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Development of a measurement method to determine rolling resistance

S Pálinkás¹, Á Tóth²

^{1,2}University of Debrecen, Faculty Engineering, Department of Mechanical Engineering; 4028 Debrecen, Óttemető u. 2-4., Hungary;

¹palinkassandor@eng.unideb.hu, ²totar98@icloud.com

Abstract. Nowadays, car manufacturers tend to produce cars of low consumption to comply with stricter and stricter environmental protection standards. Fuel consumption can only be reduced by decreasing losses emerging during vehicle operation. This is corroborated by the fact that due to the terminal capacity of batteries of electric cars, manufacturers aim to reduce losses to enhance their range of operation. The main goal of our current research is to work out indirect methods of measurement to define rolling resistance, one of the most decisive losses. Later on, the values defined will serve as input data to model vehicle energetics calculations. During our experiments, measurements were carried out with both summer and winter tires. During the evaluation losses of the engine, rolling resistance and air resistance were all considered, while losses from the driving components of the vehicle were ignored.

1. Introduction

Rolling resistance is basically caused by the motion of tires. The running surface is deformed and distorted with every rotation of the tire. Due to being in contact with the road surface during a change in shape, the tires warm up and that mechanical energy turns into heat. Most of the rolling resistance of car tires emerge in this process. Part of the energy passed on to the wheels is consumed by the tires in the process, which leaves less energy for advancing the vehicle. Thereby, the greater the rolling resistance of the tires is, the more it consumes the mechanical energy, provided by the engine. Rolling resistance cannot be eliminated completely, but decreasing it as much as possible means a considerably lower fuel consumption of the vehicle. In other words, reducing rolling resistance plays an important role in reducing fuel consumption.

It is important to note that fuel can only be saved by reducing the losses during operation. These losses are as follows [1]:

- rolling resistance,
- air resistance,
- inertial resistance,
- gradient resistance,
- side force resistance,
- transmission loss,
- losses from the use of auxiliary equipment,
- engine friction.

Factors influencing rolling resistance are the following: the structure of tires, sizes and temperature of tires, air pressure in tires, speed and mass of vehicle, material and pattern of tires, and the slippage of tires. In recent years, several researches [2-4] are focused on determining the above factors. More



equations have been defined to calculate rolling resistance. Studies focusing on characteristics of rolling losses of car tires have defined the following equation [5]:

$$f_r = \frac{R_x}{W} = C \cdot \frac{W}{D} \cdot \sqrt{\frac{h_t}{w}} \quad (1)$$

where: R_x = rolling resistance force,
 W = weight on the wheel,
 C = constant reflecting loss and elastic characteristics of the tire material,
 D = outside diameter of tire,
 h_t = tire section height,
 w = tire section width.

From this formulation, rolling resistance is seen to be load sensitive, increasing linearly with the load. Larger tires reduce rolling resistance, as do low aspect ratios (h_t/w). Some confirmation of the general trends from this equation appears in the literature from studies of the rolling resistance of conventional passenger car tires of different sizes under the same load conditions. Other equations for the rolling resistance coefficient for passenger car tires rolling on concrete surfaces have been developed. The variables in these equations are usually inflation pressure, speed, and load. The accuracy of a calculation is naturally limited by the influence of factors that are neglected. At the most elementary level, the rolling resistance coefficient may be estimated as a constant. Table 1. below lists some typical values that might be used in that case [5].

Table 1. Example values for rolling resistances [5]

Vehicle Type	Surface		
	Concrete	Medium Hard	Sand
Passenger cars	0.015	0.08	0.30
Heavy trucks	0.012	0.06	0.25
Tractors	0.02	0.04	0.20

Measuring rolling resistance goes back several centuries and emerges from the interest of the military to decrease horsepower needed to tow cannons [6]. Great scientists such as Coulomb and Reynolds took part in elaboration. In the past 50 years, standard processes have been created to measure rolling resistance. In 2011 Sandberg [7] classified measuring techniques of rolling resistance in the group below:

- Drum tests of tires,
- Trailer methods,
- Coast-down methods,
- Fuel consumption methods.

