ABOUT THE ROLLING RESISTANCE TRAILER AND PARAMETERS INFLUENCING ROLLING RESISTANCE

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ABSTRACT

The issue of global warming by an excessive amount of carbon dioxide (CO_2) in the atmosphere is a hot topic and the consequences for man and environment become more and more clear. Road transportation plays a significant role in CO_2 emission and unlike other sectors, its emission has even increased the last years. To stop this trend, different measures may be taken: e.g. tackling traffic congestion, lowering the consumption of the vehicles… Many other parameters influence CO_2 emission by transportation: e.g. tyre, vehicle and road characteristics… In this paper the influence of the road surface is investigated with a “quarter-car” trailer, suitable to measure rolling resistance with a car tyre on different road surface types. Texture measurements with a laser profilometer are performed to examine the correlation between rolling resistance and texture. The impacts of different parameters are investigated: repeatability over short and long time, speed, wind, tyre inflation pressure, tyre load, tyre type … Some rough coast down measurements are performed to compare with the trailer method. By gaining more knowledge about this topic, more environmental friendly and sustainable road infrastructure may be developed and implemented. This is expected to be an important tool for policy makers in their fight against CO_2 emission.

1. INTRODUCTION

1.1. Trailer measurements

All rolling resistance measurements mentioned in this paper are performed with the BRRC* trailer (see Figure 1).

Figure 1 – BRRC trailer with indication of α, μ and θ

* Belgian Road Research Centre

The trailer is designed as a quarter-car with a common car-suspension. It is connected to the measurement vehicle with bolts and has a fixed and a movable frame. At the end of the movable frame the extra load is attached. The total vertical force exerted on the tyre by the trailer is 1939 N.

The tyre can lean backwards and forwards thanks to the hinged connection with the fixed frame. During the measurements the tyre is pulled backwards as a result of the rolling resistance force (R). This results in the angle θ which is measured. The rolling resistance coefficient C_r is the proportion of the horizontal force (rolling resistance force, R) to the vertical force (vertical load, F_z). This corresponds to the tangent of the measured angle θ which may be approximated by θ, itself expressed in radians as it is a small angle. The principle of these measurements is shown in Figure 2.

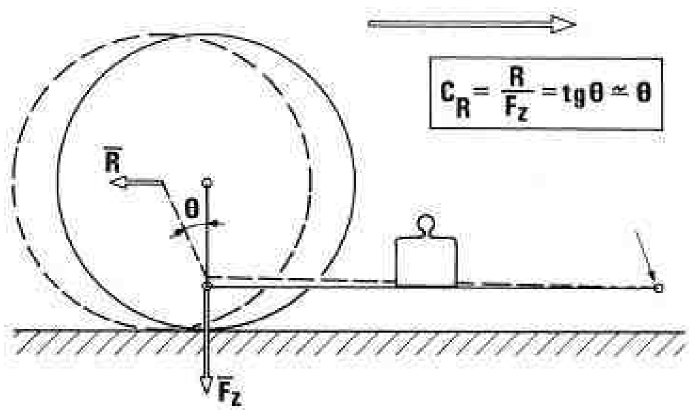

Figure 2 – Measurement principle BRRC trailer

The trailer presently has no enclosure that can prevent the tyre air drag from affecting the results. This implies that speed affects the measurements; i.e. the measured rolling resistance is higher for higher speeds.

The trailer is equipped with several sensors to register different parameters during the measurement (see Figure 1):

- Inclination θ of the wheel carrier with respect to the frame of the trailer
- Inclination μ of the frame of the trailer with respect to the horizontal plane
- Inclination α between the trailer and the towing vehicle in static condition
- Tyre temperature: an external infrared sensor is directed at the sidewall near the shoulder of the tyre
- Speed
- Acceleration

The measured data are corrected for the actual tyre temperature following the formula defined by Descornet [1]:

$C_r(T) = C_r(T_0) * e^{((T_0 - T)/T_1)}$

where $T_0 = 30$ °C, $T_1 = 50$ °C.

Equation 1

1.2. Coast down measurements

Some rudimentary coast down rolling resistance measurements were performed. No extensive, specialized measuring equipment was used for this. Two available vehicles and tyres were used. Each vehicle was coasted with transmission disengaged from a certain start point and with a specified initial speed (20 or 25 km/h) until standstill. The distance travelled by the vehicle was measured and was used as a measure for rolling resistance. The higher the distance between start and end point, the lower the rolling resistance. As this is only a simplified procedure of coast down, a lot of parameters are still influencing the measurements, e.g. vehicle rolling resistance and aerodynamical resistance are measured at the same time and cannot be excluded.

1.3. Texture measurements

Before performing the rolling resistance measurements, texture measurements were performed to verify the homogeneity of the road surface. These texture measurements are also used for the comparison of texture and rolling resistance afterwards. Texture was measured with a dynamic laser profilometer (see Figure 3).

