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Evaluation of the Coefficient of Friction of Rail in the Field and Laboratory Using Several Devices

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Accurate friction measurement is vital in order to apply appropriate friction management techniques to the wheel/rail interface. This work analyses different friction measurement techniques under a variety of conditions in the laboratory and the field. Tests have been carried out using a pendulum tester, hand-push tribometer, twin-disc machine, and full-scale rig in the UK and Colombia for a variety of interfacial conditions and rail hardness. The pendulum has been found to be more sensitive to different conditions than the hand-push tribometer. This is due to the area that the pendulum sweeps being smaller, and so it can be more carefully controlled and therefore measure the surface condition being tested. This is in contrast to the push tribometer which needs a long section of rail to take a measurement. Therefore, a small bit of contamination on one bit of rail will influence the results as the contamination will stay on the measuring wheel. Twin-disc and full-scale rig creep curves show good agreement between each other.

Keywords: Coefficient of friction; hand-push tribometer; pendulum; hardened rail; full-scale; twin-disc

1 Introduction

Controlling the Coefficient of Friction (COF) between the wheel and rail improves the performance and energy efficiency of the whole system, for example by [1], [2]:

- Reducing wear (applying a lubricant to gauge face in curves), thereby reducing maintenance work
- Reducing Rolling Contact Fatigue (RCF) (applying friction modifier to top of rail), again reducing maintenance requirements
- Fuel savings by lowering COF, thereby reducing costs
- Reducing noise, improving environmental impact and passenger comfort

- Providing adequate COF for traction/braking by increasing friction with traction gels/sand in low adhesion areas. This is essential for the safe operation of the railway, ensuring trains are able to stop at stations/signals and ascend gradients etc.

In order to realise the benefits listed above, assessing the friction level at different locations on the track/rail and under different interfacial conditions can help to know what form of friction management to apply, i.e. selecting the correct friction modifier or lubricant. This is because the open nature of the railway means that contact conditions can vary spatially (even between the two rails) as well as temporally. There are a number of ways of measuring friction in the field and in the laboratory, but there is no current consensus or standard on which to base friction tests as each method has its limitations and benefits. Many studies report friction coefficients, but most have used only one friction measurement device without considering how the COF generated relates to a real train[3]–[11]. This work included many different measurement techniques in the laboratory and the field, under different interfacial and climate conditions. This enables comparisons between the measurement devices to be made and the benefits/limitations of each device to be explored.

The aim of this paper was therefore to measure friction levels on the railhead in the field using a pendulum device and hand-pushed tribometer; and in the laboratory using full-scale rig and twin-disc rig for a variety of interfacial conditions and rail hardness. This enabled comparisons between each of the measurement devices to be made.

2 Background

A previous study [12] concluded that the pendulum has potential as an alternative friction measurement device to hand-push tribometer or twin-disc tests. This work will extend the comparisons between the pendulum and hand-push tribometer under different conditions in the field as well as comparing the pendulum to twin-disc and full-scale friction measurements in the laboratory with different rail materials.

A recent study [13] compared different COF's, reported in literature for different measurement techniques, see Figure 1. It noted that there were large ranges in values: greater than 0.4 for dry values, 0.2-0.4 for wet tests and 0-0.25 for lubricants. These large ranges are caused by a large number of factors, including: variations in contact pressure, local rail conditions, environmental conditions, and differences in measurement equipment used. Friction measurement devices can be split into the following categories:

- Small-scale laboratory methods: These are most useful for gaining fundamental understanding of friction behaviour due to easily controllable conditions.
- Full-scale laboratory methods: More realistic geometries compared to small-scale tests, but often less versatile.
- Field measurement systems: Enable conditions in the field to be measured, but often at unrealistic geometry/contact pressure, and climate/contaminants unable to be controlled. Additionally, the time allocated to perform measurements is often limited by operational requirements which means that it is difficult to collect enough data to perform statistical analysis.
- Instrumented train: Most accurate way of measuring friction due to realistic loads/speeds. However, limited control over climate and contaminants on the rail and often prohibitively expensive.