The drum test is ideal for the testing of tires in the laboratory. Trailer methods add the variation of the road surface to the testing and also monitor some of the transmission loss. Coast-down methods include further properties of the vehicle, while fuel consumption methods measure all the energy losses experienced by the vehicle [8].

One topic in mechanical engineering which integrates vehicle dynamics with technical experimentation is coast-down testing. Coast-down testing is the process of accelerating a vehicle to a high speed on a flat, straight road and coasting in neutral down to a low speed. By recording the amount of time, the vehicle takes to decelerate, it is possible to obtain a model of the loss-inducing forces affecting the vehicle. Obtaining valid coast-down results requires several steps, including experimental planning, data collection, and data processing [9].

2. Elaborating an experimental plan to coast-down testing

2.1. Choosing the right stretch of road for measurements

To test rolling resistance, it is important for the stretch of road chosen to be straight while long enough for the driver to be able to accelerate the vehicle to 80 km/h, so that it can roll on to a full stop after being put into neutral gear. Another important criterion is to choose a less busy road, that is why a road used for agricultural purposes was chosen on the outskirts of Hajdúböszörmény (Figure 1.). The road chosen was not very smooth and was full potholes due to being used by agricultural machines.

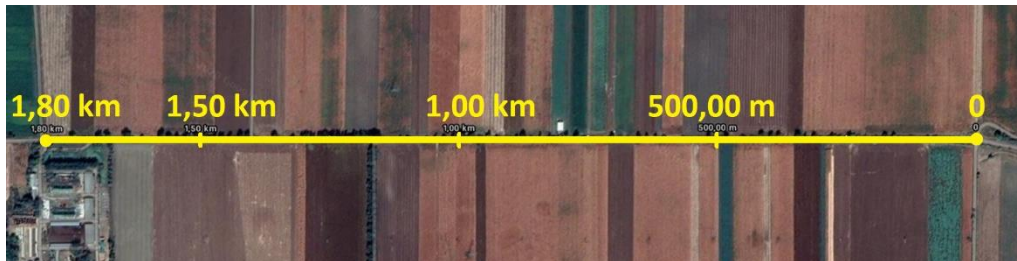


Figure 1. The stretch of road chosen to test coast-down as is shown by the satellite picture from google maps

2.2. Elaborating the aspects of measurement

During the experiments it is highly important for measurement conditions to be identical, whereby the following system of aspects has been elaborated:

- measurements should be on the same day,
- in the same location,
- in the same weather conditions (temperature, humidity, direction of wind, velocity of wind),
- same load on axis,
- same size tires and air pressure,
- closed windows,
- full fuel tank.

2.3. Experiments to test coast-down with summer and winter tires

During our experiments, our main goal was to define rolling resistance with winter and summer tires to obtain a significant difference. During the evaluation, engine losses and losses due to rolling and air resistance were accounted for. The losses emerging from the drive components of the vehicle were ignored because they were considered insignificant. During the experiments, the time needed for a full stoppage and the changes in engine power were measured.

3. Conditions of measurements

3.1. Environmental conditions of measurements

During the measurements, precise weather data is indispensable, which were obtained from the Hungarian Meteorological Service on the day of testing. Data on rain, temperature and relative humidity were obtained from the automatic station operated in Balmazújváros. The data of wind and air pressure were defined based on measurements from the meteorological station in Folyás village. During the measurements, the current temperature, which was 16 °C, was defined utilizing the thermometer installed in the vehicle.

