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# LABORATORY MEASUREMENT OF ROLLING RESISTANCE COEFFICIENT UNDER DIFFERENT CONDITIONS

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The aim of our research was to design and construct a measuring device that can determine the rolling resistance coefficient (*RRC*) under laboratory conditions. The measuring device has a drum arrangement and the *RRC* was measured on two different model surfaces. The deceleration method was used to investigate the dependence of the *RRC* on the compression force, velocity and surface temperature on steel as well as rubber surfaces. The measured *RRC* values (0.010–0.025) were similar in magnitude to those characteristic of asphalt roads. By increasing the model road surface temperature up to $T$ = 60 °C the *RRC* dropped by ~13% compared to the equivalent values at $T$ = 22 °C

**Keywords:** rolling resistance coefficient, deceleration measurement, temperature change, drum measurement, measuring device

## 1. Introduction

The motion of wheeled vehicles is hampered by the rolling resistance force ($F_{RR}$), which occurs when an object rolls on another due to the interaction between a wheel and the track it is running on. This force is characterized by the rolling resistance coefficient (*RRC*), which is one of the most important factors in today's automotive industry. The first study of losses as a result of rolling friction was carried out by Coulomb in 1785, while the first experimental method for determining the rolling resistance of vehicle wheels was drawn up by Holt and Wormeley [1].

In vehicles, one way to save energy is to reduce the rolling friction [2]. Manufacturers use different materials and pattern designs to create tires that exhibit better rolling friction properties, thereby further reducing the fuel consumption of vehicles and the greenhouse gases they emit. Research has shown that a 10% reduction in the *RRC* results in a 1 - 2% reduction in fuel consumption [2]-[3].

The $F_{RR}$ results from deformation of the rolling body (and surface) as shown in *Figure 1*. In the case of a body rolling at an angular velocity $\omega$, deformation occurs on the contact surface between the body and surface. A consequence of such deformation to the body is that forces act on it to work against the deformation. $F_m$ represents the cumulative resultant force of the system acting on the contact surface. The resultant force can be split into a vertical and a perpendicular component, which – at a constant angular velocity – are in equilibrium with the other components. $F_v$ contributes towards keeping the wheel in motion, which is balanced by the horizontal component of $F_m$. The vertical component of $F_m$ is balanced by the force $G'$, which results from the mass of the rolling body.

Since the rolling resistance can be interpreted as a force [4], the *RRC* is a dimensionless physical constant

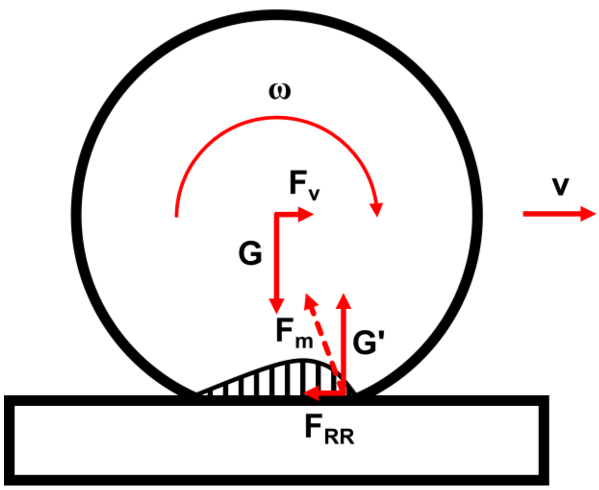


*Figure 1.* Motion of the wheel at a constant speed on a non-deformable road surface

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derived from the quotient of the horizontal and vertical components of $F_m$:

$$RRC = F_{RR}/G' \quad (1)$$

The magnitude of the $RRC$ (which typically varies between 0.001 and 0.400) depends on the ratio and magnitude concerning the deformation of the road surface as well as tire. The degree of deformation depends on the material properties as well as roughness of the tire and the pavement, in addition to the diameter, pressure and rotational speed of the wheel amongst other factors like temperature that influence these parameters [5].

