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Research paper

The correlation research between ground contact characteristics and rolling resistance of a tire

Nam Woong Kim [1], Jinwook Jung [1], Haeng Muk Cho [2] *

[1] NEXEN R&D Center, 201 Gukgasandanseo-ro, Guji-myeon, Dalseong-gun, Daegu, South 43011, Korea
[2] A Division of Mechanical and Automotive Engineering, Kongju National University, Cheonan 31080 Korea
**Corresponding author E-mail: hmcho@kongju.ac.kr*

Abstract

This study was aimed to find out the correlation between the ground contact characteristics and rolling resistance of a tire. To accomplish the goal, we used 40 sets of tires with the different rolling resistance to examined the tire ground contact characteristics and rolling resistance coefficient of the vehicles in motion. This research team assessed the tire ground contact characteristics with a dynamic contact pressure measurement system equipped with small 3-axis force sensors and 6-axis force & moment sensors, analyzing the contact patch shapes, 3-axial forces (Fx, Fy, Fz), force distribution, and vectors, which practically occur on a real track. In addition, the rolling resistance of a tire was tested according to Force Method as stipulated in ISO-28580, using the equipment (KOBE Co.). The test result showed that the magnitude of Force X among tire ground contact characteristics, which is applied in the direction a car moves, is highly correlated with rolling resistance and the rest (Force Y, Force Z, Contact Patch Shape, and vectors) turned out not significantly correlated with rolling resistance. In addition, when the characteristics of ground contact and resistance by air pressure were compared, a high correlation with Force X was reconfirmed. Moreover, coasting test confirmed the actual effect of tire rolling resistance upon the running resistance of a vehicle. In this study, we analyzed the correlation between tire ground contact characteristics and rolling resistance and experimentally derived major performance factors. In the future, we plan to conduct other experiments regarding the correlation between tire ground contact characteristics and rolling resistance in various driving environments.

Keywords: *Dynamic Ground Contact. Rolling Resistance. Contact Characteristics. Correlation Research. Coast Down Test.*

1. Introduction

As countries have more tightened regulations on environmental pollution, more interest divers to eco-friendly cars and tires. Accordingly, automobile companies and tire manufacturers have developed technologies to cope with such requirements to meet the demands of drivers and regulatory authorities. As a result, eco-friendly and low fuel consumption tires have been invented; especially such tires make a great contribution to reducing environmental pollution as well as improving fuel mileage by reducing the rolling resistance of a tire. In this study, we focused on the correlation between rolling resistance, which is most closely related to a tire among many types of resistance a car has while running, and ground contact characteristics. Tire rolling resistance was measured with the rolling resistance measurement device in accordance with the provisions of ISO-28580 while tire ground con-tact characteristics were measured and analyzed with the dynamic contact pressure tester. Based on these analyses, we carried out correlation analysis to confirm rolling resistance mechanism. In addition, various validation and reliability tests were implemented to derive the key performance factors that can explain rolling resistance.

2. Experiment

2.1. Vehicle drag

Running or tractive resistance is the resistance that a car has while running. It is largely classified into rolling resistance, air resistance, and gradient resistance. Running resistance has to be overcome by an engine power system and total running resistance determines the driving force conveyed from the engine system to the wheels. Driving performance (e.g. maximum speed, climbing capacity, and acceleration capability) of a vehicle is determined by the interaction of running resistance, engine torque and drive train efficiency.