3.2. The measuring device used for the measurements

While defining the exact environmental data, it is indispensable to use a precise method to define the speed of the vehicle while testing coast-down. Nowadays, OBD-II sensor diagnostics are widely used

to monitor vehicle operation and consumption [10-11]. An ELM327 Vgate Scan, Advanced OBD2 Bluetooth reading device (Figure 2.) was used for testing, while applying an android-based recording software that could be downloaded free of charge. The module can be fitted into the OBD-II port of a vehicle, which makes it possible to obtain data from the CAN bus of the vehicle. The unit used supports all OBD-II standards: ISO15765-4 (CAN), ISO14230-4 (KWP2000), ISO9141-2. This ensures access to further variables, such as the number of revolutions, power, fuel consumption, operational temperature, etc. in addition to checking sampling frequency. An even more precise procedure to measure vehicle speed precisely would be external sensors, but it would increase both the cost and complexity of the experiment.



Figure 2. The device used for the measurements, ELM327 Vgate Scan Advanced OBD2

3.3. *Specifications of the vehicle used for the measurements*

Table 2. The details of the experimental vehicle

List of specifications make of vehicle Suzuki Liana 1,6; 2005

Air resistance coefficient	0,5
Perpendicular surface of airflow	2,25 m ²
Mass (own mass of vehicle + 2 persons)	1225 + 105 + 70 kg
Speed aimed at coast-down test	80 km/h
Air pressure and sizes of tires	2,2 bar; 185/65 R14
Type of summer tires	Nordexx Fastmove 3
Type of winter tires	Momo W-1 North Pole

4. The measurement procedure

A specific procedure for coast-down testing can be found in the standard SAE J1263 [12]. The measurement procedure outline below was defined based on the standard and our experimental plan:

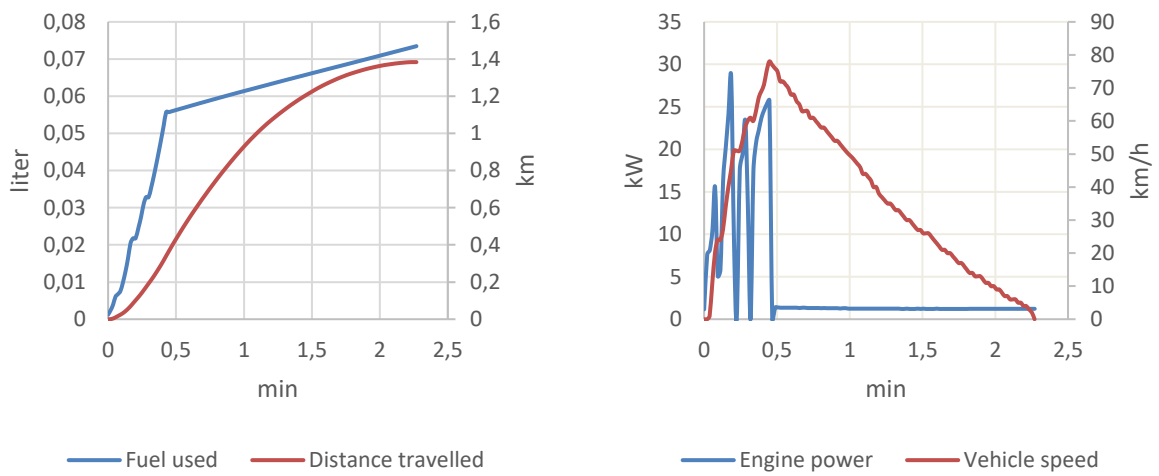
1. Prepare vehicle for testing:
 - a. Checking vehicle to comply with SAE J1263 standard [12] and production specifications.
 - b. Defining test variables: Different seasonal tires were used in our current paper.
 - c. Warm-up procedure: The vehicle is driven at 80 km/h for 30 minutes before measurement.

