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Optimising the returns from modern asphalt surfacings

Sub-Task3: Rolling resistance of asphalt surfacings

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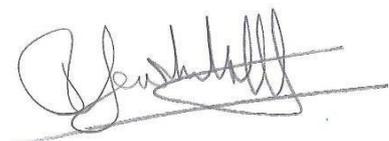
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Executive Summary

For many years, the UK central government and road construction industry, through the Highways Agency (HA), the Mineral Products Association (MPA), the Refined Bitumen Association (RBA) or their predecessors, have commissioned a rolling programme of collaborative research. Carried out by TRL, this has focussed on the practical needs of the Agency and the Industry in providing and maintaining the UK road infrastructure. This report has been produced under the 2012 Collaborative Research Programme.

Road pavements are currently designed, specified and constructed such that their surfaces deliver adequate ride quality and skidding resistance but designs do not specifically take into account the rolling resistance of the surface. In order for this to become possible in the future, the pavement factors affecting rolling resistance need to be determined, along with how practical it would be to change these factors, during maintenance or construction, and to what extent they affect rolling resistance. As part of this research, the effect of pavement surface texture on rolling resistance has been investigated using TRL's accelerated Pavement Test Facility (PTF) and the results of this work are presented within this report.

The PTF offers a controlled environment in which to traffic real pavements and this has been instrumented with bespoke equipment to record all forces, angles, temperatures etc. needed to measure rolling resistance. This research has demonstrated that this instrumentation is capable of separating the small forces due to rolling resistance under load from the other forces present during pavement trafficking. The PTF has been used to determine differences in rolling resistance on pavement strips of a selection of trial surfaces constructed with a range of texture depths that could otherwise be considered identical. The different texture depths were achieved by using a range of aggregate sizes in a proprietary thin surfacing.

The results showed that small differences in the coefficient of rolling resistance between the surfacings could be measured in repeated passes of a loaded heavy vehicle wheel and that rolling resistance increased with increasing texture depth. The implications of this are discussed and recommendations for addressing additional surfacing materials are proposed.

1 Introduction

It is well known that the construction of road pavements affects the energy required to drive over them (Benbow, 2007). Therefore it would be desirable to construct pavements to minimise fuel usage. These “Energy Efficient Pavements” would assist in reducing emissions and costs for road users, and assist in the mitigation of climate change. The energy required to drive over a pavement can be related to its rolling resistance. Even a very small decrease in the rolling resistance will deliver benefits, because it affects all vehicles. It would come in addition to other benefits resulting from changes to vehicles or driving styles. Furthermore, the properties that influence rolling resistance are likely to also influence smoothness and noise. Therefore, improving rolling resistance also has the potential to improve user satisfaction.

Pavements are currently constructed such that their surfaces deliver adequate ride quality and skidding resistance but designs do not specifically take into account the rolling resistance of the surface. In order for this to become possible in the future, the pavement factors affecting rolling resistance needed to be determined, along with how practical it would be to change these factors, during maintenance or construction, and to what extent they affect rolling resistance. Therefore, the Highways Agency commissioned TRL to investigate the relationship between pavement properties and the energy consumed when travelling over them (Benbow, 2007).

There are a number of road factors that affect rolling resistance, including gradient, road layout, crossfall, road construction (particularly the stiffness), and pavement surface properties. Of these factors, gradient has by far the largest effect on fuel consumption and the fuel bill in the UK could be reduced significantly if the road network could be flattened. However, the cost and practicality of doing this would prevent this from being an option, thus gradient isn’t something that can be changed in general. The road layout affects the speed at which the users can travel and the frequency with which they need to brake and accelerate, both of which can cause different amounts of fuel to be consumed. However, roads often have to follow set routes and they also need to join up with others, making junctions necessary. Changing junctions after construction can be costly and is not always practical, thus the road layout is also not necessarily something that could be easily changed. However (within practical limits) it is possible to change the crossfall, stiffness, roughness and texture of a road (collectively referred to as the “shape” of the surface).

The effect of pavement stiffness on rolling resistance was previously investigated and a measurement system was developed, for use in TRL’s Pavement Test Facility (PTF) to investigate this relationship (Benbow, 2007). The results from this research suggested that stiffness does have an effect but that it is very small. Thus, this project was followed by an investigation into the effect of shape on rolling resistance.

There is currently little quantitative knowledge from trials on real pavements on the relationship between shape and rolling resistance. Tyre manufacturers generally carry out measurements with smooth drums (and sometimes special rolling resistance trailers for the purpose of research) so that the performance of different tyres can be compared, under standard conditions typically defined by ISO Standard 18164 (International Organization for Standardization, 2005). Thus, a significant proportion of work on rolling resistance is carried out without measuring the effect of surface properties. As a result,

relatively little is known about the contribution of the road surface to the rolling resistance.

In the first phase of the work described in this report, a review was undertaken to establish the current level of understanding of the relationship between pavement shape and rolling resistance. This study considered truck tyres in particular because heavy goods vehicles are the vehicles for which the most significant benefit is expected, in terms of fuel consumption. The review aimed to identify the key element of pavement shape affecting rolling resistance. The second phase developed bespoke equipment to measure the forces involved in traversing the pavement and undertook trials on a set of pavements constructed in TRL's PTF.

An initial analysis of the data from these trials showed that the equipment that was developed was sensitive enough to measure rolling resistance. The purpose of the current research has been to undertake a further in-depth analysis, of the experimental data collected in the second phase, with the aim of establishing the effect of the different levels of texture on rolling resistance and hence on potential fuel economy and this has been produced under the 2012 Collaborative Research Programme.

This report presents a summary of the work carried out for the HA in phases 1 and 2 and also the results of the analysis on the data from the practical trials, carried out within the Collaborative Research Programme.

2 Review of pavement factors affecting rolling resistance

A literature review, undertaken for the HA, studied the level of knowledge of the relationship between pavement shape (including texture, transverse and longitudinal profile) and rolling resistance (Benbow & Iaquina, 2009). The review found that previous research had not been very successful in separating the effects of surface properties from other “external” factors affecting rolling resistance, such as road geometry. Previous research also did not appear to agree on whether unevenness or texture has the biggest influence on rolling resistance, and therefore did not provide a clear pointer to the surface shape parameter to be investigated. Therefore within this work it was decided that the parameter for investigation should be selected based on practical constraints.

Due to the cost of reducing the gradient of roads, and the safety implications of reducing crossfall i.e potential adverse impacts on surface water drainage and superelevation on bends, three practical options remained for parameter investigation: transverse profile, longitudinal profile and texture profile.

It was unclear from the literature whether transverse profile has any effect on the rolling resistance of a pavement, and it is likely that any effect that it does have is actually due to the longitudinal unevenness arising from transverse profile features such as rutting.

As noted above, one problem highlighted in the previously reviewed work was the fact that studies into the relationship between fuel economy and pavement properties had not been able to remove “external” effects from the practical investigations. Therefore it was proposed that the TRL work should use a carefully controlled test site constructed in the Pavement Test Facility (PTF) at TRL. To investigate the effect of longitudinal profile on rolling resistance would require pavements of differing profiles to be constructed, possibly having long lengths. Since the maximum length of pavement that can be constructed in the PTF is 10m, it was felt that the PTF would not be suitable for an assessment of the effect of longitudinal profile.