2.1.1. Rolling resistance

Rolling resistance is the overall resistance a car faces while traveling on a horizontal road. It is closely related to a tire rolling resistance on which we focused in this study. Since we assumed driving straight on the dried surface of an asphalt road for our experiments, curving resistance or water scattering was mostly ignored. Rolling resistance is calculated with total reaction force multi-plied by rolling resistance coefficient and

$$F_R = f_R \times F_n \quad (1)$$

2.1.2. Air resistance

Air resistance means air force that is applied in an opposite direction to the direction in which a car progresses. It is heavily influenced by air density, the protruded area of a car's front, the resultant velocity of headwind, and a vehicle' shape.

$$F_L = C_W \times A \times \rho/2 \times (V_{res})^2 \quad (2)$$

2.1.3 Slope Resistance

Slope resistance is the resistance applied to the back of a car's center by the opposing component of force to the progress direction of gravity when it climbs up a slanting hill. Slope resistance varies by a car's mass and the slope of a road surface. [1].

$$F_S = m \times g \times \mathrm{Sin}\alpha \quad (3)$$

2.2. Evaluation equipment

Three measurement systems were mainly used for this study. First, a dynamic contact pressure gauge (A&D Co.) was employed to measure 3-axis force and its distribution. This equipment is installed on the surface of the road on which cars actually travel and equipped with 4 small 3-axis force sensors (7.5mm x 7.5mm / Fx, Fy, Fz) and Force & Moment sensors to scan the tires and collect their data. Horizontally installed on the surface of a real road, it can analyze the tire ground contact characteristics in various driving conditions where a car's geometry is reflected. In addition, it can adjust the frictional coefficient of a road surface through processing the roughness of the dimples and plate of the sensor surface. [2] Second, VBOX 3 (Race Logic Co.) was used to improve the accuracy of the experiment. It is a GPS-based universal instrumentation device, which is mostly used by vehicle-related companies. Easy to install, the device can measure a car's velocity and strain by using GPS data. Therefore, it can travel exactly over a dynamic contact pressure gauge, excluding the external interventions that may affect tire ground contact characteristics as much as possible. Third, a rolling resistance measurement device (KOBE Co.) was employed to measure a tire rolling resistance. For the measurement methods of rolling resistance, there are some: Force Method, Torque Method, Deceleration Method, and Power Method. For this study we used Force Method stipulated in the provisions of ISO-28580.

2.3. Test vehicle and tire

Table 1 shows the vehicles and tires used for this study. 4 domestic vehicles in different segments and 40 sets of tires with different compound structures were used.

Table 1: Test Vehicle and Tire Information

Test Vehicle	Tire Type	Tire Size	Tire Variable	Quantity
A	AS SM	15 ~ 18 inch	Compound Structure Etc.	40 Set
B				
C				
D				

2.4. Test condition

To prove the repeatability and reproducibility of a test and prepare for a safety accident, only experienced drivers ran the test vehicles. Tests were conducted mainly to measure and analyze a tire rolling resistance and dynamic ground contact characteristics. For dynamic ground contact characteristics, a preliminary study had been conducted to come up with validated test conditions.

Table 2: Test Condition

Tire Rolling Resistance	Dynamic Contact Pressure Characteristics		
Method	Velocity	Method	Test Freq.
ISO 28580	80km/h	Coasting Down	Average of 5 Times
Addition			
Running Resistance of a Car with Varying Air Pressure			

3. Test result

3.1. Dynamic ground contact characteristics

The ground contact characteristics of a tire in motion are characterized by mainly 3 components of force (Force X, Force Y, and Force Z). And the data of ground con-tact force on each axis allows additional analyses on other contact characteristics such as dimension, shape, and force distribution. These tire ground contact characteristics are used as important data in understanding the driving characteristics of a car and supplementing the shortcomings. [3]

3.1.1. Force X (longitudinal force)

Force X happens in the same direction as that in which a tire progresses and has a large value mostly when a car starts and stops. The negative values are expressed in blue and the positive ones are displayed in red. The blue contact surfaces indicate the force working backward while the red contact surfaces represent the force working forward. Under accelerated driving conditions, the blue area becomes bigger because the force that works (pushes) backward is applied to most of the contact surfaces. Whereas, when it is a halting condition, the force that works forward is applied to most of the contact surfaces mode. Therefore, the red area increases.

