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Design and Calibration of Rolling Resistance Test Trailer R^{2}Mk.2

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Abstract. The paper describes construction and calibration procedures of the rolling resistance test trailer R2 Mk.2. The trailer is design to measure rolling resistance of passenger car tyres in various road conditions on trafficked roads. The trailer utilizes so called angle method also known as vertical arm method. The paper presents also calibration procedures that are necessary to ascertain good precision of the measurements.

1. Introduction

For many years different research institutions and companies carry out research focused on savings in energy consumption. This also applies to a public road transport. To reduce energy consumption of road vehicles it is necessary to reduce restrictive forces acting on vehicles during their motion. One of such a force is tyre rolling resistance that is especially important during driving with constant, moderate speed. It is common practice to describe rolling resistance as Coefficient of Rolling Resistance (C_{RR}) defined as ration of the Rolling Resistance Force F_{RR} and Vertical Load acting on the tyre (Q):

$$C_{RR} = F_{RR}/Q \quad (1)$$

Figure 1. Roadwheel facility at the Technical University of Gdańsk equipped with replica road surfaces.

As the Rolling Resistance Force is directly proportional to the Coefficient of Rolling Resistance and tyre Vertical Load there are two ways to reduce this force - making the vehicle lighter and reducing CRR. Reduction of the tyre load is out of the scope of this paper so it will concentrate on the measurements of the Coefficient of Rolling Resistance, as the ability to measure is a basic problem in each optimization process. CRR is related to many factors like properties of the tyre, road surface, load, inflation pressure and speed. Road surface characteristics play very important role in tyre energy losses [1, 2] thus it is necessary to account for them. For many years laboratory methods of rolling resistance measurements are utilized especially by tyre manufacturers, but usually they can't account for road pavement properties. The reason is that on outer drums it is not possible to mount real road surfaces due to their inadequate strength. At the best some kind of epoxy resin or polyurethane based replica road surfaces may be used - see Fig. 1. One may say that laboratory methods of rolling resistance measurements are already well established although they are lacking good representability. In contrast, the measurements of rolling resistance in road conditions poses many problems. Methods of measuring rolling resistance by towing car or coast-down are not accurate enough, and for practical reasons not suitable for use in road conditions.

For many years several research centres in Europe work on the development of effective methods of measuring rolling resistance in real road conditions. One of these centres is the Technical University of Gdańsk (TUG) that developed and constructed test trailer R^2 Mk.2 designed to measure CRR on the road. It is one of five known trailers specially designed for this type of measurements, wherein two of them were constructed and used in TUG.

In Poland, in late seventies, successful test trailer SRT-3 for skid resistance measurements was developed. Although the trailer was designed to measure tyre traction (skid resistance), it was possible also to use it for rough estimation of tyre rolling resistance. Unfortunately in order to precisely measure tyre rolling resistance it is necessary to construct specialized facilities that are immune to air drag and inertia forces as well as road grade so use of "universal" trailers is very limited.

2. Design of the test trailer

During 2012 and 2013 TUG's Faculty of Mechanical Engineering has built an enhanced version of the R^2 trailer (that was built a few years earlier) to study the rolling resistance. The trailer was named R^2Mk.2 (see Fig. 2). The idea behind the design was retained from the first trailer R^2, but a lot of improvements in design and equipment were introduced to the Mk. 2 version [3].

Trailer R^2 Mk.2 has three wheels. Two front wheels are used to stabilize it on the road while the third wheel is a test wheel and runs between wheel tracks of the front wheels. The trailer may accomodate test wheels of diameter 570 - 730 mm and width up to 245 mm.

Figure 2. Rolling Resistance test trailer R^2 Mk.2.

Both trailers of R^2 series use "*vertical arm principle*" described in Fig. 3. Rolling resistance force acting on the test wheel is transferred to the wheel hub located on a vertical swinging arm supported at the bottom end on the axle connected to the main frame of the trailer. The force acting on the arm produces momentum that deflects the arm in backward direction. The angle of deflection is measured by a laser system. To compensate for the influence of acceleration and longitudinal slope of the road surface a special counterbalance system is used (see Fig. 4). This system is patented by TUG. The trailer is loaded by a certain mass supported on a spring and shock absorber. As the angle of the vertical arm deflection is measured in relation to the frame being the reference (not to true vertical direction), it is necessary to provide information about the frame position related to the pavement and horizontal plane. To do so, two laser sensors measure and compare distance from the pavement at the front and rear of the frame. The trailer is also equipped with a system evaluating road grade operating on barometric principle. Interior of the trailer is presented in Fig. 5.