Therefore, it was decided that the investigation should concentrate on the effects of surface texture on rolling resistance. This would be achieved by constructing a set of “identical” pavements in the PTF, differing only in surface texture. As well as allowing for test pavements whose only difference was their surface texture, this approach had the additional benefit that it complemented other HA research being carried out into the use of new materials in pavement surfaces: Under the 2008-11 Collaborative Research Programme Topic 1 “Surface Requirements for Asphalt Roads”, research was undertaken to investigate the use of small aggregate sizes in surfacings on the HA network (Roe & Dunford, 2012). In the long term, the combination of the results, from both of these research areas, could provide an ability to build up ratings for different surface types, covering properties such as noise, friction and “energy efficiency”.

The review also investigated the types of tyre that could be used in practical trials. A review of the range of tyres, appropriate for use in the experiments, was undertaken in order to identify a tyre representative of typical truck tyres encountered on the UK and European road networks. It was found that the tyre type currently used for the TRL PTF’s test tyre (Michelin Super Single XTE2 385/65 R22.5) was representative of truck tyres in the UK and would therefore be appropriate for use in this research.

3 Instrumentation

3.1 Design of the instrumentation

As noted above, in the initial research, for the Highways Agency (Benbow, 2007), TRL developed a measurement system for use in TRL's Pavement Test Facility (PTF) to investigate the relationship between pavement stiffness and rolling resistance. The PTF consists of a carriage, supported by two rails, that is moved above the test pavement by an electric motor (Figure 1). Two arms attached to each side of the carriage drive a truck wheel on which a load is applied by two rams. Figure 2 shows a simplified representation of the PTF.



Figure 1: Picture of the PTF showing gantry, test wheel and the platforms

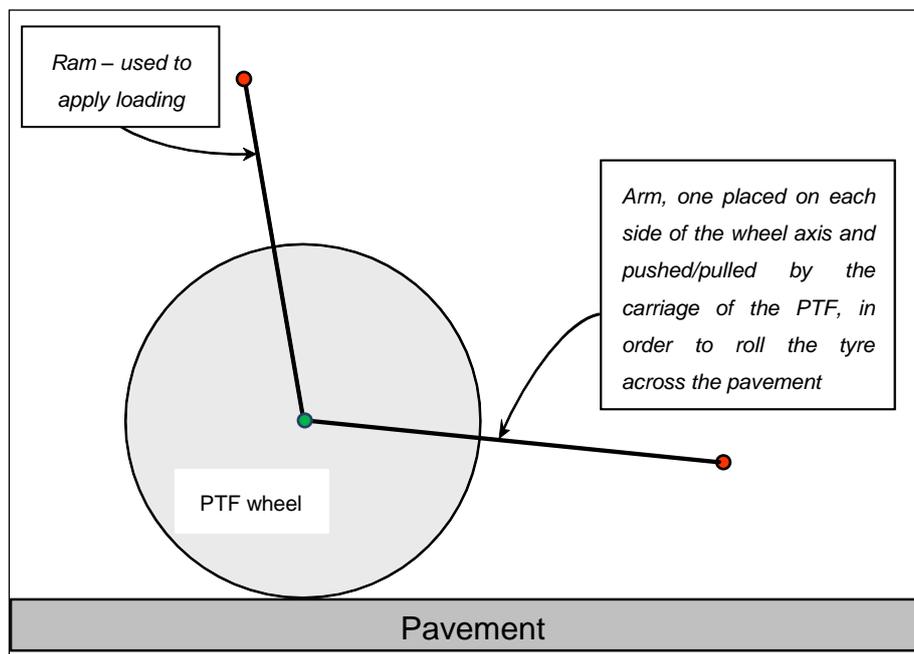


Figure 2: Simplified representation of the PTF

The rolling resistance can be broadly considered to be the force that opposes the wheel when pushed or pulled across the pavement. Theoretically this can be obtained by measuring the force present within the arms that connect the wheel to the carriage (Figure 2). However the arms are not horizontal and their angle to the horizontal can vary with wheel-load and during travel across the pavement. A range of additional

instrumentation was therefore required to monitor the movement of the various components.

In summary, the instrumentation, developed in the initial research, measured:

- The force opposing the wheel movement, using instrumented arms on the PTF carriage
- The load force applied each side of the wheel by the rams
- The acceleration of the moving assembly (carriage and wheel)
- The arm angle
- The wheel (rotational) angle
- The temperature of the surface of the tyre, pavement, and the ambient temperature.

Within the investigation the effect of pavement shape on rolling resistance, a review was carried out of the initial equipment. The review concluded that most of the existing instrumentation could be applied in any future work. However, the earlier work had been adversely affected by limitations in the capability of the instrumentation installed in the arms to measure the force opposing the wheel. The design of the instrumented arms was such that bending could occur in the middle of each arm causing the instruments to measure values outside their calibration range. Therefore it was recommended that a new approach be applied to improve the accuracy, sensitivity and measurement range.

Therefore, two new arms were constructed, each attached to the PTF carriage using a new instrumented pivot pin, as shown in Figure 3. An important change from the previous design applies the ram loads directly to the wheel axle, via plain bearings either side of the clamp securing each arm to the end of the axle. This avoids the induction of bending in the arms by the ram load. Each pair of bearings is part of a saddle distributing the ram load equally. The instrumented pins, shown in detail in Figure 4, connect the arms to the carriage. The central section of each pin is a close fit in a bore through the end of its arm, while its ends are supported in self-aligning roller bearings mounted on the carriage. Each pin contains a cylindrical bore and the wall-thickness is reduced between the central section and the bearing ends, as seen in the figure. Resistance strain-gauges are attached to the inside surface at these positions, arranged to measure the shear strains in two orthogonal directions at either end of each pin. A locking screw ensures that each pin is located in its housing in the arm with the measuring directions aligned with and normal to the arm axis. The gauges are connected electrically in full Wheatstone bridges arranged to respond to shear strains due to forces normal to the pin axis but cancel any axial, bending or torque-induced strains. Figure 5 shows the PTF test wheel with the instrumentation installed.