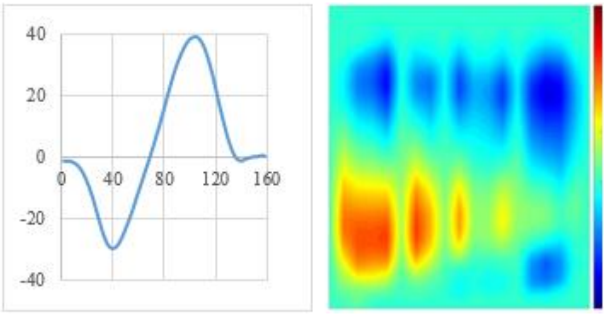

Fig. 1: Force Distribution & Shape (Longitudinal).

3.1.2 Force Y (lateral force)

Force Y occurs to the sides of the direction in which a tire progresses and has a large value mostly when a car turns. The negative values are expressed in blue and the positive ones are displayed in red. The blue contact surfaces indicate the force working to the left of the direction in which a car progresses while the red contact surfaces represent the force working to the right of the direction. When a car turns, most of the force is applied in the opposing direction to that in which the car turns.

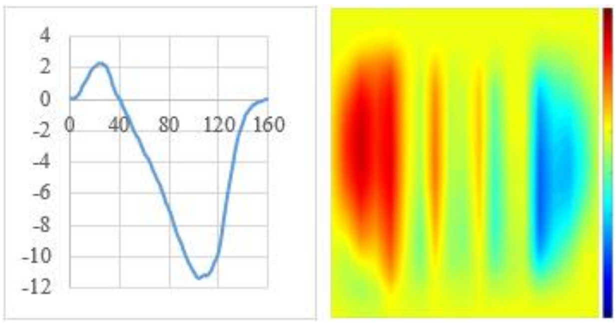

Fig. 2: Force Distribution & Shape (Longitudinal).

3.1.3. Force Z (vertical force)

Force Z is generated at right angles to the direction in which a tire progresses and the pressure applied to a tire at this time is proportional to the wheel load of the car. It al-ways works in a positive direction because of gravity. This character allows Force Z to be mainly used in analyzing dimension and shape among tire ground contact characteristics. Besides, it is also used to estimate the areas of a tire where wear progresses quickly and abnormally by analyzing the pressure and vectors applied to the tire.

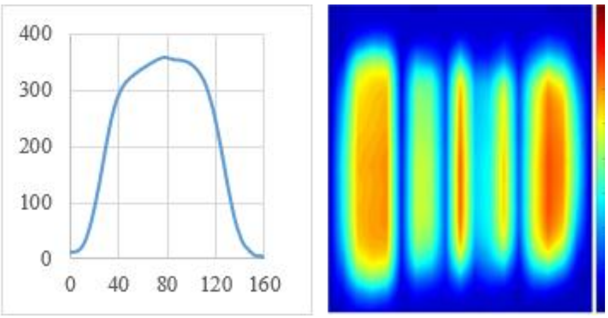

Fig. 3: Force Distribution & Shape (Vertical).

3.2. Rolling resistance mechanism

Force X, which is applied to a road surface when a tire turns, works as in Figure1. The force that pushes back-ward first hap-pens at the leading edge and then one that pushes forward occurs after passing some sections, which is closely related to the rolling resistance of the tire. After all, one of the two directions of forces, which hap-pen to the surface of a road, becomes the force to pre-vent the tire from rolling. This experiment revealed the mecha-nism that Force X, which works to the road surface, has such characteristic, and the result is well explained in Figure 4. [4]