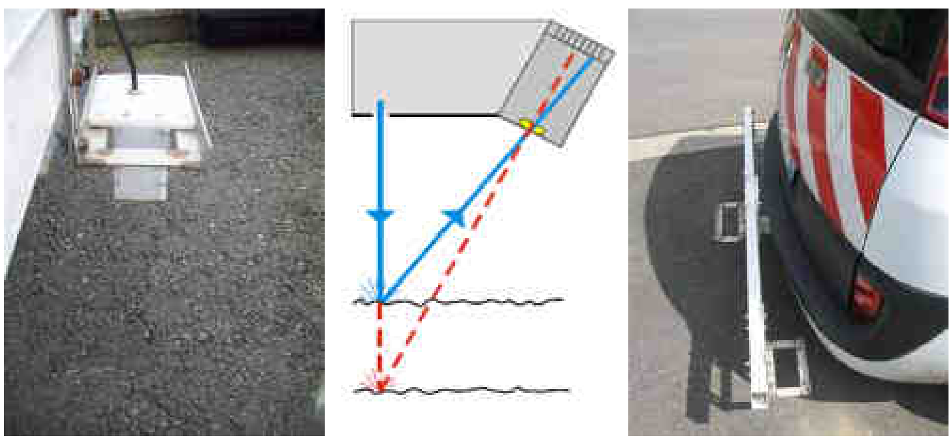

Figure 3 – Dynamic laser profilometer BRRC

One laser is mounted on a vehicle which allows performing measurements very efficiently. It may measure in the wheel track or in the middle of the traffic lane. The dynamic laser profilometer directs a laser beam perpendicular on the road surface which is then reflected (diffuse reflection). By laser triangulation the sensor determines the vertical position of the measurement point. For this research the laser was mounted in the middle of the traffic lane as the tyre from the rolling resistance trailer is also positioned in the middle.

The laser profilometer has a sampling frequency of 78 kHz and a small laser diameter beam (0.2 mm). Vehicle speed may vary between 0 and 40 km/h when measuring in steps of 0.2 mm. When a higher speed is necessary to avoid traffic disturbance, the measuring interval is 1 mm. The laser profilometer has a vertical measuring range of 64 mm and uses a 16-bit system. The vertical resolution is thereby 1 μm and it has a horizontal resolution of 0.2 mm. These measurements and further analysis are carried out in accordance with ISO-13473 [2].

1.4. Outline

The paper is outlined as follows. Section 2 deals with measurements performed with the trailer. This is followed by section 3 which deals with coast down measurements. Results of both rolling resistance measurement methods are linked to texture measurements in section 4. In section 5 some conclusions are made.

2. TRAILER MEASUREMENTS

This section deals with measurements performed by two Artesis University College students: Hans De Bie and Chris Hofmans [3].

2.1. Long and short time repeatability

Research performed about long term repeatability can be separated into two parts. In part one (I) the two measurement campaigns on ten test sections were performed by two different groups of researchers. Between these measurements there was a period of eight to eleven months. In part two (II) both measurement campaigns were performed by the same group of researchers on nine other test sections than in part one. Between these measurement campaigns there was a period of three months. The results (part I and part II) are shown in Figure 4 and Figure 5. All outliers were included in the graphs and analyses.

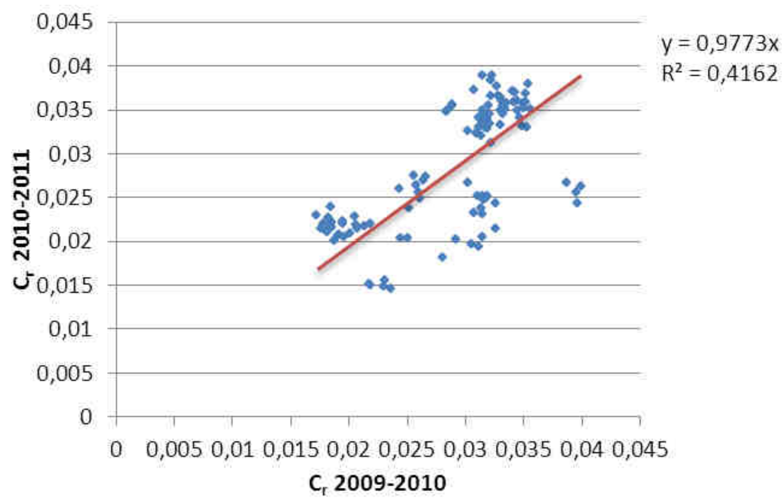

Figure 4 – Long time repeatability (part I)

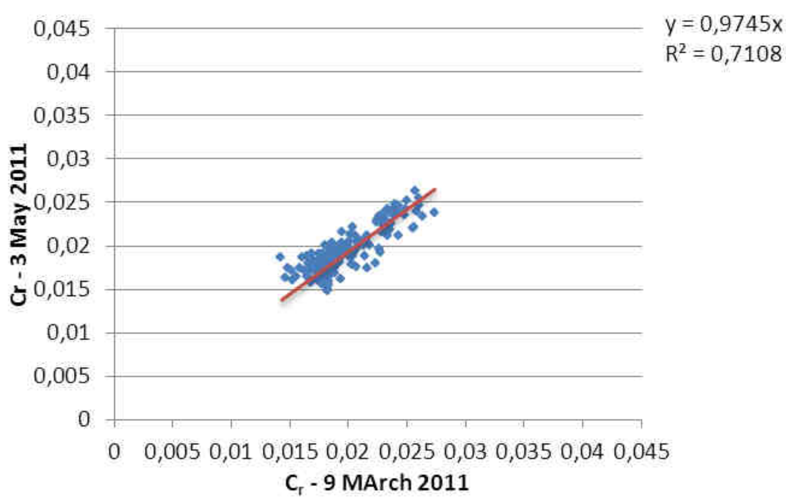

Figure 5 – Long time repeatability (part II)

The short time repeatability was performed on the same nine test tracks as for the long time repeatability (part II). The short time amounts five days. This result is shown on Figure 6. To be able to compare the results a temperature correction was applied.