2. Fixing the initial environmental data:
 - a. Recording variables: environmental temperature, air pressure, parallel and cross-directional wind speed and maximum wind speed observed.
 - b. Should any of the variables above exceed the limit of SAE J1263 [12] the test cannot continue.
3. Testing coast-down:
 - a. If the data collecting system is on standby and the staff carrying out experiments is ready for measurement, the data collecting system has to be started to setup operational characteristics of the vehicle. Then the vehicle is accelerated up to 80 km/h along a straight plain smooth road.
 - b. After reaching the desired speed the accelerator pedal is let up and the clutch pedal is pressed to put the vehicle into neutral gear. The fall in the number of revolutions while changing into neutral gear is considered while processing data. This is necessary due to the impression of the person's reaction, carrying out measurement and the feedback of devices.
 - c. The vehicle must be kept in neutral gear along a straight track while coast-down testing is taking place. Should any dangerous situations arise, such as objects appearing on the road, the test has to be aborted immediately and restarted later.
 - d. Once the speed of the vehicle is at 0 km/h, the data collecting system is stopped and the data files are saved.
4. Repeating testing:
 - a. Step 3 tests are repeated by using both winter tires and summer tires 3 times.
 - b. All together 6 experimental measurements are carried out to get a full picture of the operational characteristics of the vehicle, while using different seasonal tires.
5. Recording environmental data:
 - a. After carrying out a series, which consists of 6 experimental measurements, the weather conditions are recorded.
 - b. It is checked if the weather conditions are within the limitations of SAE J1263 [12]. If there are data outside of the limitations step 3 has to be repeated until all 3 relevant running procedures are recorded.

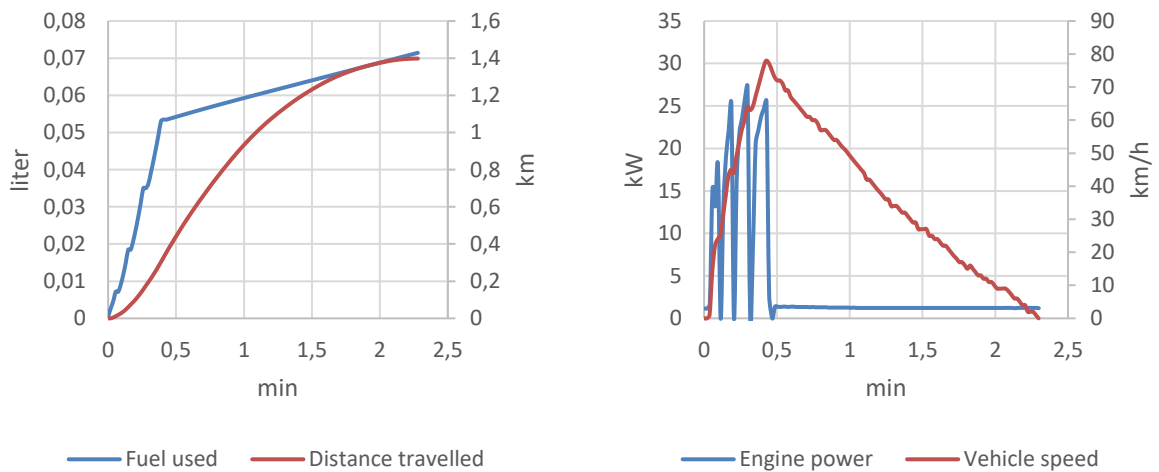
5. Measurement results

The measurements were carried out according to the description above. Three measurements were carried out with summer tires, then winter tires were used. The measurements were carried out along the same stretch of road with both summer and winter tires, whereby influencing factors emerging from potential level differences were avoided. Results of the measurements with summer tires are given in Figure 3., whereas those of the winter tires are summarized in Figure 4. In diagrams on the right, the power of the engine and the speed of the vehicle is shown. In the diagram on the left the total fuel consumption and distance travelled are demonstrated. They show that the vehicle covered a shorter distance with winter tires due to the obviously greater rolling resistance.