Our aim was to study the dependence of the $RRC$ on various measurement conditions such as velocity, compression force and surface temperature on different surfaces. For this purpose, a laboratory-scale device was designed and constructed by us which can measure the $RRC$ of a model tire on two different model surfaces in the event of various conditions.

## 2. Experimental

### 2.1. Measurement system

In industry, the methods and conditions for measuring the $RRC$ are specified in the standards ISO 18164:2005 and ISO 28580:2018. In practice, the most common currently used measurement setups are trailer measurements, the coast-down method, measurements based on fuel consumption and drum measurements [6]. However, these all measure the value of the $F_{RR}$ indirectly and infer the value of the coefficient. Each measurement method has different advantages and disadvantages, moreover, none of them can be used to carry out a complete study. The appropriate measurement method must be chosen according to the situation and opportunities presented by it. The drum measurement method is the most widely used technique for determining the $F_{RR}$ and $RRC$ under laboratory conditions [6]. The measuring device designed by us is based on this principle.

Our apparatus consists of a drum with a large diameter on which the model road surfaces are mounted, a drive chain, a test wheel, a mechanism that presses the wheel and drum together as well as sensors needed to make the measurements (*Figure 2*).

From the values of the $F_{RR}$ and compression force measured, the $RRC$ can be obtained using the parameters of the drum and wheel. In the drum measurement method, the curvature of the model road surface causes an error, but this can be corrected according to the following equation:

$$F_{RR} = F_{RR,measured}\sqrt{\frac{r_{drum}}{r_{drum}+r_{wheel}}} \quad (2)$$

where $r_{drum}$ and $r_{wheel}$ are the radii of the drum and wheel, respectively.

Using this arrangement, the rolling friction force can be determined by direct force measurements. In this case, the force acting on the axis of the wheel (or drum)

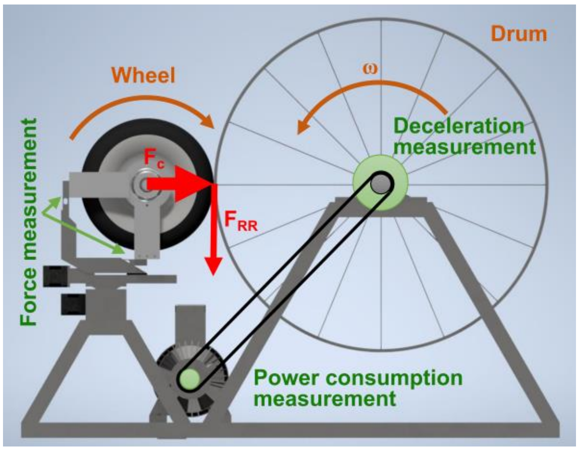


*Figure 2.* Schematic diagram of the measurement system

is measured by applying a given compression force. Furthermore, the $F_{RR}$ can be determined indirectly by measuring the torque, power or angular deceleration.

When measuring the power, the rolling friction force and its coefficient are determined from the difference between the amount of power required to drive the freely rotating drum and the power that is needed when the wheel is pressed against it ($\Delta P$). Due to the differential measurement, the bearing and aerodynamic losses do not affect the result. One disadvantage is that the power consumption changes as the driving motor heats up and could lead to an error.

The deceleration method is similar to the one based on power measurements, however, instead of $\Delta P$, the difference in the deceleration of the drum is measured. Since this is also a differential method, the aforementioned sources of errors are not present. An additional advantage of measuring the deceleration rather than the power is that heating of the driving motor is also cancelled out.