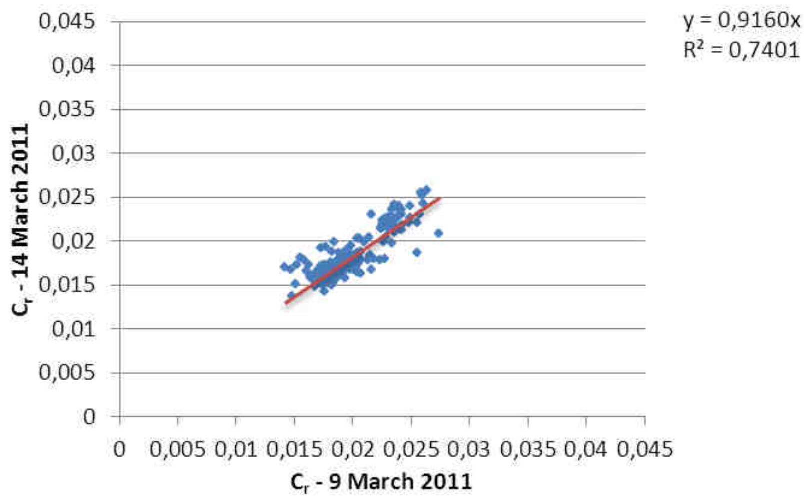

Figure 6 – Short time repeatability

The results of long time repeatability show that the repeatability of the rolling resistance measurements is good, because the slope of the regression lines approaches 1 and a reasonable correlation is shown. However the correlation of long time repeatability part I is not so good. One of the possible causes is that the first measurements were performed by another group of students and communication errors occurred. Another cause can be the wear of the road surface. Most probably however a calibration error was made by one of the two groups of students. The correlation factor of part II is good.

The slope of regression line of short time repeatability differs more from 1, but is still acceptable. Also a reasonable correlation can be noted.

2.2. Tyre load

The influence of the vertical load on the rolling resistance force and the rolling resistance coefficient was investigated. Normally on the BRRC trailer a load of 1939 N is applied on the tyre. To investigate the influence of the load the C_r measurements were performed with the following loads: 1285 N, 1416 N, 1547 N, 1678 N, 1809 N and 1939 N. In Figure 7 the rolling resistance force as a function of the vertical load is shown.

The influence of the load on the rolling resistance force is linear. The rolling resistance force is dependent on the load. However this means that the rolling resistance coefficient is constant and more or less independent of the load. In Figure 7 the results are shown with and without temperature correction (as defined in Equation 1). Applying a temperature correction yields a better correlation. Measurements were performed in two directions (on opposite lanes) of the street: east and west.

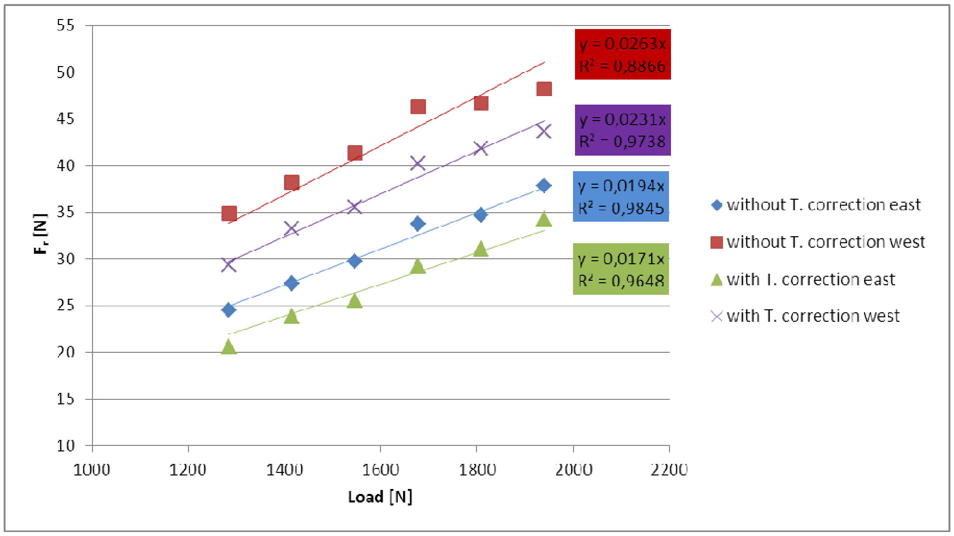

Figure 7 – Influence of vertical load on rolling resistance force

2.3. Tyre inflation pressure

To investigate the influence of tyre inflation pressure C_r measurements are carried out while increasing the tyre inflation pressure from 1.2 bar to 3.2 bar in steps of 0.5 bar. In Figure 8 the correlation between C_r and tyre inflation pressure is shown.