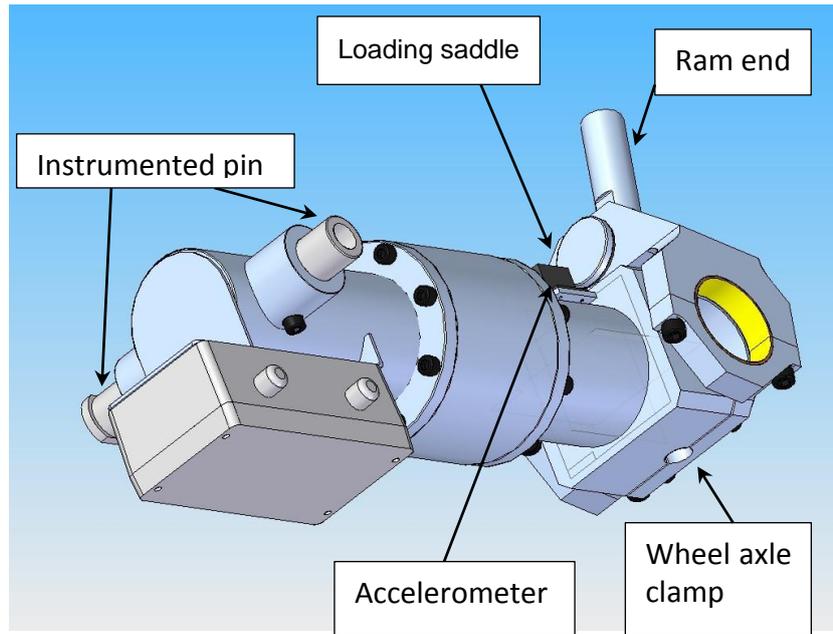


Figure 3: Design of the new arm for the PTF, showing where ram load is applied and pins are located



Figure 4: New instrumented pin

In addition to the instrumentation listed above, a remotely controlled “artificial load” was installed on the PTF carriage (Figure 5). This equipment is essentially a generator connected to an electrical load and to the wheel hub by a toothed belt. It allows three different levels of a small, but controlled, additional rolling resistance to be introduced that enables the sensitivity of the measurement equipment to be characterised.

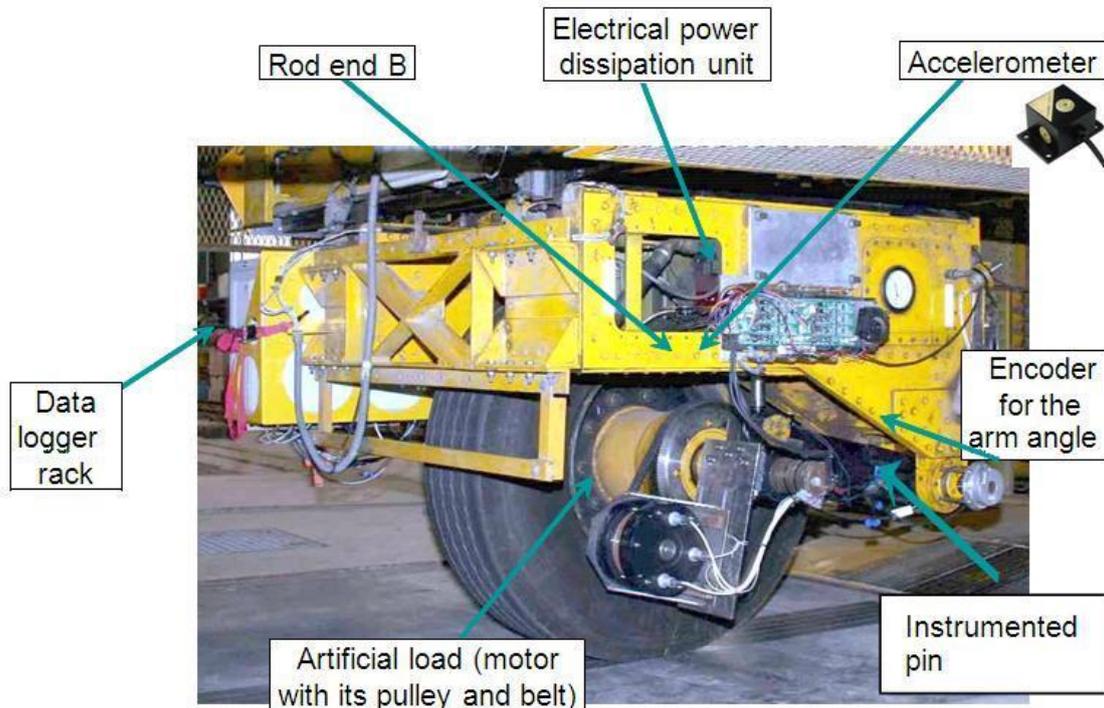


Figure 5: Sensors mounted on the PTF

3.2 Calculating Rolling Resistance

The instrumentation installed on the PTF enabled all forces, angles, and temperatures to be measured, as the wheel travelled over the pavement strips. These measurements were recorded for each 10mm travelled along the pavement surface, resulting in approximately 2 million data points per there-and-back pass of the wheel.

This data was then used to calculate the average coefficient of rolling resistance for each pass performed and the details of this calculation are given in Appendix A.

3.3 Commissioning the instrumentation

Commissioning trials of the new instrumentation were carried out on the PTF’s concrete test strip, which provides a smooth, stiff surface, ideal for such trials. The tests were carried out (as much as possible) in steady state tyre temperature conditions, with a tyre pressure of 621kPa (90psi). Speeds ranged from 5 to 20km/h and artificial (rolling resistance) loads ranged from zero up to full load in three equal steps. The PTF was run with a vertical load of between 20 and 35kN applied. Analysis of the data, showed that:

- 1) When applying the artificial rolling resistance load, a difference of $\sim 100\text{N}$ was measured between no load and full load, with steps of $\sim 33\text{N}$ clearly measurable between the different levels of load (no load, 1/3 load, 2/3 load, full load). These were in close agreement with the changes expected to be caused by the artificial load. This

showed that the equipment was capable of accurately measuring very small changes in rolling resistance.

2) A linear increase in rolling resistance could be seen when increasing the speed from 5km/h to 20km/h, confirming theoretical predictions and observations of other researchers (Bendtsen 2004, Popov 2003). This gives an improvement over the capability of the equipment used in previous TRL research, which gave non-linear results for speeds >15km/h (Benbow, 2007).

3) A linear increase in rolling resistance could be seen when increasing the applied vertical wheel load from 20kN to 35kN, agreeing with that expected (Bendtsen 2004, Popov 2003). Again, this is an improvement over the previous equipment, which gave non-linear results for loads >25kN.

It was felt that these results demonstrated that the new equipment should be suitable for use in the investigation of the effect of texture on rolling resistance.

4 Test Pavements

Test pavements were constructed in the PTF having a range of surface textures. These were characterised to determine their texture depths, profile and structural properties.

4.1 Design and construction

To ensure that the trials assessed only the effect of texture on rolling resistance there was a need to ensure that the primary difference between them was their surface texture (i.e. any differences in stiffness, longitudinal and transverse profiles should be as small as possible), and there should be no gradient. Advice was sought, from pavement construction experts, on how this could be achieved and an innovative method of construction was employed.

To obtain the same level of stiffness, the underlying layers of the pavements were constructed using the same material and thickness, with only the surface course being different. Five pavement structures with different surface courses were constructed in the PTF, as shown in Figure 6.

The thin surfacings were constructed using products subject to the same design process and using the same aggregates (Mountsorrel) and binder. This was done in order to minimise any effect that microtexture might have on the rolling resistance measured and the surface texture was varied by using different sized coarse aggregate in the mix. Two were constructed using a 14mm aggregate size, to provide repeat data for the experiment, and act as a control.