Our equipment can determine the $RRC$ on two different model surfaces, namely rubber and steel, by measuring the force, power and deceleration. The temperature of the surfaces can be controlled by heating blankets mounted on the inner surface of the drum. The blankets consist of a resistance heating wire embedded in silicone rubber and are powered by a high-performance HP 6030A power supply. Using the blankets, the surface temperature was set between room temperature and 60 ± 2 ºC. *Figure 3* shows that the heat distribution on the surfaces of the drum was uniform, a small difference

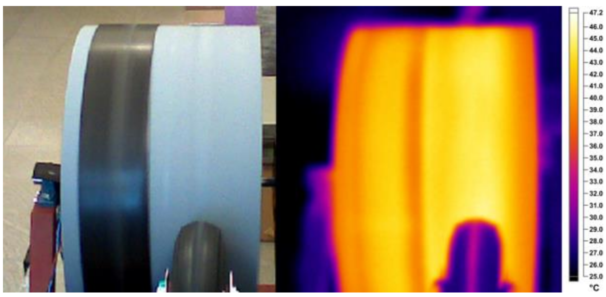

*Figure 3.* Heat map of the drum at 10 km/h

of ~2 ºC between the temperature of the rubber and model steel surfaces was observed.

The drum is driven by a 0.28 kW Robax asynchronous motor controlled by a Siemens SINAMICS CU240E-2 PN-F control unit connected to a SINAMICS PM340 power module. The rotational speed and, therefore, the deceleration of the drum are measured by a custom-made inductive rotary encoder based on a BALLUFF BES 516-360-S4-C inductive sensor. The wheel is positioned by two linear units, which are perpendicular to each other.

Control functions and data acquisition are provided by a Python program running on a Raspberry Pi single-board computer described in [7].

### 2.2. Measurement method

Taking into account the advantages and disadvantages of the applicable methods concerning the drum setup, the measurements were made using the deceleration method. Firstly, the drum was accelerated to a constant angular velocity before the driving motor was disengaged, causing the drum to decelerate. The rate of deceleration was measured in the form of angular deceleration ($\beta$) and this measurement repeated by pressing the measuring drum and wheel together by applying a given force. Together, the rate of deceleration of the drum and wheel was greater due to losses resulting from their interaction caused by the $F_{RR}$, which can be calculated by the moments of inertia of the drum ($I_{drum}$) and wheel ($I_{wheel}$) according to the following equation:

$$F_{RR} = \beta_{drum}\frac{I_{drum}}{r_{drum}} + \beta_{drum}\frac{I_{wheel}r_{drum}}{r_{wheel}^2} - \beta_{l.wheel}\frac{I_{wheel}}{r_{wheel}} - \beta_{l.drum}\frac{I_{drum}}{r_{drum}} \tag{3}$$

where $\beta_{l.drum}$ and $\beta_{l.wheel}$ denote the angular deceleration of the compressed drum and wheel, respectively, and $\beta_{drum}$ stands for the angular deceleration of the freely decelerating drum.

## 3. Results and discussion

The measurements were carried out at an initial tire pressure of ~2 bars. The compression force was changed between 30 N and 60 N, moreover, the circumferential speed was varied between 5 km/h and 20 km/h. The surface temperature of the drum was adjusted by changing the feeding current of the heating blankets. A minimum of three data points were measured under each set of conditions before their averages and standard deviations were calculated. The standard deviations of the compression force and surface temperature were also calculated. Error bars X and Y were generated using these standard deviations. The value of the *RRC* on the rubber surface was higher than on the steel one in most cases.

### 3.1. Measurements when different compression forces were applied

According to the literature, the *RRC* does not depend on the magnitude of the compression force. Our measurement data, which is presented in *Figure 4*, show that the *RRC* increases as the compression force rises. The reason for this disagreement may have occurred as the tire pressure of the model wheel, which depends on the compression force applied, was set in the unloaded state. Increasing the tire pressure can either increase or decrease the *RRC* depending on the surface it is in contact with [5]. With the current measuring device, the tire pressure cannot be changed during the measurement. This could be an option for future development. It is worth mentioning that the standard deviation of the data in the case of the rubber surface is higher than in that of the steel surface.

### 3.2. Measurements at different velocities

The dependence of the *RRC* on the circumferential velocity of the drum was measured between 5 km/h and 20 km/h at an initial tire pressure of ~2 bars while subjected to a compression force of 40 N. The measured values (*Figure 5*) show an increasing trend, which is consistent with data in the literature [5], [8] from which large changes in the *RRC* are only expected above 50 km/h.