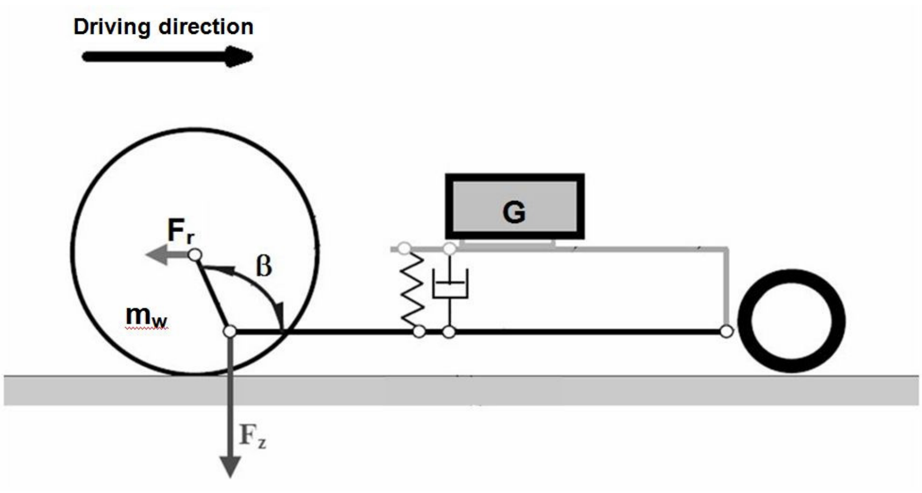

Figure 3. Principle of the vertical arm measuring method.

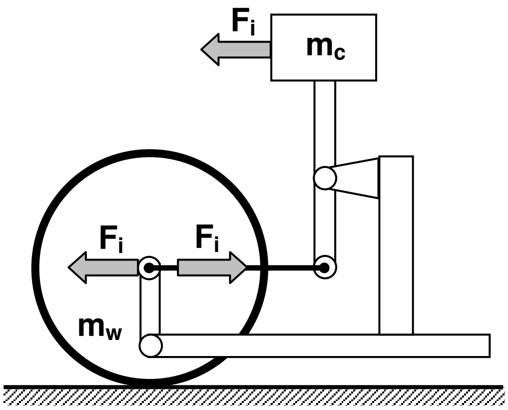

Figure 4. The counterbalance system.

Figure 5. Interior of the R^2 Mk.2 trailer.

3. Calibration of the test trailer R^2 Mk.2

In order to ascertain that test trailer measures rolling resistance accurately it is necessary to perform many calibration procedures. Some of the procedures must be performed only once just after finishing the construction, some others must be performed frequently to check condition of the systems and properly set up the measurements. Most important calibration procedures are described below.

3.1. Tyre load test

Trailer R^2 Mk.2 is equipped with gravity based tyre loading system thus calibration was necessary only during initial testing and after major modifications. During load calibration the test wheel is placed on legalized weighting scale class III with measuring range of 6000 N and accuracy ±3 N - see Fig. 6. In order to ascertain that the trailer is properly levelled two pads are placed under front wheels of the trailer. In years 2014-2015 the test tyre load was 4002 N while in early 2016 it increased to 4150 N due to the trailer's modernization. TUG uses test wheel with tyre P1 [4] weighting 212 N and test wheel with tyre H1 weighting 186 N.

Figure 6. Calibration of R2 Mk.2 trailer - testing tyre load.

3.2. Road grade influence

Trailer R^2 Mk.2 is equipped with patented system that compensates the road grade influence on tyre rolling resistance measurement results. The calibration is performed in order to adjust this system for optimal work. During calibration, the test wheel of the trailer is replaced by the hardened steel disc of 620 mm diameter and weight of 200 N (see Fig. 7.A) in order to eliminate hysteresis attributed to the pneumatic tyre. During the whole calibration the measuring system is subjected to periodical oscillations induced by the rotating shaker presented in Fig. 8. At first the calibration of the system is performed on levelled steel surface plane. Level of the surface is checked with accuracy of 0.5 mm / 1m. Backward acting force of 40 N is applied to the test disc spindle in direction parallel to the road plane. The force is applied via flexible rope and the tilt angle of the measuring arm (g_o) is recorded. After this the graded steel blocks are placed under the steel disc and the front wheels of the trailer. The geometry of the blocks is such that they simulate road grade of 3% (see Fig. 7-B). Trailer is calibrated both for up-hill grade and down-hill grade. During the calibration, for each grade the test disc spindle is subjective to force of 40 N acting parallel to the road surface and corresponding (g) angle is recorded. It should be the same like in the case of no grade conditions (g_o). If there is difference between the tilt on the graded and horizontal road surface the adjustments of the compensation mechanism are made and the calibration is repeated.

a) b)

Figure 7. Calibration of R^2 Mk.2 trailer - testing grade influence; (a) - steel disc resting on tilted steel block, (b) - pads under front wheels to control the tilt.