The thin surfacing sections had the construction shown in Figure 7 and the HRA section had the construction shown in Figure 8. As can be seen, the surface layers of all pavements were constructed to have a 300mm thick fully flexible construction.

Each strip had a width of 1.2m. The HRA was constructed with 14mm pre-coated chippings (also Mountsorrel aggregate), smaller than the more common 20mm pre-coated chippings used on the strategic road network. This was chosen for this research to enable a pavement with positive texture to be compared to one with negative texture, without the results being affected by aggregate size.

Double door end of PTF – Concrete end of pit		PTF platform
1.2m	TS4 - Thin surfacing, using 6mm aggregate	
1.2m	TS3 - Thin surfacing, using 14mm aggregate	
1.2m	TS2 - Thin surfacing, using 10mm aggregate	
1.2m	TS1 - Thin surfacing, using 14mm aggregate repeat	
1.2m	HRA - HRA with 14mm pre-coated chippings	
(Pit containing subgrade but no pavement along this edge)		
← 10m →		

Figure 6: Layout of test pavements (plan view)



Figure 7: Thin surfaced pavement construction

Figure 8: HRA surfaced pavement construction

4.2 Characterisation

The macrotexture of the pavements was measured with a circular texture meter (CTM) at 1m intervals along the centrelines of the strips. Output from the CTM can be used to obtain a single mean profile depth (MPD) value for each measurement location. The MPD values measured on all pavements was consistent along the lengths. The MPD measured on the thin surfaced pavements increased with increased aggregate size, as was expected. The values of texture were similar to those measured on equivalent thin surfaced pavements found on the HA network. The value for the HRA pavement is lower than would be found on the HA network due to the use of 14mm pre-coated chippings, as discussed above.

The average MPD values for measurements taken on the length of the pavements on which analysis was carried out (see Section 5.3) are given in Table 1. This table also contains the estimated texture depth (ETD)¹.

Table 1: Mean Profile Depth measurements on test pavements

Pavement strip	MPD measured on length used for data analysis	ETD ¹
TS1 14mm (repeat)	1.27 mm	1.22 mm
TS2 10mm	1.18 mm	1.14 mm
TS3 14mm	1.26 mm	1.21 mm
TS4 6mm	0.99 mm	0.99 mm
HRA with 14mm chips	1.02mm	1.02 mm

¹ BS EN ISO 13473-1:2004. "The MPD may be transformed to an Estimated Texture Depth by the equation $ETD=0.2\text{mm} + 0.8*MPD$. The use of this equation should give ETD values which are as close as possible to MTD when measured with the volumetric patch method."

The longitudinal profile of the base courses, binder courses and surfaces were measured on the centrelines of each of the test pavements using the ARRB Walking Profiler, during each stage of pavement construction. These measurements were also corroborated by

optical levelling. The profile measured on all of the pavements was within $\pm 5\text{mm}$ from flat for the whole length.

For the 2.6m length on which analysis was carried out (see Section 5.3), the profile for four of the pavements was within $\pm 2\text{mm}$ from flat, whilst the fifth was within $\pm 3.15\text{mm}$ from flat. These profiles are shown in Figure 9.

While ideally the surfaces should have been perfectly flat it is expected that the effect of such (relatively) small undulations in the pavement's surface on rolling resistance will cancel out over the measuring length. It is considered that only the overall slope of the pavements could have any noticeable effect. As can be seen from Table 2, all pavements had an overall slope of less than 0.45mm/m , which would equate to a gradient of 0.05% . This would cause an apparent increase of the coefficient of rolling resistance in one direction, and a reduction in the other, of less than 0.0001 (Hammarström, 2012). However, to further minimise the effect of gradient, rolling resistance in the trial was calculated by averaging data from pairs of passes in opposite directions (see Appendix A).

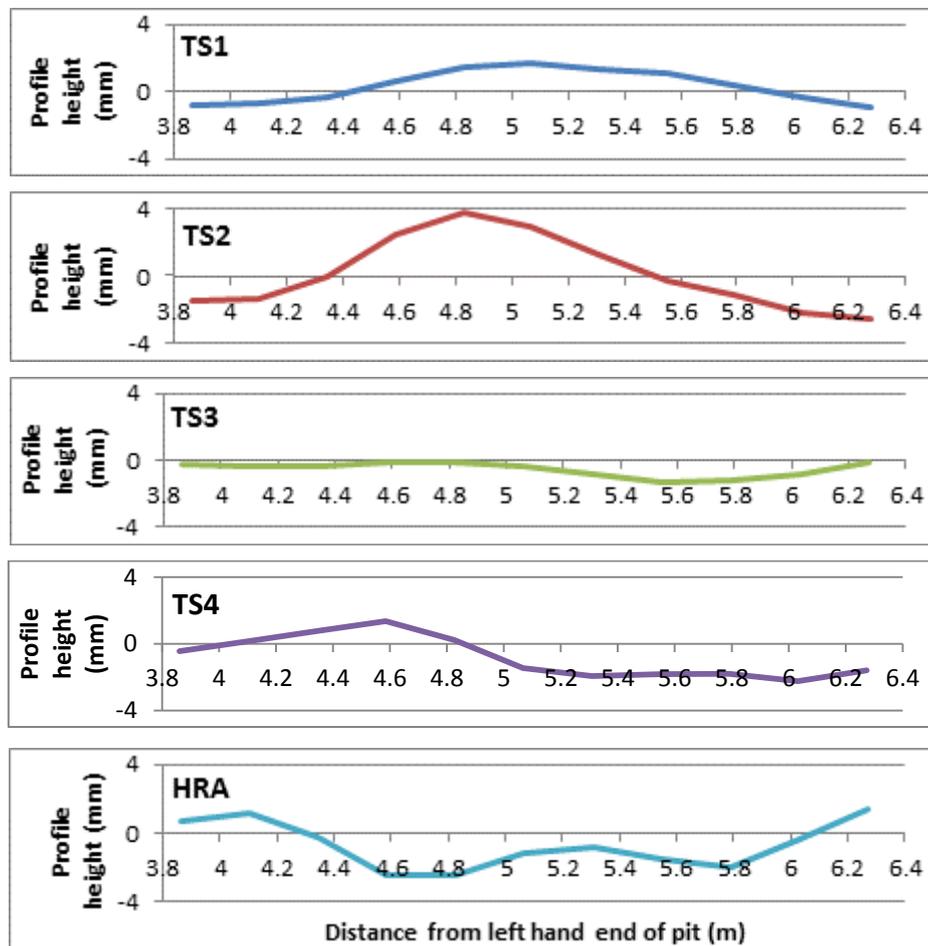


Figure 9: Profiles of test pavement strips

Table 2: Change in height between left and right hand ends of analysis length

Pavement strip	Change in profile height, from left to right	Overall slope of pavement
TS1 14mm (repeat)	-1.16 mm	-0.45 mm/m (0.05%)
TS2 10mm	0.09 mm	0.04 mm/m (0.00%)
TS3 14mm	-1.07 mm	-0.41 mm/m (0.04%)
TS4 6mm	-0.11 mm	-0.04 mm/m (0.00%)
HRA with 14mm chips	0.72 mm	0.28 mm/m (0.03%)

The friction of the pavement surfaces was measured, using a Griptester. A small decrease in friction could be seen with increasing aggregate size on the thin surfaced pavements. This decrease has been observed on similar pavements laid on the network, thus the friction of the pavements is as expected.

