B at -20°C (11% delta compared to 24°C)
2. *RR curve comparison of a single tire at different temperatures:* All three curves measured at different temperatures matched the tendency that RR increased as temperature decreased. Meanwhile, as the curves were not parallel, it showed that the RR differences between temperatures were greater at high speed and lower at low speed.

Overall Observations and Conclusions:

1. Compared to ICE vehicles, tire rolling resistance has a higher contribution to vehicle fuel economy/range for EVs.
2. Tire RRc performance is strongly influenced by temperature. RRc increased as the temperature decreased and is more sensitive at low temperatures compared to high temperatures.
3. At low temperatures, as the temperature decreased, the change rate of RRc increased (steeper slope).
4. Notable low-temperature RRc differences between tire manufacturers objectively exist.
5. After years of tire development, RRc performance of current OE tires is already at a comparatively low level (i.e., ISO 28580 RRc around 7.0). Assuming that there is no revolutionary breakthrough in tire technology, every improvement in RRc at room temperature often comes with a cost increase or trade-off in other tire performance characteristics. Compared to improvements in fuel economy/range by requiring significant RRc reduction at room temperature, improving low-temperature RRc performance through tire innovations could be a more effective and cost-efficient solution.

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Henry joined Smithers in 2012 and has supported the Smithers tire, wheel, and product testing groups in various technical and management roles. Currently, as General Manager, he leads a team of technical experts supporting the tire industry, wheel industry, vehicle OEMs, and raw material suppliers.

Henry has accumulated expertise in test and data analysis, experimental method development, business operations, and management during his years of experience. He oversees durability and performance testing of tires and wheels for suppliers across the industry value chain.

Henry is an expert group member in the Rubber Testing Professional Committee and committee member in the China Technical committee for Tire/wheel Standardization. He earned his first ISO 9000 internal auditor qualification in 2006 and ISO 17025 internal auditor qualification in 2010.

Henry received his Bachelor's degree in Measurement & Control Technology and Instrumentation from Anhui Polytechnic University and Master's degree in Business administration from East China Jiaotong University.

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Edward joined Smithers in 2022 as the Lead Technical Engineer in the Materials Science and Engineering Division, Asia Pacific. He is primarily focused on Smithers tire and wheel testing solutions development, consulting services in tires and vehicle dynamics, internal R&D studies, and technical decision-making.

Edward is proficient in various performance requirements for tire development and corresponding test methods, such as rolling resistance, force and moment, NVH testing, tread wear, as well as others.

Over the past 11 years, he worked in for Giti Tire, FCA, and Ford focusing on tire performance, design development, tuning, and experimental verification of passenger vehicle tires. Edward graduated from the Vehicle Engineering Department of Anhui Agricultural University with a bachelor's degree.