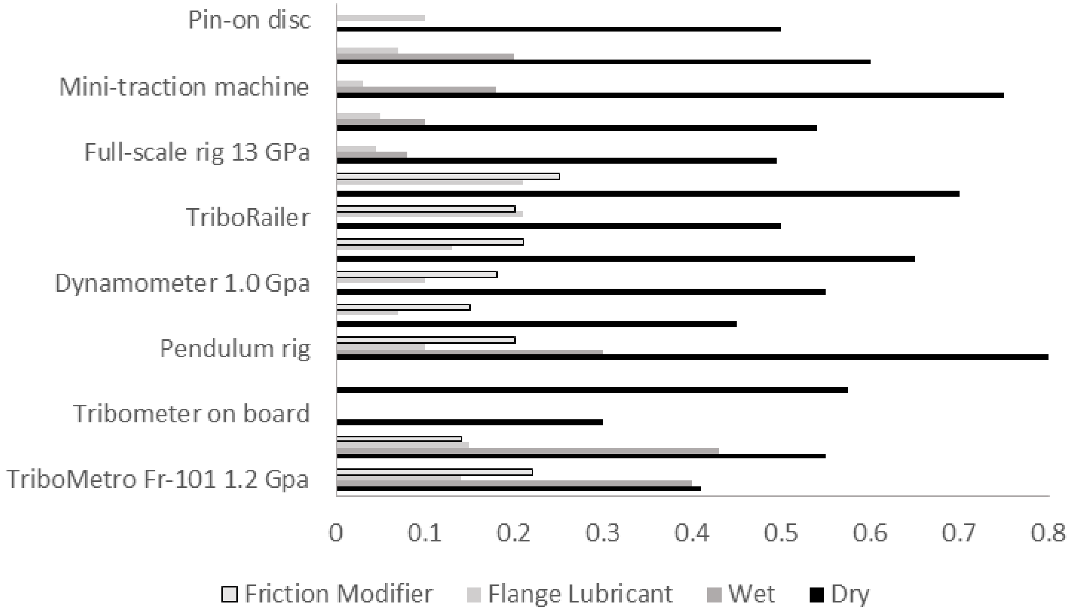

Figure 1 Typical values of COF measured using different devices [13]

3 Measurement Methods

3.1 *Laboratory Tests*

In the laboratory, experiments were performed using the Full-Scale wheel/rail Test Facility (FSTF) (shown in Figure 2A), Sheffield University ROlling and Sliding (SUROS) twin-disc machine (Figure 3), and the pendulum (Figure 4). The roughness of the specimens in both cases is similar.

The FSTF consists of a longitudinally fixed wheel that is free to rotate. A hydraulic actuator slides the rail longitudinally on a low-friction bed, and the load is applied via a load cell located above the wheel. Creep is controlled by a chain resisting rotation of the wheel. Three different interfacial conditions were used for the tests: dry, wet, and Top Of Rail Friction Modifier (TORFM). The TORFM used was a water based particle suspension which evaporates in the contact leaving the solid particles behind to mix with the third-body layer present on the railhead. For the FSTF, a travelling distance of at least 350 mm was used with a velocity of 100 mm/s. Two different contact pressures were used for all the tests: 1.1 and 1.3 GPa corresponding to wheel loads of 80 and 110 kN [14] respectively. The tests were performed on R260 and hardened R400HT rails. A complete creep curve was obtained for the different interfacial conditions with at least three repeats at each creep level analysed to calculate the mean and standard deviation. Prior to the tests being carried out, 50 'cleaning' wheel passes were carried out at low contact pressure (0.8 GPa). This removed the oxide layer that was present on top of the rail. The wet tests were performed by applying three sprays to the contact band from a standard spray bottle containing deionized water. Each spray from the bottle resulted in approximately 0.7 g of water being emitted. For the TORFM tests, 3 ml was applied to the contact band by syringe, see Figure 2B. Five wheel passes at low contact pressure (0.8 GPa) were run to ensure the TORFM was spread across the contact evenly.