Surveys with a Falling Weight Deflectometer (FWD) showed the thin surfaced pavements to have a deflection of around 190 μ m (range of 188 to 195 μ m), whilst the HRA pavement was 200 μ m. That this is slightly higher than the others may be due to the lack of support from an adjacent pavement or pit edge on one side (Figure 6). However, the most important requirement for stiffness was met in that all of the thin surfaced pavements had very similar results.

5 Trials

5.1 Use of nylon sheeting

In previous work, it was found that the rolling resistance was significantly affected by the temperature of the pavement, the tyre and also the ambient temperature in the PTF hall (Benbow, 2007). This dependence on temperature appeared to differ for different pavement constructions and surface types.

Since it was not practical to control the temperature in the PTF, the previous research had tried to overcome the influence of temperature fluctuations by running trials for extended periods (24 to 48 hours) and using only measurements collected at similar temperatures in the analysis. However, despite the large amount of data collected for each pavement type, there was very little data that had been collected in a similar temperature range. Thus, for the latest trials, a method that would enable all data to be used was devised.

It was thought that if the same smooth surface could be traversed, in addition to the pavement surface under test, for each run, then measurements on this “calibration” surface could be used to correct the measurements, collected on the test pavement, for the effects of temperature. A review of materials was carried out, to identify a material suitable to fix to the pavements in the PTF, that would be thin enough to not cause disruption to the profile experienced by the PTF wheel when leaving the material and going onto the pavement but also robust enough to be subjected to many passes by the PTF wheel.

It was concluded that a 3m long sheet of 2mm thick nylon would be fixed to the surface of each test pavement to provide these reference measurements. This was done as shown in the plan of one pavement strip in Figure 10, such that the wheel would roll off the ramp across the pavement and then the nylon sheet and then back to the ramp on each double traverse.

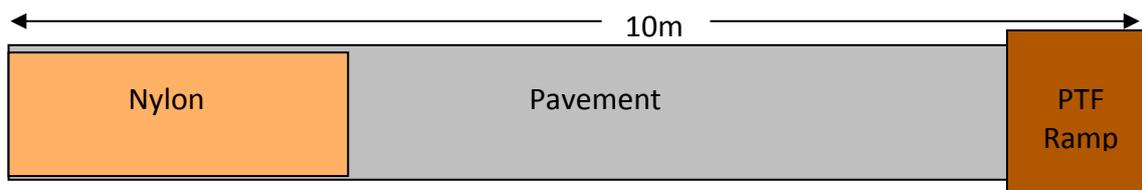


Figure 10 Position of nylon sheet on pavement strip (plan view)

A small-scale trial was carried out, which determined that the presence of the nylon sheets did not cause the PTF wheel to bounce (thereby affecting the data collected). Therefore, the sheets were left in-situ for the duration of the trials.

5.2 Trials

To carry out the trials, the tyre pressure was set to 827kPa (120 psi), the speed of the PTF to 15km/h, with a wheel load of 35kN and no artificial load applied.

The trials were carried out over a non-consecutive 3 day period and the pavements were trafficked in a different order on each day:

Day 1: TS1, TS2, TS3, TS4, HRA

Day 2: HRA, TS4, TS3, TS2, TS1

Day 3: TS3, TS1, HRA, TS4, TS2

To enable all pavements to be trafficked each day, trafficking was limited to one hundred passes (left to right and right to left) each time a pavement was trafficked.

5.3 Data used for analysis

In previous trials, it had been observed that the PTF wheel appeared to bounce after traversing a step in height e.g. the end of the PTF ramp.

Therefore data, collected in areas where the wheel may have been bouncing, was excluded from the analysis. This resulted in measurements being taken over 2.6m of the nylon sheets and a further 2.6m of pavement (i.e. 5.2m per cycle) – see Figure 11.

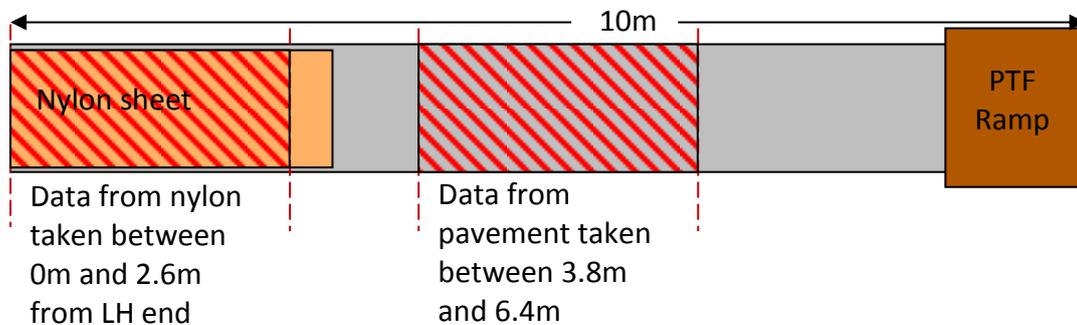


Figure 11: Diagram showing where measurements were taken for analysis

6 Results

The results are displayed principally as a series of charts in Figure 12 to Figure 17. All the charts have been drawn to the same rolling resistance scale and range, on the vertical axis, to facilitate comparisons. The coefficient of rolling resistance (C_{RR}) for each of the three trials on each strip was calculated from the average of 100 passes in each direction. Figure 12 shows the C_{RR} values obtained on the nylon sheet control section for each trial. The variation seen was assumed to be dependent on the effects of uncontrolled variables such as ambient temperature. It was assumed that the results directly on the pavement would be similarly affected and that these effects could be cancelled by an adjustment derived from this control data.

Figure 13 shows the uncorrected C_{RR} results for each trial. It is seen that there is a reducing trend in C_{RR} from HRA through the largest to the smallest aggregate-sized thin surfacing.