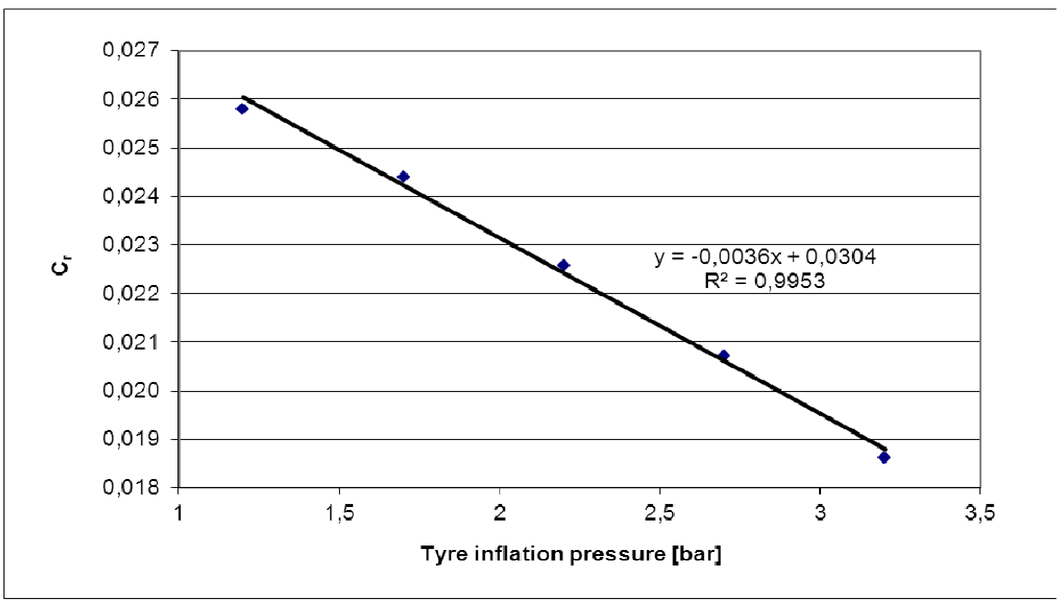

Figure 8 – Correlation between average C_r and tyre inflation pressure

The results show that when the tyre inflation pressure decreases, C_r increases. A difference of 1 bar gives a raising or lowering of approximately 0.004 of the C_r value, which is about 15 to 20 %. This means that tyre inflation pressure is a very important factor for the rolling resistance.

Tyre inflation pressure increases with temperature. Therefore it is necessary to observe a good warm-up procedure before performing measurements. When the tyre is warmed up a constant temperature and tyre inflation pressure is achieved.

2.4. Wind shielding

As earlier research [4] indicated a significant influence of wind on a trailer, this was further investigated. A removable wooden windscreen was made (see Figure 9).

Figure 9 – Wind screen on BRRC trailer

The measurements were performed with the old and the new tyre and at different speeds (30, 50, 70 km/h), because also the influence of tyre type and speed was looked into (see sections 2.5 and 2.6). In Table 1 the influence of the windscreen is shown, together with the influence of the speed and the comparison between the old and the new tyre. The latter two will be discussed in the next sections.

Table 1 – Influence speed, windscreen and tyre type

	Speed (km/h)	Direction	Tyre	Average C_r whitout windscreen	Average C_r with windscreen	Relative difference between with/without windscreen
	30	East	Old	0.030	0.030	0.33%
	30	East	New	0.027	0.017	60.71%
Relative difference old / new tyre				12.22%	79.76%	
	30	West	Old	0.031	0.029	8.74%
	30	West	New	0.012	0.018	-32.04%
Relative difference old / new tyre				152.85%	58.01%	
	50	East	Old	0.033	0.031	7.12%
	50	East	New	0.028	0.018	54.49%
Relative difference old / new tyre				20.36%	73.60%	
	50	West	Old	0.034	0.031	8.68%
	50	West	New	0.014	0.018	-22.35%
Relative difference old / new tyre				143.17%	73.74%	
	70	East	Old	0.034	0.032	3.40%
	70	East	New	0.025	0.020	26.77%
Relative difference old / new tyre				33.47%	63.64%	
	70	West	Old	0.034	0.033	3.64%
	70	West	New	0.017	0.021	-21.43%

In Table 1 it can be seen that using a windscreen has a significant influence on C_r. The values are generally lower than without windscreen. However this is not always the case, as the measurements with the new tyre in direction west show a smaller C_r without windscreen than with windscreen. This deviation may be explained by the presence of an eastern wind while the measurements were made. This also explains the big differences between the measurements in direction east. In general one can conclude that the windscreen is absolutely necessary for the measurements, but a windscreen all around the tyre and to ground level would even be better. Now the windscreen is only situated at one side of the tyre and not to ground level, so the wind can still blow under the car and thereby influence the measurements.

2.5. Speed

Measurement results are shown in Table 1 and Figure 10. A distinction between different tyre types (see also section 2.6) is made in the chart by plotting the graphs representing measurements with the old tyre with dashed line and those with the new tyre with full line.

Generally C_r increases when the speed increases but this is not the case for the measurements with the new tyre and without windscreen in direction east.

The increase of C_r seems larger than expected. According to the formula of speed correction obtained by Descornet [1] a change of 20 km/h relative to 50 km/h leads to a difference in C_r of ± 0.00048, while the measured differences are much larger (e.g. 0.0012 – 0.0035).

Recent research reveals that a larger windscreen, encapsulating the whole tyre, is advisable to eliminate wind influence at higher speed [5]. The wind may still have influenced the measurements as the windscreen as shown in this paper is small.