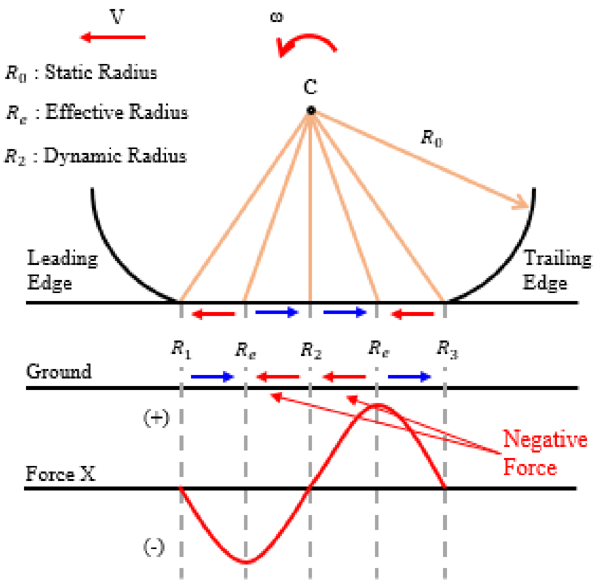

Fig. 4: Rolling Resistance Mechanism.

The tires of a car in motion have four different radii of rotation (R0, R1=R3, R2, Re). The speed of a tire in motion (road velocity) is easily calculated by multiplying effective radius (Re) by angular velocity. All radii of rotation but effective radius become shorter or longer than effective radius. The difference causes the speed to change in every section. Eventually, change of speed (velocity) becomes the direct cause for which the direction of Force X changes and make it have such force characteristics as in Figure 1. Because the speed at a tire's leading edge is greater than Re ω, which is a tire's progress speed of an actual tire, a slip occurs to a road surface and the tire, which eventually makes the force to push the surface back-ward. For the reason, Force X starts in a negative direction at the leading edge of the tire. Force X keeps in-creasing in (-) direction until the section of the effective radius where the speed of the tire turns identical to that of the road surface and records its peak there. And in the section of loaded radius (R2) where the speed of the tire becomes lower than that of the surface, the force to push the surface forward occurs. From the point, Force X increases in (+) direction. The ever-increasing Force X reaches its peak again at the section of effective radius (Re) where the speed of the tire and that of the road surface becomes same and decreases from trailing edge (R3) for the same reason as in leading edge (R1), returning to the original speed. This mecha-nism was confirmed in the experiment and this finding helped indirectly find the section where the force to prevent a tire from rolling, which became the foundation for correlation analysis.

3.3. The correlation between dynamic ground contact characteristics and tire rolling resistance

Based on the mechanism previously described, correlation analy-sis was conducted between dynamic ground con-tact characteris-tics and tire rolling resistance. The result con-firmed that the larg-er the size of Force X, which works in (+) direction, is, the greater tire rolling resistance is. Figure 5, Table 3 shows the results of the correlation analysis between tire rolling resistance and (+) Force X.

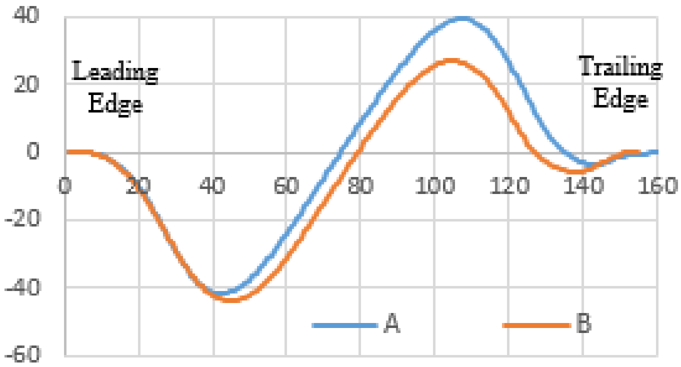

Fig. 5: Force X Distribution.

Table 3: Relation between RR and Area

Tire Size	Load	Tire	RR	Area
195/60R16	464kg	A	8.71	1391
		B	5.65	797

It was confirmed that the greater tire rolling resistance is, the wid-er the size of (+) Force X is. And a reliability test was conducted with 40 sets of test tires to verify the result. As a result, it was known that 80% of the results were reliable and some results, which were less reliable, were considered interfered by the exter-nal forces such as wind. It is expected that the correlation coeffi-cient will be much higher if external conditions are controlled to minimum. Because tire ground contact characteristics change, however, by the size of a tire or a car condition, it is still difficult to conduct an integrated correlation analysis.