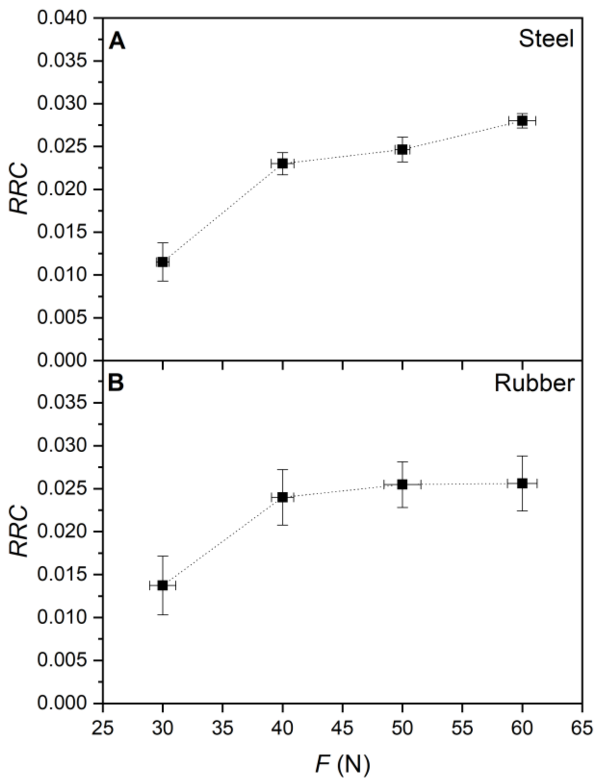


*Figure 4.* Measurements when different compression forces were applied with an initial tire pressure of ~2 bars and a velocity of 10 km/h in the case of the steel (A) and rubber (B) surfaces

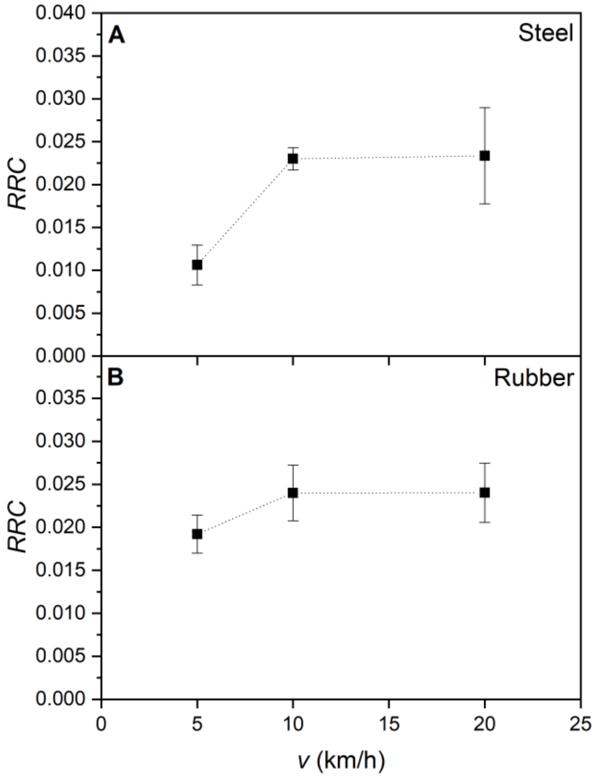


*Figure 5.* Measurements at different circumferential velocities with an initial tire pressure of ~2 bars and by applying a compression force of 40 N in the case of the steel (A) and rubber (B) surfaces