1. measurement with summer tires



2. measurement with summer tires



3. measurement with summer tires

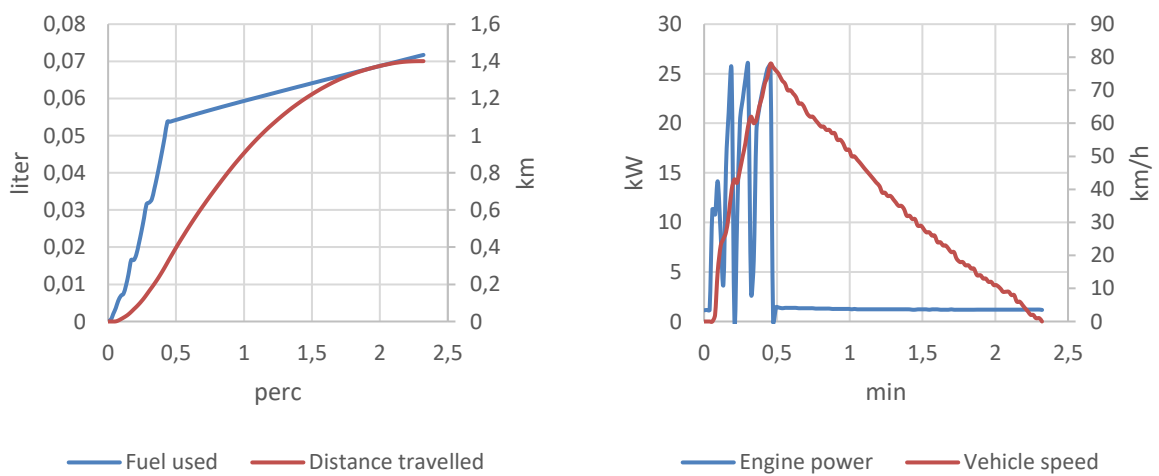
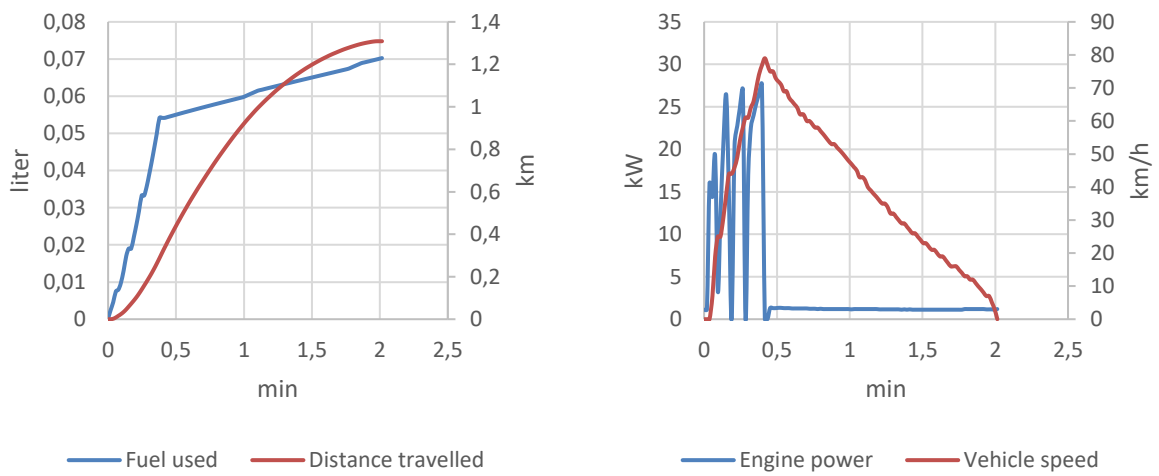
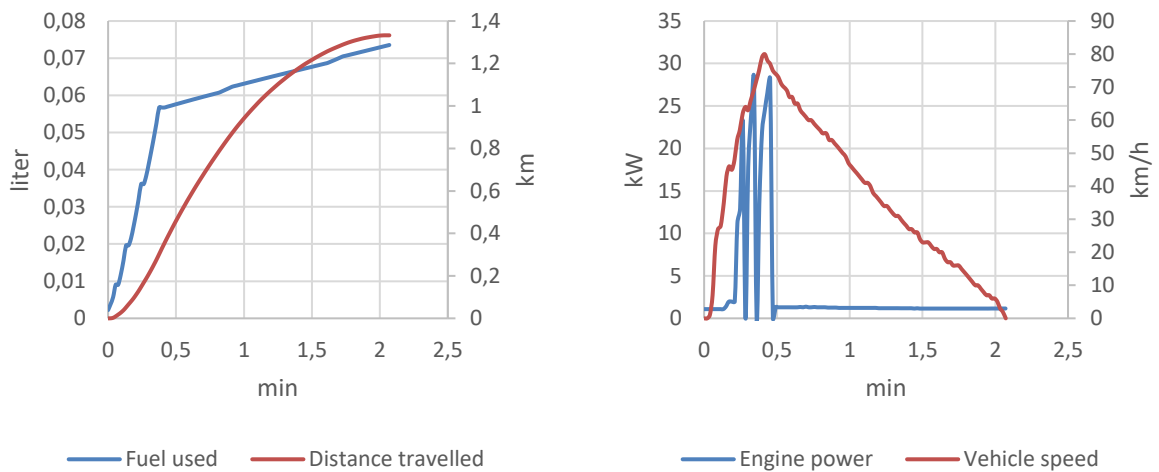