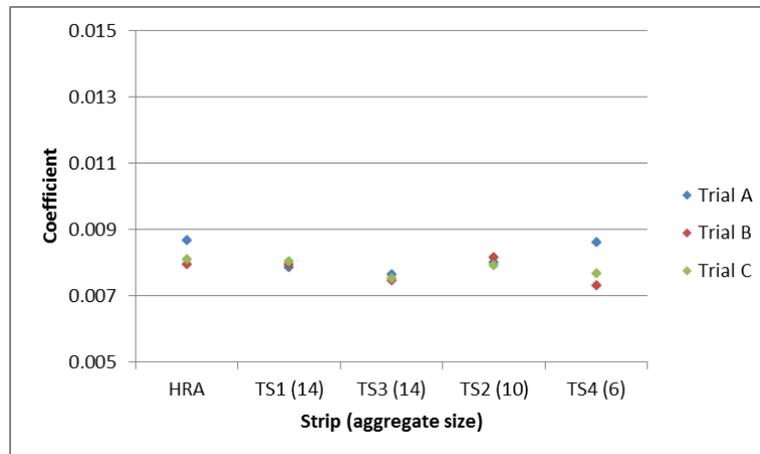


Figure 12: C_{RR} on nylon sheets

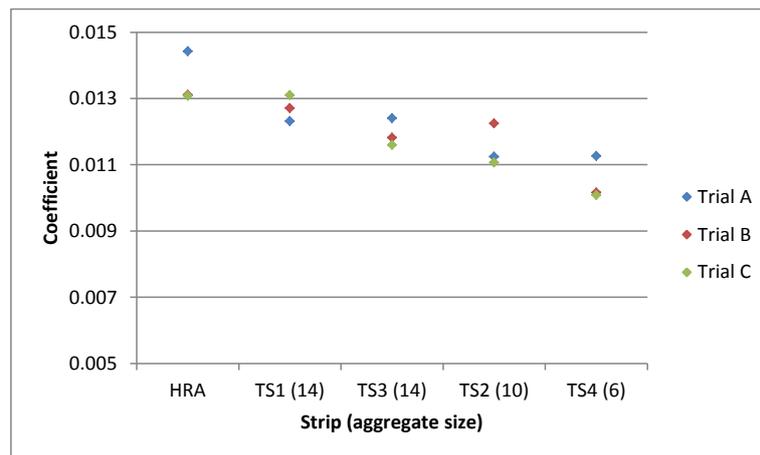


Figure 13: C_{RR} on pavements

Figure 14 shows the same results as Figure 13 but corrected using the control values from Figure 12. The correction factor for each trial and strip is the corresponding nylon data divided by the mean value of all the nylon data for every trial. The differences between the results for each trial are seen to be reduced by the correction.

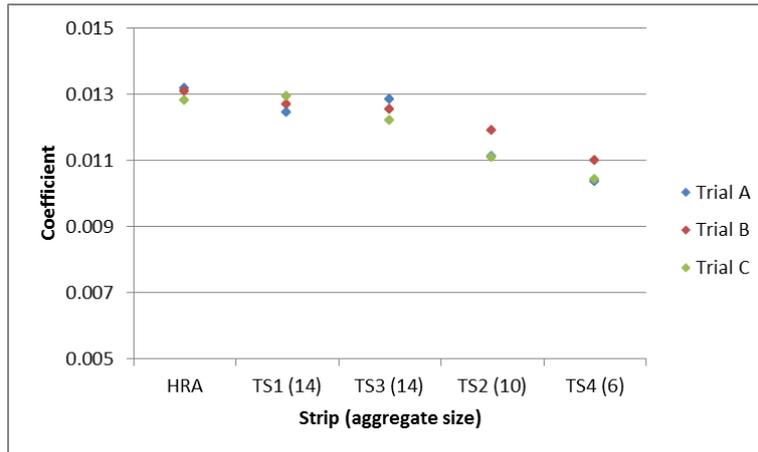


Figure 14 Corrected C_{RR} on pavements

Figure 15 shows the averaged data over all three trials for each pavement type. The average control value and the corrected pavement values of C_{RR} are shown. This plot shows that the corrections are relatively small.

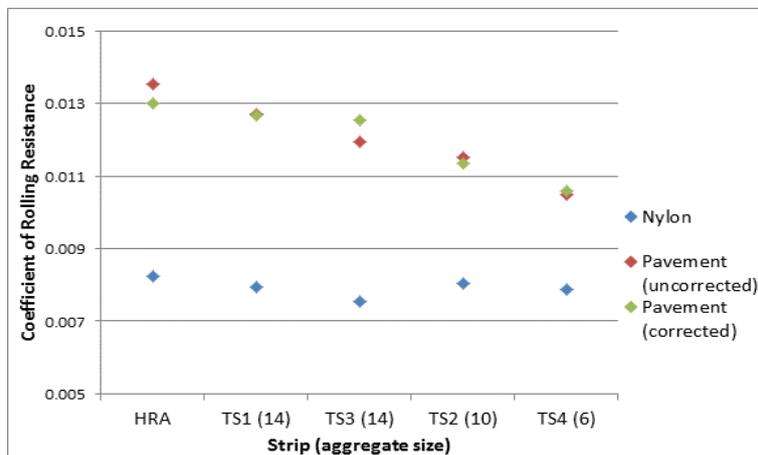


Figure 15: Average C_{RR} by pavement type

Figure 16 compares the effect of texture depth in terms of ETD for the thin surfacings and HRA. For the thin surfacings the C_{RR} is seen to increase with increasing texture depth, while the HRA exhibited the highest C_{RR} , by a small margin, despite having a low MTD. (It should be remembered, as described in Section 4.2, that the HRA was not truly representative of HRA on the network.)

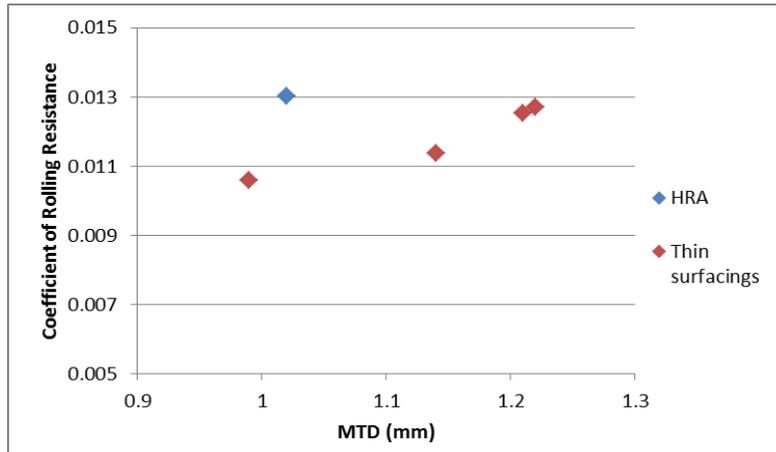


Figure 16: Average C_{RR} by pavement texture depth

An Analysis of Variance (ANOVA) was used to test whether the differences in C_{RR} between the texture depths are statistically significant, taking into account variability across different trial days. The results of this have shown that the mean values of C_{RR} measured on each of the four thin surfacing pavement strips were significantly different from each other, with a confidence of well over 95%.

Figure 17 shows mean values of C_{RR} measured on each thin surfacing pavement strip and the 95% confidence range in these values is shown by the error bars. That these confidence intervals do not overlap is a graphical demonstration that the mean values are significantly different from each other. (Note that in order to see the size of the error bars, this chart has a smaller vertical range compared with the others.)