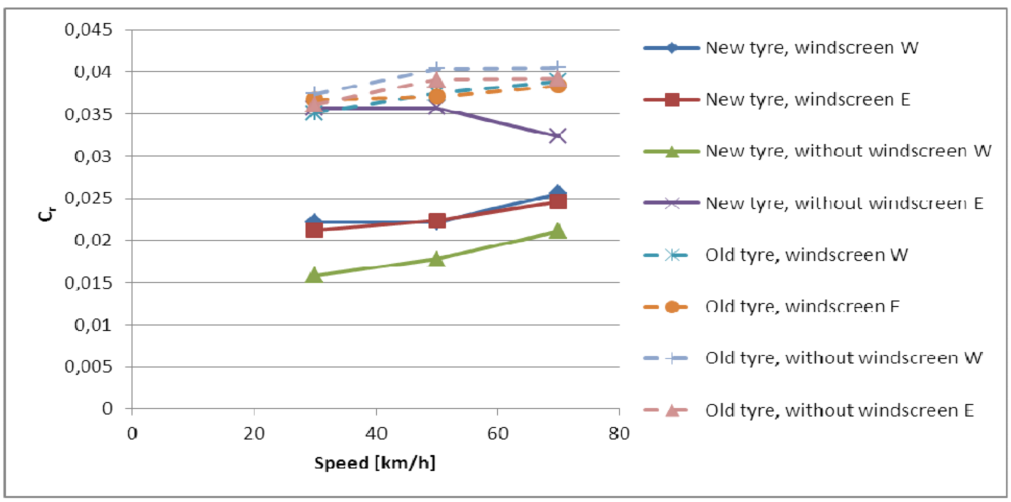

Figure 10 – C_r as a function of speed

2.6. Tyre type

The old tyre, a slick Michelin SB-15/63-14X, mounted on the trailer was about 30 years old. Because the rubber hardened significantly, it was necessary to change the tyre. The new tyre is a Michelin Energy Saver 195/70 R14 91T. Both tyres are shown in Figure 11. The difference between the two tyres was measured and is shown in Table 1.

Figure 11 – New Michelin Energy Saver tyre (left) and old Michelin slick tyre (right)

The C_r values of the new tyre are lower than the values of the old tyre. Because both tyres are completely different types, this result is possible. Clearly not only the road surface has an important share on the rolling resistance, but as can be expected also the tyre. A well thought selection of tyre can provide a lower CO_2 consumption.

2.7. Calibration issue trailer

In general it can be concluded that most of the results are logical, but the measured C_r are higher than expected in comparison with other research. Normally C_r typically has a value between 0.006 and 0.02 [5]. Meanwhile the reason for these high values has been found. A calibration error related to the BRRC trailer of the angle θ was present and amounts 0.4°. This issue has been solved in the meantime an d does not influence the conclusions of this paper but only the absolute values of C_r.

2.8. Texture

Texture measurements were performed to select the most homogeneous road surfaces for the analysis. The texture spectra of all test sections used for assessing the correlation between rolling resistance and one-third-octave band texture levels (see section 4) can be seen in Figure 12.

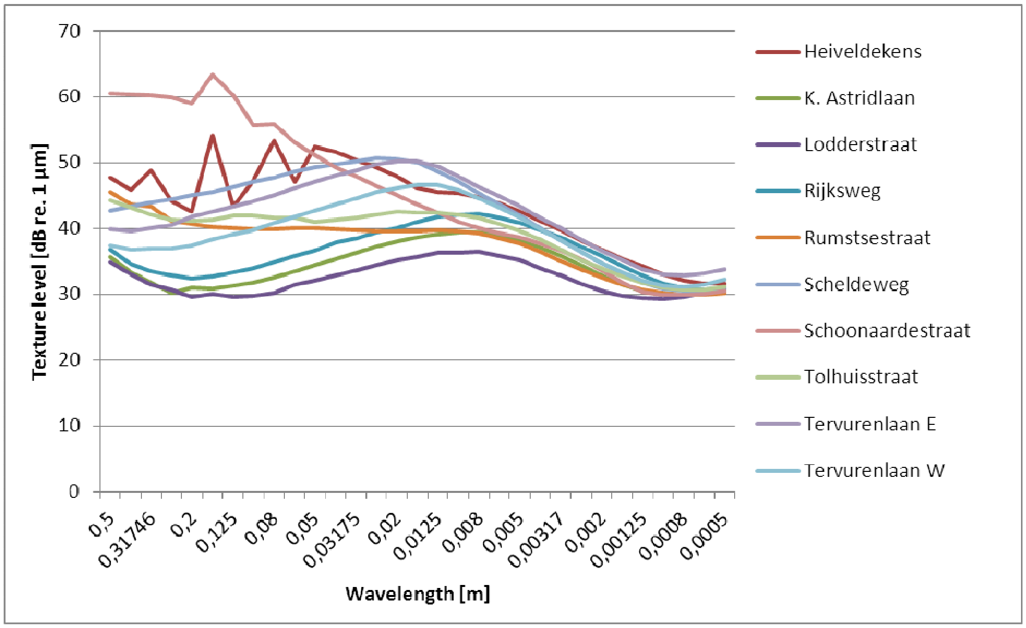

Figure 12 – Overview texture spectra test sections De Bie-Hofmans

3. COAST DOWN MEASUREMENTS

This section deals with measurements performed by two Artesis University College students: Jorien Aerts and Melissa Cools [6].

3.1. Measurement procedure

Two different vehicles were used to perform coast down measurements (see section 3.2). To obtain a constant vehicle weight always the same person drove the vehicle and the fuel tank was filled up before starting the test. Tyre pressure was measured in cold condition. At least 10 km was driven to warm up the tyres.