Figure 3. Measurements with summer tires

1. measurement with winter tires



2. measurement with winter tires



2. measurement with winter tires

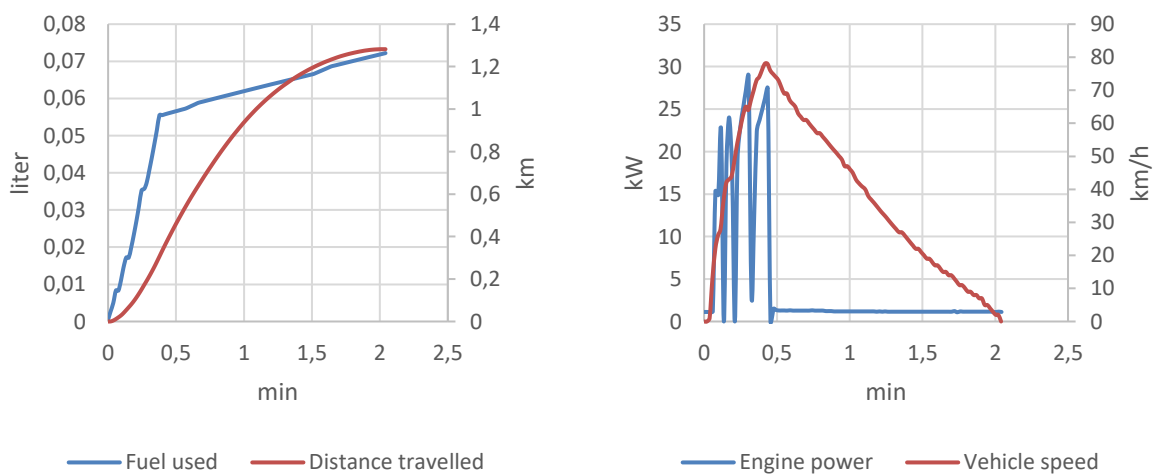


Figure 4. Measurements with winter tires

6. The measurement evaluation

The time needed for complete coast-down was defined in each case based on the measurements carried out as shown in Table 3.

Table 3. Overall time needed for complete coast-down [s]

	measurement 1	measurement 2	measurement 3	average
Summer tires	110,49	113,41	113,12	112,34
Winter tires	96,96	100,51	98,63	98,7

While evaluating the measurements we concluded that we did not manage to achieve the 80 km/h defined experimental plan in each case during the experiments because the driver happened to switch to neutral gear too soon. Based on this fact, we chose 78 km/h as the basis of the calculations as this was the only data available in all the six cases.