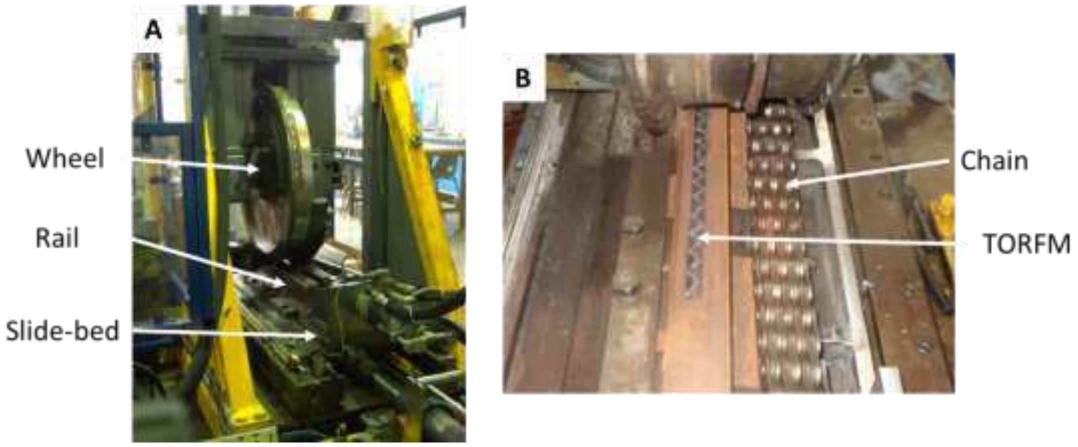

Figure 2 A) Full-Scale Test Facility at The University of Sheffield B) Application of TORFM to contact band of rail

The SUROS twin-disc machine (Figure 3) is a Colchester lathe with an independent AC motor attached to it to allow two 47 mm-diameter discs to be driven independently. Load is applied to the wheel disc via a hydraulic actuator and friction is measured via a torque transducer attached to the shaft on the rail disc side of the machine. Tests were carried out on three rail steels: R260, R350HT, and R400HT. All tests were carried out dry and at 1.5 GPa. The discs were cleaned using an ultrasonic bath before tests were carried out.