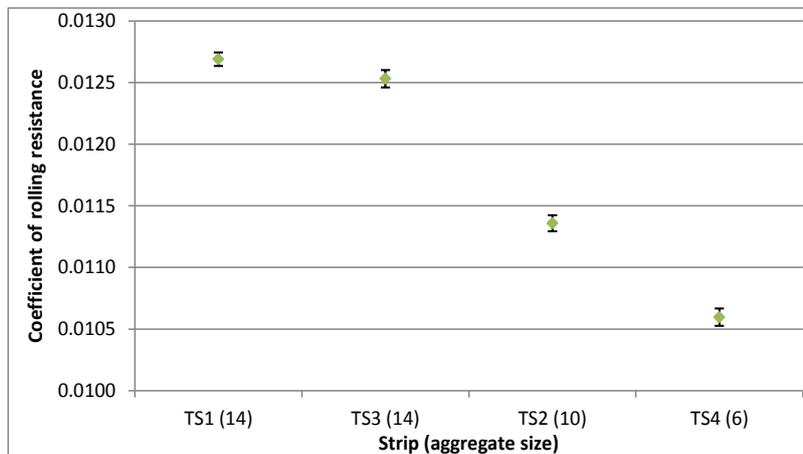


Figure 17: Mean and 95% confidence interval for C_{RR} by pavement type

The difference in the average coefficient of rolling resistance and standard deviation of data are given in Table 3. A difference in C_{RR} of 0.00117 can be seen between the 14mm aggregate pavement (TS3) and that with 10mm aggregate (TS2). Also, the standard deviation of the rolling resistance data varies between 0.00042 and 0.00057 for all pavements.

The trials, to investigate the effect of stiffness, were performed with different measuring equipment and pavements from the current trials, so the results are not directly comparable. However, the standard deviation of the data collected by the old equipment on the flexible pavement is roughly double (Table 4) that for the data measured with the

new equipment (Table 3), suggesting that the new equipment has markedly improved the robustness and statistical reliability of the measurements. Also, the difference seen between the average C_{RR} on the stiff and flexible pavements was less than half that seen between the pavement with 10mm aggregate and that with 14mm aggregate, suggesting that the surface texture may have a slightly greater effect than stiffness, much greater if the difference between 6mm and 14mm is considered.

Table 3: Differences and standard deviation of data from current research

Pavement	Change in C_{RR} ref TS3	Standard deviation of C_{RR} data
HRA	0.00048	0.00044
TS1 (14)	0.00016	0.00042
TS3 (14)	0	0.00057
TS2 (10)	-0.00117	0.00057
TS4 (6)	-0.00193	0.00047

Table 4: Differences and standard deviation of data from stiffness research

Pavement	Change in C_{RR} ref Flexible	Standard deviation of C_{RR} data
Flexible	0	0.00108
Stiff	-0.00050	0.00067

7 Discussion and Conclusions

Pavements are currently constructed such that their surfaces deliver adequate ride quality and skidding resistance but designs do not specifically take into account the rolling resistance of the surface. In order for this to become possible in the future, the pavement factors affecting rolling resistance needed to be determined, along with how practical it would be to change these factors, during maintenance or construction, and to what extent they affect rolling resistance. The work presented herein formed part of this investigation.

It was determined that, of the road factors affecting rolling resistance, only crossfall, stiffness, roughness and texture could be practically controlled during construction or maintenance of a road.

Initially, the effect of pavement stiffness was investigated (Benbow, 2007) and a measurement system was developed, for use in TRL's Pavement Test Facility (PTF) to investigate this relationship. The results from this earlier research suggested that stiffness does have an effect but that it is very small. Thus, this project was followed by an investigation into the effect of shape on rolling resistance. Within this more recent investigation, further bespoke equipment was developed.

This research has demonstrated that the instrumentation fitted to the PTF is capable of separating the small forces due to rolling resistance under load from the other forces present during pavement trafficking. This has been used to determine differences in rolling resistance on pavement strips of a selection of trial surfaces constructed with a range of texture depths that could otherwise be considered identical. The texture depths were achieved by using a range of aggregate sizes in a proprietary thin surfacing.

The results showed that small differences in the coefficient of rolling resistance between the surfacings could be measured in repeated passes of a loaded heavy vehicle wheel. It has been demonstrated that the element of rolling resistance due to the surface texture of a pavement can vary by a factor of up to about 16.5% over the range of texture depths that were tested in the trial described.

To put these results into context it is possible to express them as predicted changes in fuel consumption using the relationship that, for heavy vehicles, the proportionate change in fuel consumption is about 20% of a change in rolling resistance (Descornet, 1990).

The fuel consumption per km per year can then be estimated as:

$$\text{fuel consumption (l/km)} \times \text{number of vehicle km per year} \quad [1]$$

The fuel consumption of heavy vehicles is in the region of 0.33l/km (8.5mpg). According to DfT transport statistics for 2009 (DfT, 2010) the number of vehicle km for all goods vehicles on trunk roads and motorways was 16.4 billion veh km. Using these figures in the above equation, the total fuel used by heavy vehicles on HA trunk roads and motorways, was about 5.4 billion litres. The results in Table 5 could then be taken to suggest, using the assumption that all surfaces could be changed from an MTD of 1.21mm to 0.99mm, the saving in heavy vehicle fuel might be about 3.3% (Table 5). Although small this would equate to about 177 million litres of fuel per year (466 million kg CO₂e), considering only heavy vehicles and trunk roads. Reducing the level of texture

on surface course materials could also have positive benefits in terms of increased durability.

Table 5 Texture depth, mean C_{RR} and estimated change fuel consumption

	ETD (Equiv MTD)	Mean C_{RR}	Change in C_{RR} ref TS3 (%)	Change in fuel consumption (%)
HRA	1.02 mm	0.01302	2.6	0.5
TS3 (14)	1.21 mm	0.01269	0.0	0.0
TS1 (14)	1.22 mm	0.01253	-1.2	-0.2
TS2 (10)	1.14 mm	0.01136	-10.5	-2.1
TS4 (6)	0.99 mm	0.01060	-16.5	-3.3

There is a need to confirm that the behaviour observed in this work can be expanded to apply to the existing pavements on the network, in particular that the texture/rolling resistance relationship holds for a whole range of pavement types. If this can be confirmed, then this would offer a valuable additional tool for engineers when selecting a pavement type for a new construction or repair, providing an ability to establish an energy rating for a pavement type.

8 Recommendations

How these questions may be addressed in the future was considered, and the following recommendations are suggested.

An HRA with 14mm pre-coated chippings, smaller than the more common 20mm pre-coated chippings used on the strategic road network, has been assessed within this research. The measurements show that the rolling resistance is higher on this particular pavement than any of the thin surfacings. The more commonly used HRA with 20mm pre-coated chippings would be expected to produce a higher C_{RR} than the HRA tested. If the results are as suggested by the current research, the HA may want to consider replacement of these pavements sooner than required for safety, to improve the rolling resistance of the pavement.

At the moment, the methodology involves constructing full pavements in the PTF, which is quite a large undertaking. If the methodology could be expanded, to allow testing of pavement samples within the PTF, then this would make the process much more efficient. If this were to be achieved, it would be possible to obtain the relative energy efficiencies of all pavement surfacings, which could then be used alongside other factors such as durability, sustainability, safety, and cost, when deciding on which pavement surfacing to use for new or maintained pavements.