3.4. The change of tire ground contact characteristics by tire air pressure

There is an empirical formula that explains that a lower tire air pressure leads to the increase of tire rolling resistance as shown in Figure 6.

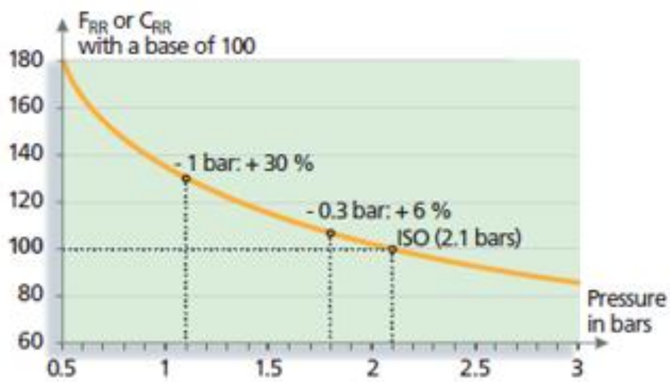

Fig. 6: Effect of Tire Air Pressure (Passenger Car) [5].

$$F_{RR} = F_{RR} \times (P/P_{ISO})^{\alpha} \quad (4)$$

Using testing actual cars, we carried out additional correlation analysis between tire ground contact characteristics and the change of tire air pressure. Air pressure was set from 14psi to 44psi, changing it by 5psi. Figure 7 and 8 show the air pressure distribution and Force X changing by air pressure, respectively.

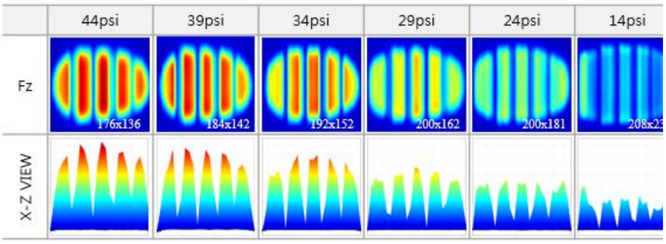

Fig. 7: Tire Contact Pressure Distribution by Tire Air Pressure.

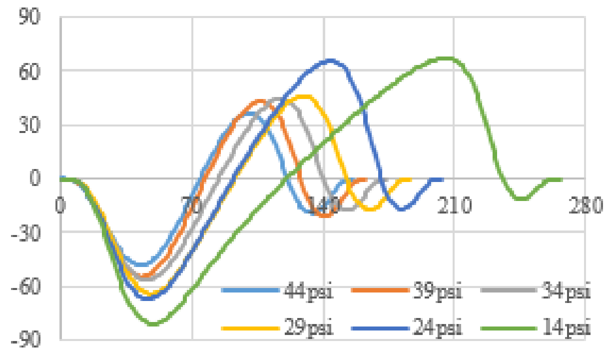

Fig. 8: The Characteristics of Force X by Tire Air Pressure.

It was confirmed that the size of (+)Force X, which was de-rived as the main factor for tire rolling resistance in the earlier section, increases as tire air pressure de-creases. In addition, the contact distribution suggests that when a tire has a high level of air pressure, load concentrates on the center of the tire while a tire has a low level of air pressure, load concentrates on the inside or outside of the tire, which can give a clue to a tire friction and wear. [6]

3.5. The comparison of running resistance through coasting test with actual vehicles

To know the effect of tire rolling resistance on the running resistance of a vehicle, we implemented coast down test. With the tires with the similar rolling resistance coefficient to that of the two tires explained in 3.3, we con-ducted a coasting test from 115km/h and 15km/h. A Two-way test was adopted to minimize the effect of wind and running resistance coefficient was calculated using the weather information of a meteorological observatory. The result is shown in Figure 9, confirming that the difference of tire rolling resistance has an effect on the running resistance of a vehicle.