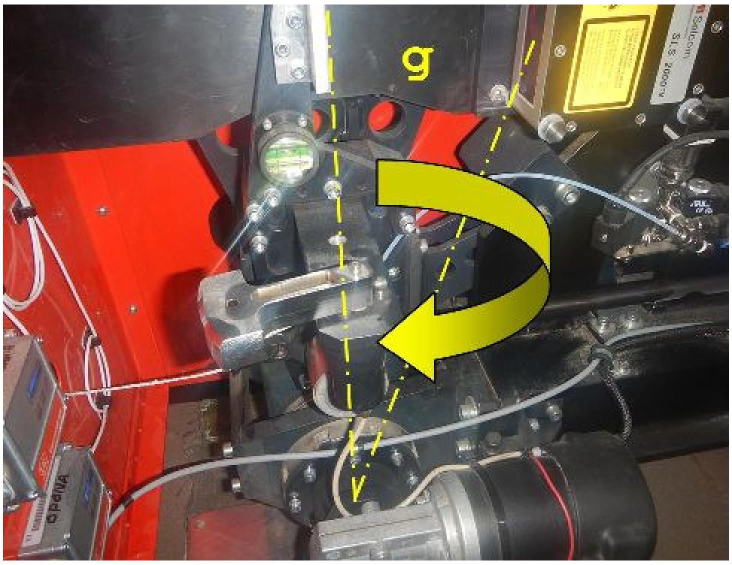

Figure 8. Rotating shaker and angle *g*.

3.3. Acceleration/deceleration influence

TUG's trailer R^2 Mk.2 is equipped with a mechanical system compensating for road grade and acceleration/deceleration. Unfortunately, with this system it is not possible to fully correct the road grade and acceleration/deceleration at the same time as grade acts only on mass, while acceleration acts on mass and rotational inertia (as a moment of inertia). In the case of R^2 Mk.2 trailer it was decided to compensate for the road grade as much as possible and accept certain uncompensated influence of acceleration/deceleration. Calibration of the R^2 Mk.2 trailer in respect of the acceleration/deceleration is based on the rolling resistance measurements performed on uniform, levelled, good quality road surface when driving with intentional acceleration and deceleration. The tests are composed with three phases. During the first phase test vehicle is driving with fairly constant acceleration as close to 0.4 m/s^2 as possible starting with speed of 40 km/h. When speed of 50 km/h is reached the vehicle drives with constant speed for at least 200 m (phase two) and after this the phase three (deceleration as close to -0.4 m/s^2 as possible) is performed.

In Fig. 9 results of calibration performed for R^2 Mk.2 trailer are presented. In the shown example the regression line CRR=0.0034*a+0.0088 describes influence of acceleration/deceleration on the measured results. Based on the slope and intercept of this line it may be calculated that for acceleration of 0.02 m/s2 for tested tyre and road surface (SMA8) the measured CRR = 0.008868 while for deceleration -0.02 m/s2 the measured CRR=0.008732. This corresponds to 1.5% difference in CRR results.