9 References

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Appendix A Calculating Rolling Resistance

Figure 18 shows a schematic of the geometry of the measurement system as installed on the PTF, assuming that motion take place from right to left. Note that Figure 18 is not to scale, and the angles are exaggerated for the sake of clarity.

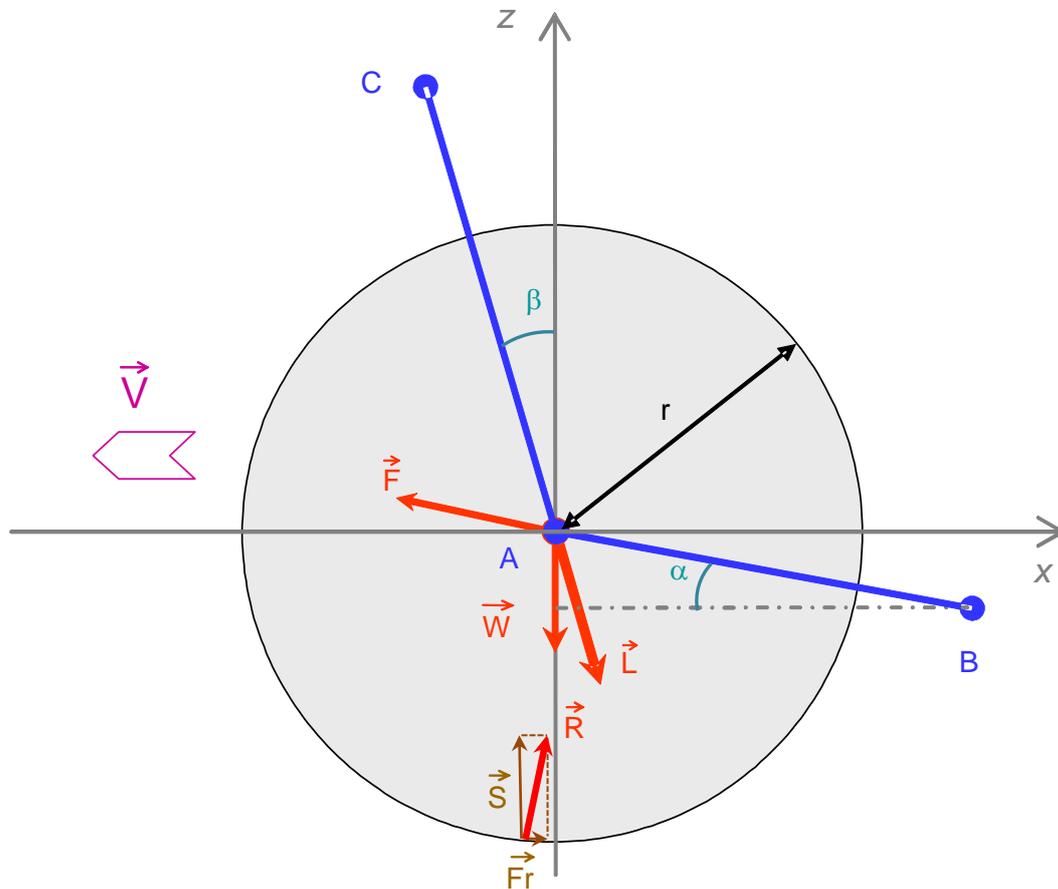


Figure 18: Simplified representation of forces in balance for travel right to left

We define the following:

- The arm is AB.
- The loading ram is AC.
- r is the radius of the tyre.
- A is the centre of the wheel (also considered as the centre of gravity of the system).
- B is the arm pivot point.
- C is the ram pivot point.
- The angle between the arm AB and the x-axis is α .
- The angle between the ram and the z-axis is β .

One rotary encoder provides the angle of the arm, α . Geometrical considerations allow the computation of the ram angle, β , given the length of AB, the fixed vertical distance, BC_V , between the top of the ram and the arm pivot, using the following equation:

$$\tan(\beta) = \frac{AB * [1 - \cos(\alpha)]}{BC_V - AB \sin(\alpha)} \quad [2]$$

The system of mass m moves with a velocity \vec{V} and an acceleration \vec{a} (which is not null).

The weight is $\vec{W} = m\vec{g}$, where \vec{g} represents gravity.

\vec{F} is the force driving the carriage and wheel assembly, measured in the strain gauges in the pins (which are pushed during the travel from right to left and pulled from left to right).

\vec{L} is the load applied by the ram, which is always directed downward nearly vertically (β is about 2°).

The rolling resistance can be modelled as a force \vec{R} applied at the pavement surface. This force can be split in two components, namely a vertical force \vec{S} directed upward, which is the reaction of the surface, and a horizontal force \vec{Fr} opposed to the motion.

With these notations, the balance of forces becomes:

$$m\vec{a} = \vec{F} + \vec{L} + \vec{R} + \vec{W} \quad [3]$$

By projection on the x-axis (in the horizontal plane, parallel to the direction of travel) we obtain (in algebraic notation):

$$m\overline{a_x} = \overline{F_x} + \overline{L_x} + \overline{Fr} \quad \text{where } F_x = F \cos(\alpha) \text{ and } L_x = L \sin(\beta) \quad [4]$$

and along the z-axis (vertical):

$$m\overline{a_z} = \overline{F_z} + \overline{L_z} + \overline{S} + \overline{W} \quad [5]$$

The accelerations, $\overline{a_x}$ and $\overline{a_z}$ can be obtained from the accelerometer, which is mounted on one of the arms. Since the accelerometer is mounted on one of the arms and these are at an angle, a rotation has to be made to get the components along the true x, y and z-axes.

Now considering the horizontal relationship in the two directions of travel gives:

- from right to left

$$-ma_{x_{RL}} = -F_{x_{RL}} - L_{x_{RL}} + Fr_{RL} \quad [6]$$

- from left to right

$$ma_{x_{LR}} = F_{x_{LR}} + L_{x_{LR}} + Fr_{LR} \quad [7]$$

It was assumed that the friction is the same in the two directions, and since the aerodynamic drag and wheel-bearing resistance were neglected, the rolling resistance, D , is defined by $D = Fr_{LR} = Fr_{RL}$. Combining Equations [6] and [7] then gives:

$$D = \frac{1}{2}(-m(a_{x_{RL}} + a_{x_{LR}}) + (F_{x_{RL}} + F_{x_{LR}}) + (L_{x_{RL}} - L_{x_{LR}})) \quad [8]$$

Note: For all trials the arm angle (α , Figure 18) was positive, i.e. the arm was higher at the wheel axis end than the end joining it to the PTF carriage. As expected, when the vertical load was increased the angle of the arm decreased linearly, ranging between 10

and 13°. Similarly, the rams always stayed to the left of the vertical (if viewing the PTF from the same side as displayed in Figure 18), the angle ranging between 1.8 and 2.5° (β , Figure 18). This meant that, since the geometry of the system remained the same for the whole of the trial, the same calculation could always be used to obtain rolling resistance.

The coefficient of rolling resistance is then defined to be

Coefficient of rolling resistance (C_{RR})=Rolling resistance (D)/Load (L) **[9]**