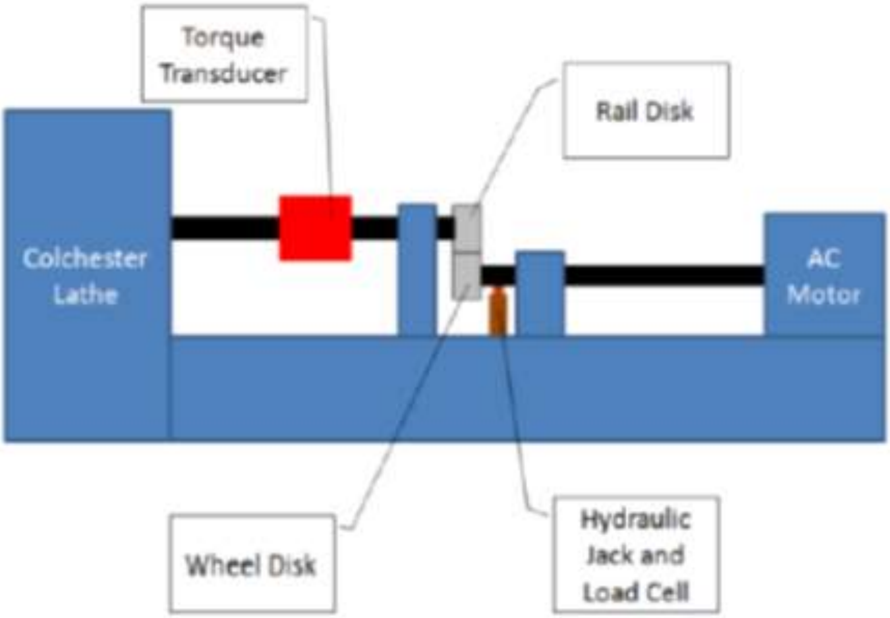

Figure 3 Schematic of SUROS twin-disc machine

Friction measurements were performed using the pendulum [15] (as shown in Figure 4). The pendulum is placed on a flat level stand next to the rail. When released, the arm of the pendulum swings down, the rubber pad contacts the surface of the rail, and the arm pushes a needle up the scale. It works on an energy loss principle. The more friction there is in the contact between the rubber pad and the test surface, the more energy is lost, and the higher the Pendulum Test Value (PTV) is. The PTV is converted to a Coefficient of Friction (COF) by using equation (1) [15]. The test method detailed the in UK Slip Resistance Group guidelines was followed [15]. This method has been previously used for measuring friction on the rail in the laboratory, and showed good agreement with traction coefficients derived from twin disc testing [16]. Different rail materials were tested at various interfacial conditions: R400HT (dry, wet, dry TORFM, dry TORFM sprayed with water), R260 (dry, wet), R260 clad with Martensitic Stainless Steel (MSS) (dry only), R260 clad with *stellite*® (dry only). For the different rail materials, five repeats were performed for each combination. Additional tests were performed on two separate days using R260 rail to evaluate if different environmental conditions in the laboratory affect results. 100 swings were carried out in dry and wet condition to evaluate how the measurement changes over a period of time. For the wet tests, the rail was only sprayed with water at the start of the test. 100 swings were also performed with different amounts of TORFM: 1.0 g, 0.5 g, 0.2 g, 0.1 g. The 0.2 g was applied via a roller whereas the rest of the amounts were applied via a brush. The test was performed immediately after applying the TORFM, so it was still in its liquid form. The pendulum and products were stored in the same laboratory overnight prior to tests being carried out, this means that they took place at ambient conditions.

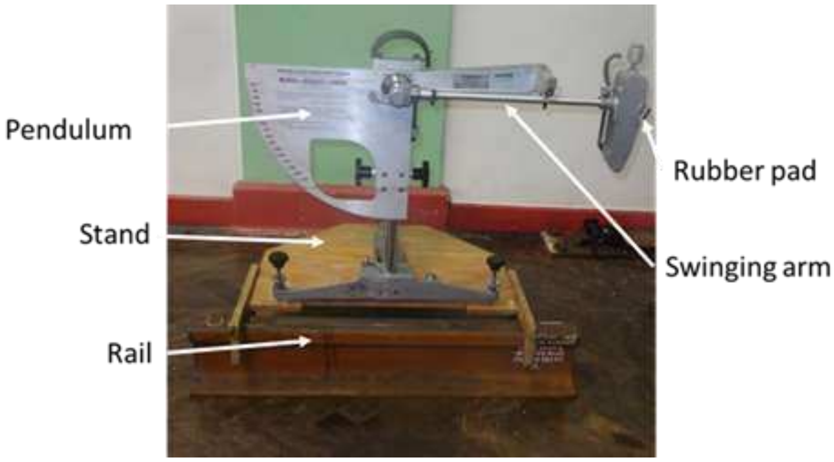

Figure 4 Pendulum set-up in the laboratory

$$COF_{pendulum} = (\frac{110}{PTV} - \frac{1}{3})^{-1} \quad (1)$$

3.2 Field Tests

In the field, tests were carried out in eight locations: Long Marston (LM), Seven Valley Railway (SVR), Windermere and Oxenholme in the UK, and four different curves on Metro de Medellín (MDM) in Colombia. SVR is a heritage railway located near Kidderminster. Three sites were tested near a grease applicator, Figure 5 shows a schematic of the sites. LM is a test loop located at Quinton Rail Technology Centre near Long Marston village. Friction measurements were carried out on a straight section of the test loop. The Oxenholme site is located on a 50 m section of curve near to Oxenholme station, near Kendal. The Windermere site is located on a 50 m section of curve near to Windermere station in the Lake District. Oxenholme and Windermere are two ends of the same rail line. The MDM curves are in a commercial line with a traffic amount of approximately 20 MGT/year.

Two different tribometers, along with a pendulum, were used to obtain friction readings under different rail conditions. Table 1 shows the details of the different field locations and Table 2 shows the different test conditions at each of the sites. The same method as detailed in section 2.1 was used to gain friction readings using the pendulum (Figure 6A). A Salient Systems push tribometer [17] was used for the hand-pushed tribometer readings in the UK (Figure 6B), and a TriboMetro FR-101 [13] tribometer was used in Colombia. The tribometers have a small wheel that can be set to measure any position across the railhead. As the tribometer is pushed along the rail, a brake is increasingly applied to the wheel until slip occurs. The torque and downward force required for slip to occur are recorded and coefficient of friction calculated. The TriboMetro FR-101 records an entire creep curve whereas the Salient Systems tribometer only displays the final coefficient of friction. For all tests a minimum of five repeats were made for each measurement site and condition.