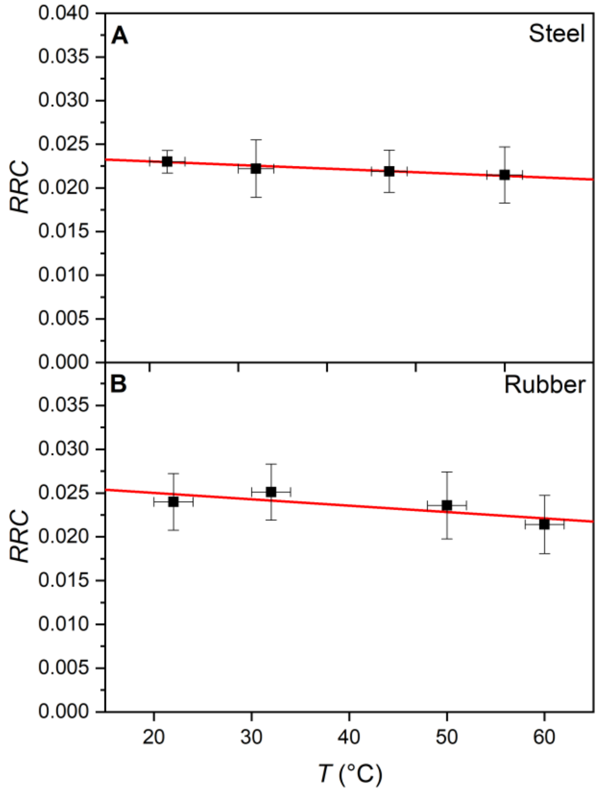


*Figure 6.* Measurements at different surface temperatures with an initial tire pressure of ~2 bars by applying a compression force of 40 N and at a velocity of 10 km/h in the case of steel (A) and rubber (B) surfaces (The red line denotes the linear regression.)

### 3.3. Measurements at different model road-surface temperatures

The effect of the road-surface temperature on the *RRC* was investigated by adjusting the temperature of the drum, thereby modelling driving on a hot road surface. The surface temperature was set at constant values between 20 °C and 60 °C. In all cases, the drop in temperature due to rotation of the wheel was below 2 °C. It should be noted that the temperature of the model wheel was below the surface temperature throughout the experiment. The *RRC* decreased linearly between 0.024 and 0.021 as the temperature increased (*Figure 6*), therefore the following equation was fitted to the measurement points to determine the temperature ($T$) dependence of the *RRC*:

$$RRC = RCC_0 - aT \qquad (4)$$

where $RRC_0$ denotes the extrapolated value of *RRC* when $T = 0$ °C and $a$ stands for the slope of the regression line.

*Table 1.* The parameters of the fitted curve

| | $RRC_0$ | $a$ (°C$^{-1}$) |
|---|---|---|
| Steel | 0.024 | $-4.15 \cdot 10^{-5}$ |
| Rubber | 0.027 | $-7.28 \cdot 10^{-5}$ |

The parameters of the linear regression are shown in *Table 1*.

In our experimental setup, the small change of the *RRC* with the temperature shows that the temperature of our model wheel remained less than that of the surface. Based on the literature [9], it is expected that the decrease in the *RRC* would be greater if the temperature of the surface and wheel were identical. An additional possible research direction could be the use of a closed system in which the temperature of the drum and wheel can be adjusted simultaneously by means of the built-in heating blankets.

## 4. Conclusions

In our work, a laboratory device to measure the *RRC* based on the drum measurement method was designed and constructed, which is able to determine the *RRC* on two different model surfaces at various temperatures. The dependence of the *RRC* on the compression force, velocity as well as the temperatures of the two surfaces, namely steel and rubber was determined based on the deceleration method. The measured *RRC* values (0.010–0.025) were similar in magnitude to those characteristic of asphalt roads.

- The *RRC* increased as the compression force rose. Since the *RRC* is independent of the compression force, this discrepancy may have resulted from changes to the tire pressure that affected the measurements. A possible solution to this problem is to continuously adjust the tire pressure as the compression force changes.
- The dependence of the *RRC* on the velocity was investigated at three different speeds, that is, 5 km/h, 10 km/h and 20 km/h. The data shows an increasing trend, which is consistent with the literature.
- The dependence of the *RRC* on temperature was also tested. By increasing the temperature of the model road surface up to $T = 60$ ºC, only a slight decrease (~13%) in the measured *RRC* was observed.

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