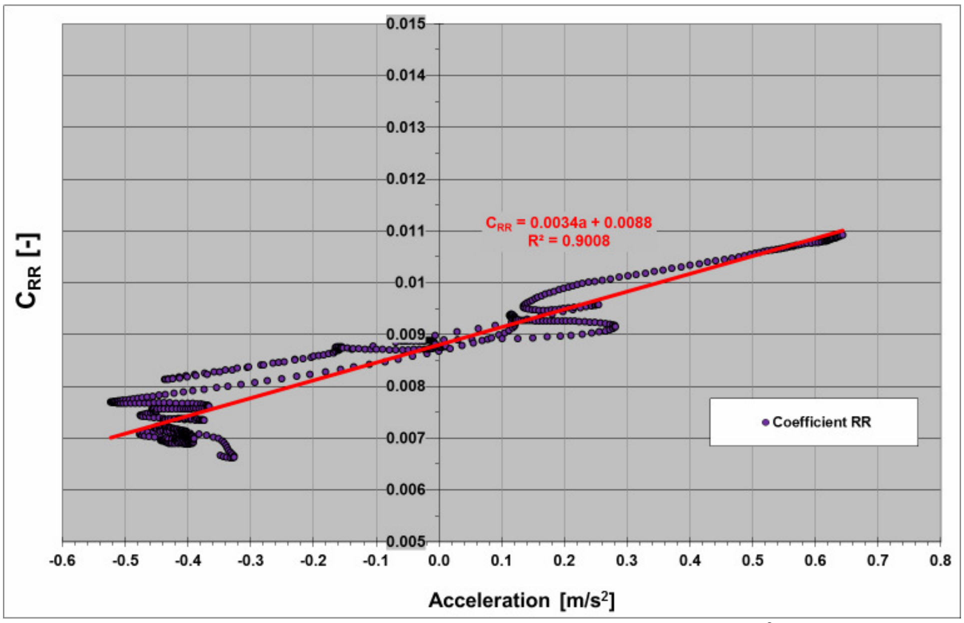

Figure 9. Results of acceleration/deceleration calibration of R^2 Mk.2 trailer.

3.4. Calibration of the temperature sensors

In the trailer R^2 Mk.2 air temperature is measured by the thermistor sensor Pt100 while road and tyre temperatures are measured by IR sensors. Calibration involves comparing the indications of the sensors with reference temperature measured by system with thermocouple (Fluke 52 II, accuracy 0.3°C) - see Fig. 10.

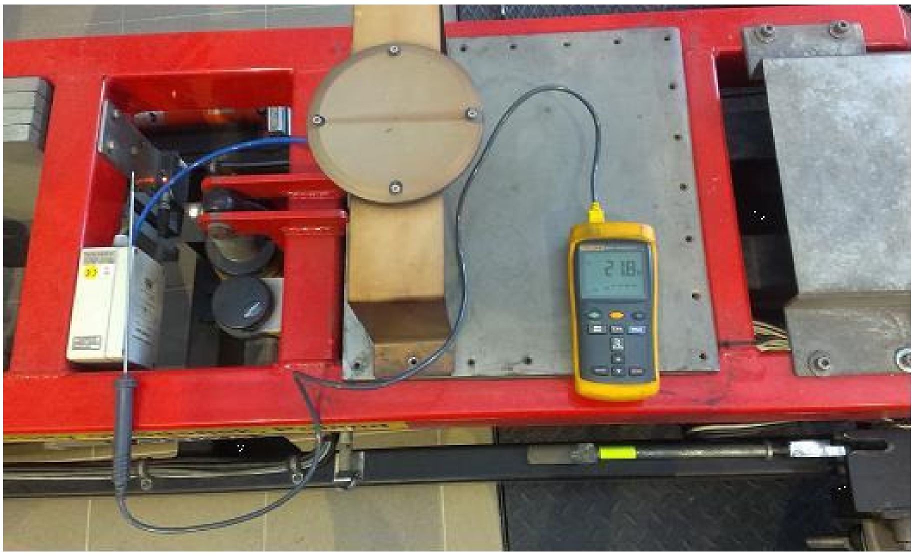

Figure 10. Testing of the temperature sensors (in TUG trailer air temperature sensor is mounted outside the wind protective chamber).

During periodic calibrations the trailer is stored for at least 5 hours in the room with constant temperature of 20±2°C and the comparison of indications is made. To check road temperature sensor mounted at the trailer a piece of asphalt concrete surface having ambient temperature is placed in the beam of the sensor. This ascertains that calibration accounts for typical surface emissivity. If necessary the sensors are readjusted. Checking of calibration at 10±2°C and 30±2°C was done only once, when the system was initially tested.

3.5. Calibration of tyre inflation sensor

TUG's trailer R^2 Mk.2 is equipped with two inflation pressure sensors. The first sensor sends data to the data recorder and control display while the second one is used by the system automatically adjusting the inflation pressure, thus the measurements may be performed in two modes - capped and regulated inflation pressure. Calibration of the system is performed by comparing readings from the first sensor with readings from certified manometer of accuracy 0.6%. During initial calibration the readings were compared for inflation pressures from 150 kPa to 250 kPa (with increment of 10 kPa). During periodical checks calibration is made only for 210 kPa.