Test sections have a length of only 100 to 200 m so a low initial speed was chosen: 20 km/h for vehicle A and 25 km/h for vehicle B (except for test section “Roekstraat” where 20 km/h was used because of the short length of the test section). Speed as shown on the odometer was checked. The real initial speed was 19.3 km/h for vehicle A, while vehicle B drove at 23.7 and 18.4 km/h respectively.

To obtain the start speed the first gear was used. When reaching the start point at the correct speed, the clutch pedal was pushed. The vehicle was coasted from the start point until standstill. When the vehicle came at standstill the brake pedal was pushed and the distance travelled by the vehicle was measured.

To eliminate the influence of the slope, the measurements were done in two directions. However because of safety (test sections were streets with traffic) in most cases the vehicle could not drive on exactly the same track in both directions so this was done on the opposite driving lane. Texture of both driving lanes/directions was measured with the dynamic laser profilometer to check homogeneity. Three coast down measurements were performed in each direction.

Measurements were performed in dry weather conditions and with low wind. Air, tyre and road surface temperature were registered. Ambient air temperatures ranged from 5.6 - 20.5 °C albeit no temperature corrections were appl ied.

3.2. Vehicles

Table 2 – Characteristics vehicles and tyres used for coast down measurements

	Vehicle A	Vehicle B
Vehicle type	Audi A3 S-Line (2003)	Peugeot 307 (2005)
Vehicle weight (driver included)	1480 kg	1400 kg
Picture of vehicle		
Tyre Inflation	2.5 bar	2.4 bar
Tyre type	Triangle 225/45ZR17	Michelin 205/55R16
Tread depth tyre	6.0 mm	4.8 mm

Picture of tyre		

3.3. <u>Results</u>

3.3.1. Texture

Figure 13 shows the texture spectra of all test sections. The graphs of “Nekkerhal 1”, “Nekkerhal 2” and “Prinsendreef” have an “irregular” course which is due to the fact that these are cobble stones and concrete pavings. An attempt was made to have a high variety of various road surfaces.

Figure 13 – Overview texture spectra test sections Aerts-Cools

As most coast down measurements were not performed on the same line in both directions, the homogeneity and similarity was checked for both measuring lanes/directions. The analyses of “Nekkerhal 1” (see Figure 14), “Nekkerhal 3”, “Steenweg op Heidonk” and “Van Den Nestlaan “show some difference between both measuring lanes. The other test sections reveal no significant difference.

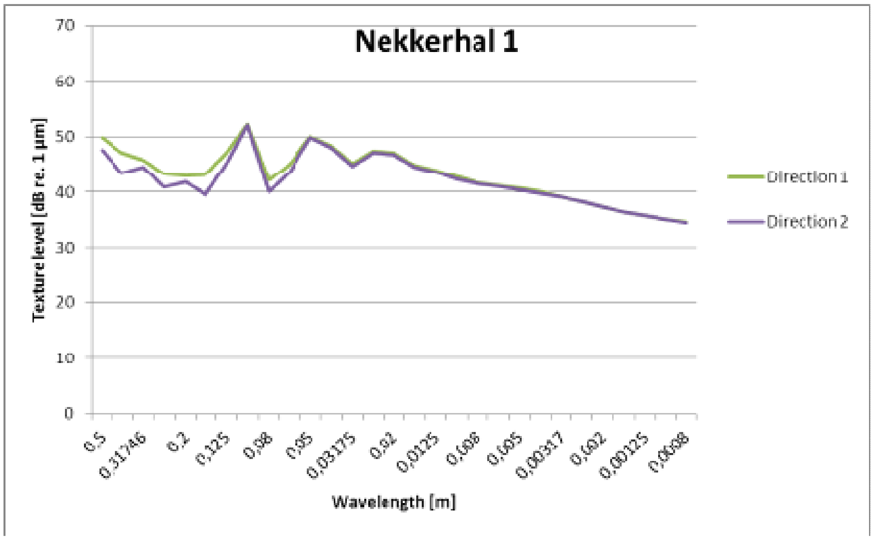

Figure 14 – Texture spectra both measurement directions test section "Nekkerhal 1"

3.3.2. Coast down

Air, road and tyre temperature for all test sections and the various vehicles can be found in Table 3. The table also comprehends the average distance of the coast down measurements in both directions.

Table 3 – Coast down measurement results of both vehicles (air, road and tyre temperature; average value of two directions) – Indication with * means that this measurement was performed at 20 km/h; See section 3.3.3 for the meaning of (+)

Test section	Vehicle A – 20 km/h				Vehicle B – 25 km/h			
	Air temp. [℃]	Road temp. [℃]	Tyre temp. [℃]	Mean distance [m]	Air temp. [℃]	Road temp. [℃]	Tyre temp. [℃]	Mean distance [m]
Hooiendonkstraat	9.0	14.2	16.6	119.0	17.0	19.2	24.2	140.1
Nekkerhal 1 (+)	19.7	10.8	12.8	89.0	-	-	-	-
Nekkerhal 2 (+)	5.6	11.5	16.2	86.0	28.5	22.0	27.5	184.7
Nekkerhal 3	7.5	12.9	14.3	91.0	22.0	25.8	28.9	187.5
Roekstraat	12.0	16.2	20.4	93.9	*15.5	*19.2	*22.7	*122.8
Steenweg op Heindonk	7.0	14.7	16.1	103.6	19.6	21.6	25.6	186.6
Corluylei (+)	16.7	21.0	21.0	87.0	22.5	20.3	26.3	165.0
Prinsendreef (+)	19.1	9.3	9.8	101.5	16.1	13.5	13.0	130.7
Van Den Nestlaan (+)	19.1	21.8	26.6	102.9	16.9	17.3	23.2	174.9
Stijn Streuvelslaan (+)	13.8	16.0	21.5	94.5	18.5	23.8	24.0	163.9

Correlations between measurements performed with the two vehicles are plotted in Figure 15 for direction 1, 2 and the average. Test section "Roekstraat" is not included in this analysis as this was the only test section that was measured with a different speed by vehicle B. Some correlation is found for measurements in direction 2.