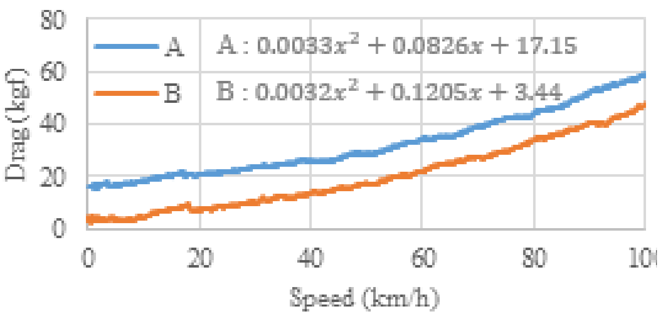

Fig. 9: The Comparison of the Running Resistance.

$$Me\, dv/dt = A_m + B_m V + C_m V^2 + 1/2rAV^2 \pm Mgdh/ds \quad (5)$$

In this express, the second-order terms are determined by air resistance and the first-order terms and the constant are determined by mechanical resistance. And we can see that as tire rolling resistance changes, mechanical resistance except air resistance decrease to a great extent. Explained by the mechanism of tire rolling resistance, which we derived earlier in this paper, this difference reconfirmed the correlation be-tween tire ground contact characteristics and tire rolling resistance.

4. Conclusion

In this study, we used 40 sets of tires and 4 vehicles in different segments, we first examined 3-axis force that hap-pens to the contact surface of a car in motion. Second, in-vesting Force X, which is most closely related to tire rolling resistance, allowed us to find and establish the mechanism of tire rolling resistance. Third, based on the mechanism of tire rolling resistance, we carried out a correlation analysis between tire running resistance and tire ground contact characteristics. Fourth, we derived (+) Force X, which is the dynamic contact performance factor that explains tire rolling resistance. Fifth, we found out that as tire rolling resistance increases, the size of (+) Force X increases and verified the fact through an additional test. This study was attempted to examine the dynamic characteristics of a tire that has been difficult to visualize and resulted in a satisfactory outcome of the correlation between tire rolling resistance and tire ground con-tact characteristics. In the future, this team plans to conduct research in the correlation between a tire and a vehicle performance in various driving environments.

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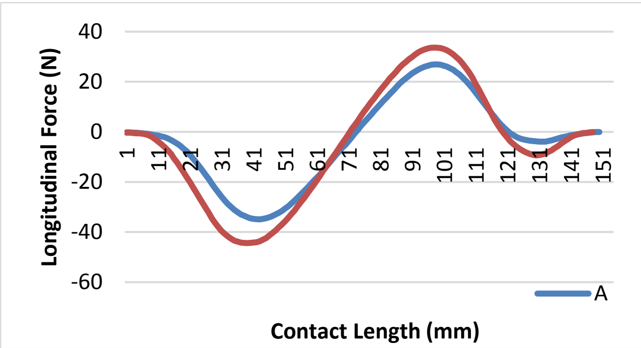
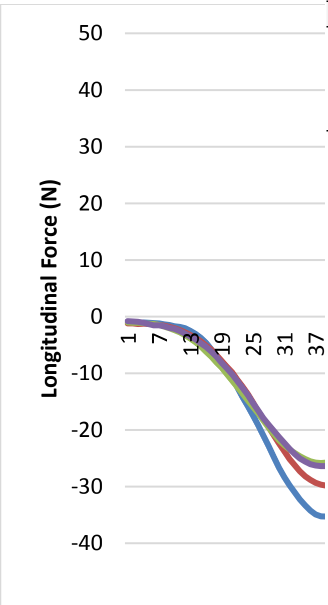


Appendix

Test Result 1



Tire Size	Load	Tire	RR	Area
195/65R15	491.8kg	A	8.93	1406
		B	9.52	1534
		C	9.11	1439
		D	8.71	1292

Test Result 2

Tire Size	Load	Tire	RR	Area
205/60R16	491.8kg	A	7.38	777
		B	8.04	1005