3.6. Tyre size influence

During calibration the test wheel of the TUG's trailer R^2 Mk.2 is replaced by a hardened steel disc having sectors of following radiuses: 300, 310 and 320 mm (see Fig. 11). The calibration plane is determined by three steel plates (positioned under the test and front wheels) set with an accuracy of 0.5 mm per 1 m. The steel on steel interface eliminates hysteresis of the tyre and ascertains good accuracy of the calibration. During whole calibration the measuring system is subjected to periodical oscillations induced by the rotating shaker presented in Fig. 8.

After levelling of the trailer the backward acting force of 40 N is applied to the test disc spindle in direction parallel to the road plane. The force is applied via flexible rope and the tilt angle of the measuring arm (g_o) is recorded. The measurements are repeated for all three radiuses of the steel disc. During the measurements the distance between test surface and front and rear of the trailer is also recorded by on-board laser sensors. Resulting data are used to calculate influence of the test wheel radius on the measured rolling resistance force. The obtained characteristic is used later during measurements to account for influence of test wheel radius.

Figure 11. Calibration of R^2 Mk.2 trailer - radius of the test wheel influence.

3.7. Calibration of speed measuring equipment

Information about trailer speed is NOT used in TUG's system for corrections of inertia forces thus standard GPS based system is adequate. This system operates without calibration. If there is a drop of satellite signal, the information about speed is taken from sensors evaluating rotational speed of the trailer's supporting wheels. This system self-calibrates when GPS signal is available. The calibration is performed on straight road section 1000 m long.

3.8. Calibration of the rolling resistance force sensor

During calibration the test wheel of the TUG's trailer R^2 Mk.2 is replaced by hardened steel disc of 620 mm diameter (see Fig. 11). The calibration plane is determined by three steel plates (positioned under the test and front wheels) set with an accuracy of 0.5 mm per 1 m. The steel on steel interface eliminates hysteresis of the tyre and ascertains good accuracy of the calibration. During whole calibration the measuring system is subjected to periodical oscillations induced by the rotating shaker presented in Fig. 8.

After levelling of the trailer the backward acting force is applied to the test disc spindle in direction parallel to the road plane. The force is applied via flexible rope. The force increases from zero up to 110 N and then decreases back to zero. Readings of the measuring system are recorded and compared with known forces applied to the test wheel spindle via gravitationally loaded system (see Fig. 12). In Fig. 13 relation between tilt of the measuring arm and horizontal load applied to the test wheel spindle is presented. In Fig. 14 relation between measured and calibration force is presented together with the hysteresis loop.

Figure 12. Calibration of R^2 Mk.2 trailer - force calibration (arrows indicate flexible rope pulling the test wheel spindle).

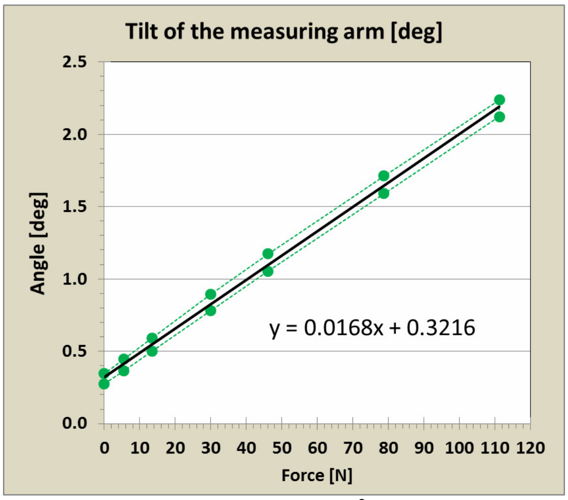

Figure 13. Calibration of R^2 Mk.2 trailer - relation between tilt of the measuring arm and calibration force for steel disc of 620 mm diameter.

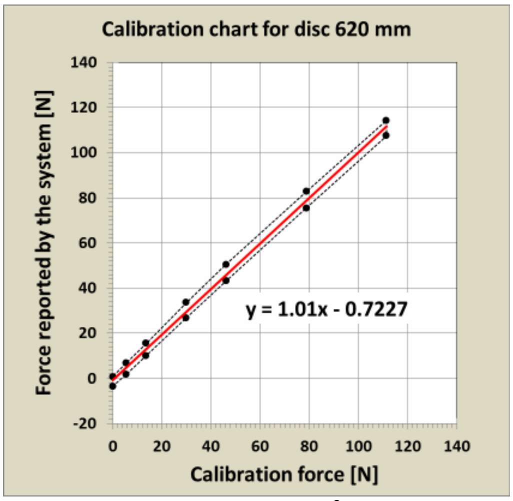

Figure 14. Calibration of R^2 Mk.2 trailer - relation between measured force and calibration force.