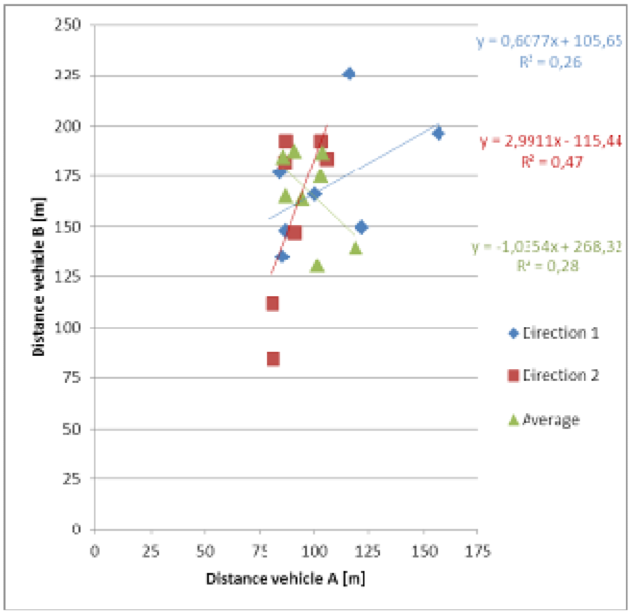

Figure 15 – Correlation between coast down measurements both vehicles – all test sections

It can be assumed that the texture inhomogeneity of opposite measuring lanes causes some extra uncertainty. Therefore the same chart was plotted, eliminating nonhomogeneous test sections (see section 3.3.1). Correlations indeed improve by doing so (see Figure 16). A good correlation is found for the average of both directions.

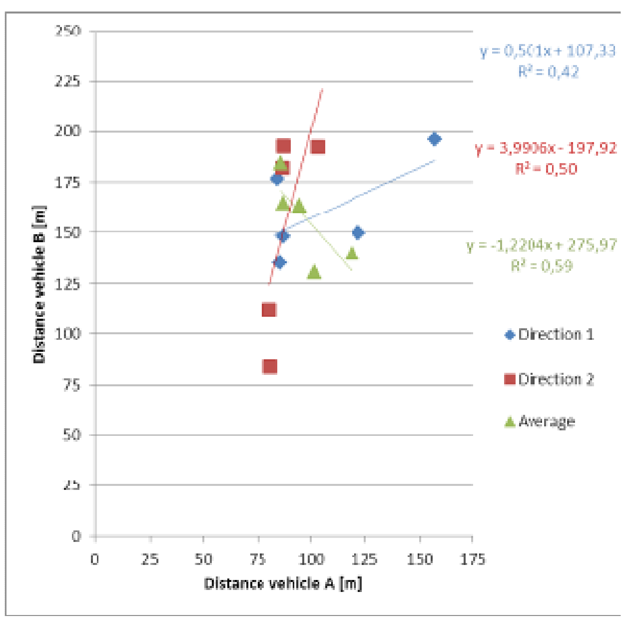

Figure 16 – Correlation between coast down measurements both vehicles – only test sections with similar texture spectra in both directions

3.3.3. Correlation with trailer measurements

Two other Artesis University College students, Vyacheslav Dotsenko en Bert Helsen [7], performed BRRC trailer measurements in the same year on some common test sections: in Table 3 these test sections are marked with (+). The correlations between the trailer measurements (C_r) and coast down measurements (distance) for both vehicles are shown in Figure 17. Vehicle B shows some correlation, while the correlation of vehicle A is low. Perhaps the measurements performed with vehicle A are less accurate because of the lower initial speed and/or the fact that these were the first measurements and the operators were not yet used to the measurement method. However no certain clarification which explains the difference between the vehicles can be given.

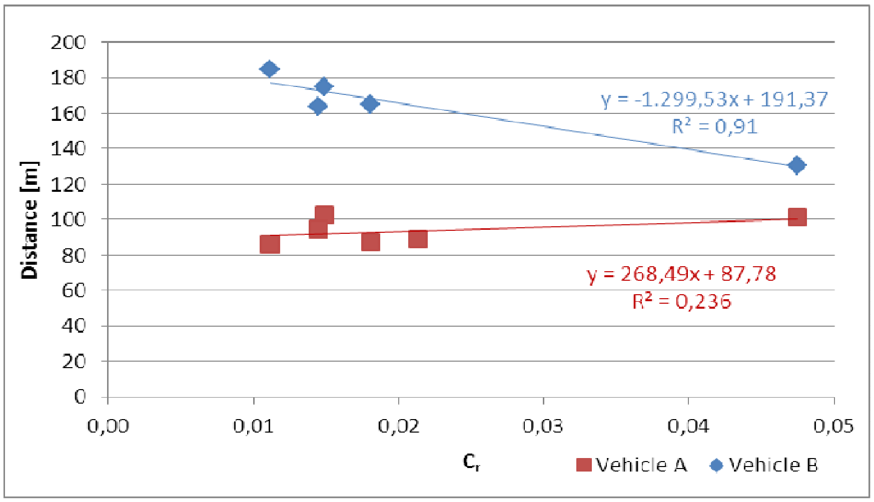

Figure 17 – Correlation between C_r measured by Dotsenko-Helsen and coast down distance measured by Aerts-Cools

4. ONE-THIRD-OCTAVE BAND TEXTURE LEVELS

The correlation between rolling resistance and one-third-octave band texture levels has been determined for all measurements performed by Artesis students. The correlations (R^2) have been calculated for all texture wavelengths. The results are compared with previous research by Descornet [1].