During our calculations we defined the air and rolling resistance. While calculating air and rolling resistance the data in Table 2 were considered.

The air resistance force (F_L) and the power (P_L) to cope with air resistance were calculated as follows:

$$F_L = \frac{\rho}{2} \cdot A \cdot c_w \cdot v^2 \tag{2}$$

where: F_L = air resistance force,
 ρ = density of air on 15 °C,
 A = perpendicular surface of air-flow,
 c_w = air resistance coefficient,
 v = vehicle speed.

$$P_L = F_L \cdot v \tag{3}$$

It can be observed in Figures 3 and 4 that the power of the engine was always constant when the vehicle was rolling freely, which was considered the loss of the engine. The power of the engine was measured, the air resistance was calculated in compliance with equation 2 and the internal loss of the engine was considered, whereby the output needed to cope with the rolling resistance could be defined. Figure 4 shows the percentage rate of engine power needed to cope with various losses at a speed 78 km/h.

Table 4. The percentage rate of engine power used to cope with various losses

	Rolling resistance [%]			Air resistance [%]			Engine loss [%]		
	1.	2.	3.	1.	2.	3.	1.	2.	3.
Summer tires	67,56	67,33	67,65	27,2	27,4	27,1	5,24	5,27	5,25
Winter tires	71,31	71,86	70,11	24,3	23,9	25,5	4,29	4,24	4,39

The differences in the table can be explained by the fact that the winter and summer tires are different both in terms of their patterns and material compositions allowing them to be applicable in the right weather conditions. The most important property of a summer tire is to ensure safety at a higher temperature on wet road surfaces, whereas the winter tire ensures safety on snowy and slushy road surfaces. Its dense grooves facilitate adhesion on a snowy road surface, which does not change in cold weather either, owing to its composition. This is the reason why most of engine power was used to cope with the rolling resistance during the experiments.

As the power (P_G) needed to cope with rolling resistance at a given speed was defined, the force (F_G) needs of rolling resistance could be calculated as follows:

$$F_G = \frac{P_G}{v} \quad (4)$$

The knowledge of rolling resistance force needs allowed us to define the rolling resistance factor (f) according to the following equation:

$$f = \frac{F_G}{m \cdot g} \quad (5)$$

where: m = the mass of vehicle with the persons carrying out the measurement included,
 g = gravitational constant.

Table 5. The value of calculated rolling resistance factor, f

	measurement 1	measurement 2	measurement 3	average
Summer tires	0,058	0,057	0,059	0,058
Winter tires	0,067	0,069	0,065	0,067

The values in Table 5 coincide with the ones given in the literature, which is proved by the fact that the rolling resistance factor value in Table 1 in case of a passenger car and a poor-quality road (medium hard) is 0,08. Only a slight difference can be observed compared to data in the literature, which can be explained by the fact the texture of the stretch of road chosen, where the test was carried out was somewhat different from the road surface given in the special literature.

7. Conclusion

Our main goal defined at the beginning of our research, to provide a measurement method to define rolling resistance has been achieved. Both winter and summer tires were used during our coast-down tests. A significant difference could be shown during the evaluation in terms of the time needed for total coast-down. The engine power percentage rate needed to cope with different losses. The value of the rolling resistance factor between seasonal tires were shown. Although the rolling resistance can be increased by reducing air pressure in the tires, the air pressure was 2,2 bars with both summer and winter tires during the test. This proves clearly that coast-down time is reduced with winter tires owing to the structural formation, material composition and patterns of the wheels. Fuel consumption also appears in the measurement diagrams of the coast-down test, which suggests that the vehicle covered a shorter distance during the test carried out with winter tires. This is another potential method to measure rolling resistance, more specifically the fuel consumption method, which is not specified in detail in the test, but we are going to carry out tests in future to focus on this issue too.

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