3.9. Influence of the rutting

During calibration the test wheel of the TUG's trailer R^2 Mk.2 is replaced by a hardened steel disc of 620 mm diameter (see Fig. 11). The calibration plane is determined by three steel plates (positioned under the test and front wheels). The steel on steel interface eliminates hysteresis of the tyre and

ascertains good accuracy of the calibration. During whole calibration the measuring system is subjected to periodical oscillations induced by the rotating shaker presented in Fig. 8. Calibration is perform for situations where steel plate under the test wheel has different heights than plates positioned under the supporting wheels. Following heights differences are tested: -30, -20, -10, 0, 10, 20, 30 mm - see Fig. 15.
The backward acting force of 0, 10, 20, 40, 60, 80 N is applied to the test disc spindle in direction parallel to the road plane. The force is applied via flexible rope. The tilt of the test arm is recorded and on the base of those results the influence of rutting (trailer tilt) is established. During standard measurements tilting of the trailer is constantly monitored by two laser sensors and is used to correct the results.

Figure 15. Calibration of R2 Mk.2 trailer - rutting influence.

4. Example of results obtained by the R^2 Mk.2 trailer

Fig. 16 shows an example of the results obtained by the R^2 Mk.2 trailer. These measurements were performed at a speed of 80 km/h, the tyre load 4150 N and inflation pressure 210 kPa. Test section 1200 m long was divided into two sub-sections: the first covered by road surface SMA 8 and the second covered by experimental surface SMA 6.

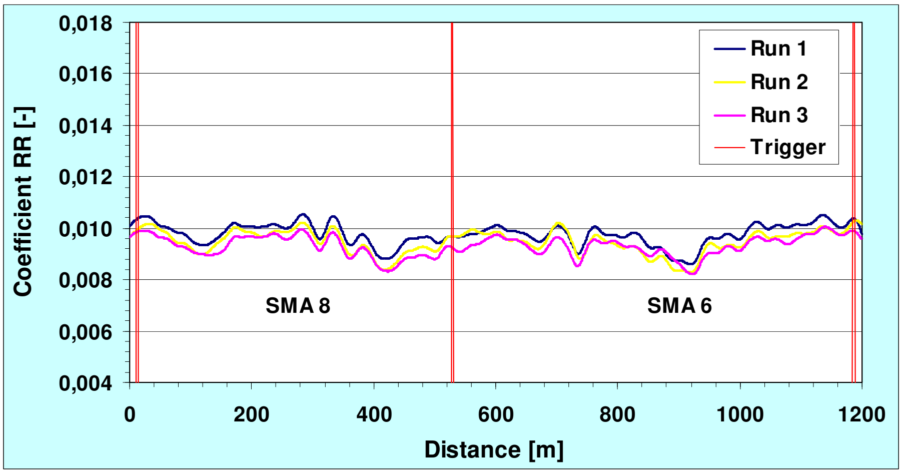

Figure 16. Example of measurement results.

Test tyre P1 (SRTT - UNIROYAL P225 / 60R16 97S M + S Tiger Paw) was used during measurements. Temperatures were as follows: air 20.2°C, road surface 32.9°C and the tyre sidewall 36.3°C. The measurements were repeated three times, one after another. Each run is marked with different colour in Fig. 16. The figure shows very good correlation between each run and the same "details" of the rolling resistance changes along the test sections that are caused by the pavement non-uniformity.

5. Conclusions

The coefficient of rolling resistance of tyres is a very important parameter because of its influence on energy consumption. Equally important is having the right tools to measure this factor in road conditions. Therefore, Technical University of Gdańsk has built a test trailer to study the rolling resistance of tyres in real road conditions. After successful introduction of the first R^2 trailer in 2003 its modified version was developed in 2012-2013. This trailer was a base for rolling resistance measurements in several national and international projects including ROLRES [5], ROSANNE [6] and LEO [7].

Due to the severity and complexity of the trailer, calibration and testing procedures are numerous, complex and time-consuming. Nevertheless, all procedures performed by TUG proofed high quality of the R^2 Mk.2 trailer. The calibration procedures described in this paper are also used in pre-standard developed by the ROSANNE project that will be used in further standardization activities of international bodies. At present R^2 Mk. 2 trailer owned by TUG is the most advanced trailer of this type in the world and is extensively utilized in many European countries as well as in USA.

Acknowledgements

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