All results are shown in Figure 18. The blue graphs represent results by Aerts-Cools [6] for coast down measurements with vehicle A and B (see section 3). The pink line shows results for BRRC trailer measurements by De Bie-Hofmans [3] (see section 2). The green line is the result of research performed with BRRC trailer by Dotsenko-Helsen [7], Artesis students in 2009-2010. The red line displays results obtained by Descornet in the eighties with the “old” BRRC trailer [1].

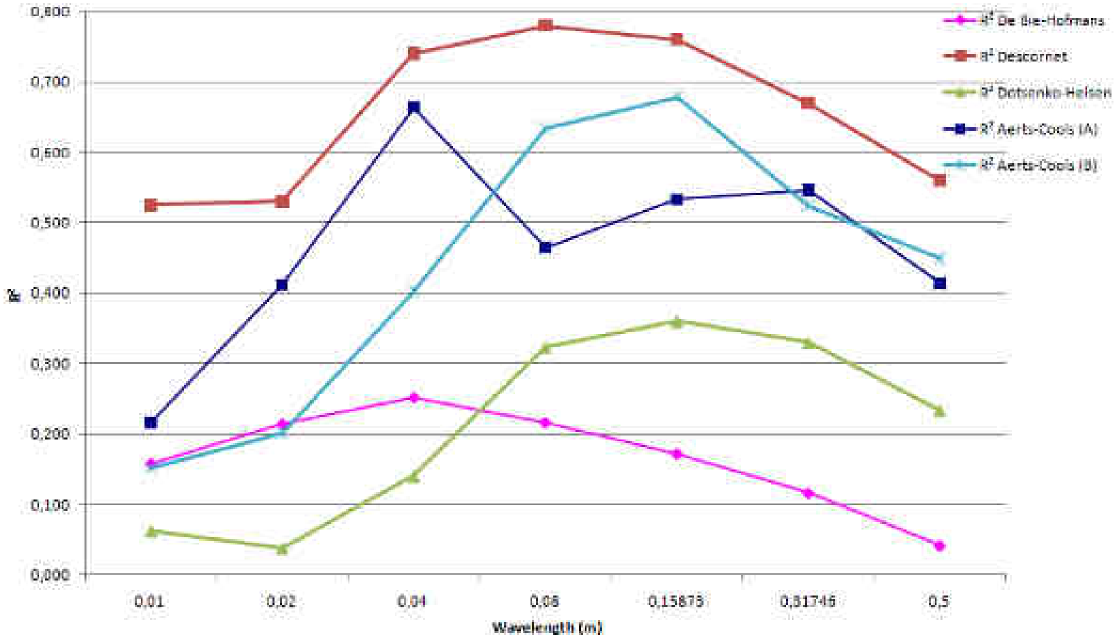

Figure 18 – Comparison results various research projects

In contrast with previous research, very low correlations are found in the latest research with the BRRC trailer (see Figure 18). The results of Descornet and the coast down method from Aerts-Cools give better correlations. The pink curve De Bie-Hofmans also has another course than found by Descornet and master students Aerts-Cools and Dotsenko-Helsen. An explanation for this is probably that the trailer as it was used for this research still had a lot of uncertainties (change of tyre, new sensors, change of tyre temperature measurement, … resulting in calibration issues).

A typical contact area length of a car tyre is 0.15 m, depending on other parameters like tyre inflation pressure, load, type… [8] The maxima of the graphs Dotsenko-Helsen and Aerts-Cools (B) are situated around 0.16 m wavelength, which is about the same dimension as the contact area length. One can state that this contact area length probably has a large influence on rolling resistance.

5. CONCLUSIONS

The following conclusions can be made:

When considering research performed with trailer measurements performed by one group of students, long and short time repeatability are found to be reasonable.

The influence of the load on rolling resistance force appears to be linear. The rolling resistance force is dependent on the load. The rolling resistance coefficient however is constant and more or less independent of the load.

Tyre inflation pressure has a large influence on rolling resistance measurements and should always be considered. A difference of 1 bar is found to give a raising or lowering of approximately 0.004 of C_r, which is about 15 to 20 %.

Wind shielding of the trailer (tyre) is necessary to obtain more accurate results at higher speeds.

C_r increases slightly when speed increases. However more research is needed with larger windscreen to determine exact values.

Not only the road surface has an important share on the rolling resistance, but also the tyre. A well thought selection of tyre can provide a lower CO_2 consumption.

Calibration of the trailer is very delicate and has a high influence on all measurements. The smallest change of the trailer can cause large differences.

Even rudimentary coast down measurements seem to give plausible rolling resistance results.

Coast down measurements show very good correlations between rolling resistance and megatexture. Rather low correlations are found between recent trailer rolling resistance measurements and texture. However in the research by Dotsenko-Helsen the same course was found as in previously performed research by Descornet, also indicating the highest correlations in the megatexture area.

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