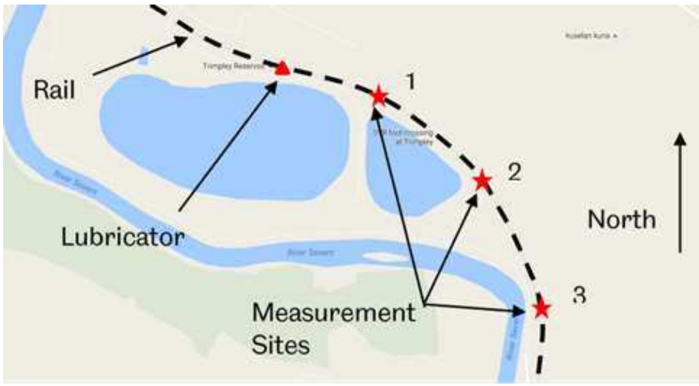

Figure 5 Schematic of SVR test site

Site	**Date**	**Description**	**Temperature and Humidity**
LM	10th October 17	One site was tested, straight track	12 °C, 91% RH.
SVR	21st October 17	Three sites were tested around a curve near a grease applicator	12 °C, 81% RH
Windermere and Oxenholme	30th July 12	Two sites tested near to the two stations	Not recorded
MDM- C4 Tribometer	1st October 17	Three different sites in the same curve were tested	21 °C, 65% RH
MDM-C15-Tribometer	26th June 17	Curve radius: 300 m	22 °C, 63% RH
MDM-C32 Pendulum	26th June 17	Four sites tested around the curve. Curve radius: 350 m	18°C, 74% RH
MDM- C15-Pendulum	18th May 18	Three sites tested around the curve. Curve radius: 300 m	17°C, 80% RH

Table 1 Details of field measurements

Site	Measurement Device	Conditions Tested	Rail Material
LM	Pendulum, Salient Systems Tribometer	Dry	R260
SVR	Pendulum	Dry, wet, wet and contaminated	R260
	Salient Systems Tribometer	Wet, wet and contaminated. Top of rail (TOR) and gauge face (GF)	
Windermere and Oxenholme	Salient Systems Tribometer	Dry, grease. TOR and GF	R260
MDM- C4	TriboMetro FR-101	Dry, wet	R260
MDM-C15	TriboMetro FR-101 and pendulum	Dry	R400HT
MDM-C32	Pendulum	Dry	R350HT

Table 2 Field test conditions

Figure 6 A) Pendulum at SVR, B) Salient Systems tribometer at LM

4 Results

4.1 *Laboratory test results*

The results from the Full Scale Test Facility (FSTF) showed that the traction coefficient varies when the contact pressure is modified (see Figure 7). For the dry tests, the coefficient of friction was greater for the low pressure and for high slippages (10%) the traction coefficient was very similar for both pressures. When water was added to the contact the same trend was found, the traction coefficient was lower for the higher contact pressure. There are several explanations for such behaviour. For wheel/rail contact the most plausible explanation is that friction is dominated by adhesive interactions at the interface instead of sub-surface deformation (according to the classical Bowden and Tabor binomial theory of friction) [18]. This means that the friction coefficient is mainly determined by the ratio between shear stress and hardness of the softer component of the tribological pair. Given that the contact between rail and wheel steels is very plastic, a significant increase in strain hardening is expected for greater loads. This causes the friction coefficient to reduce, since the shear stress is much less affected by the plasticity effects [13]. The hardening effect has been previously observed in the field for R400HT.

However, when a TORFM was added to the contact, the trend changed and the traction coefficient increased 43% for the high contact pressure; the contact changed significantly and a protective layer is thought to have formed at the surface, in the mixed lubrication regime (see Figure 8). When the contact pressure increased, the lubrication parameter on the x-axis of the Stribeck curve plot reduced, and consequently the friction coefficient increased. An increase in shear strength of the protective film with pressure also explains the increase in traction coefficient with load. Another interesting result was that, when the contact patch was completely saturated (high creepages around 10%), the traction coefficient was very similar for water and TORFM, and for both the different pressures. This suggests that, for high creepages, the increase in relative velocity might have caused the same lubrication regime during the test for water and for TORFM. That regime could be located in a Stribeck curve (see Figure 8) on the plateau dividing the boundary and mixed lubrication zones. In addition, with TORFM added to the rail, the traction coefficient was very low for low creepages. This could have been caused by the water in the TORFM acting as a lubricant. It might be interesting to perform additional tests on the rig by applying the TORFM to the top of rail, run 50 cycles at low slip to spread the TORFM and form the dry layer. After that, determine the creep curve to see if it is different when the TORFM has formed a dry layer.

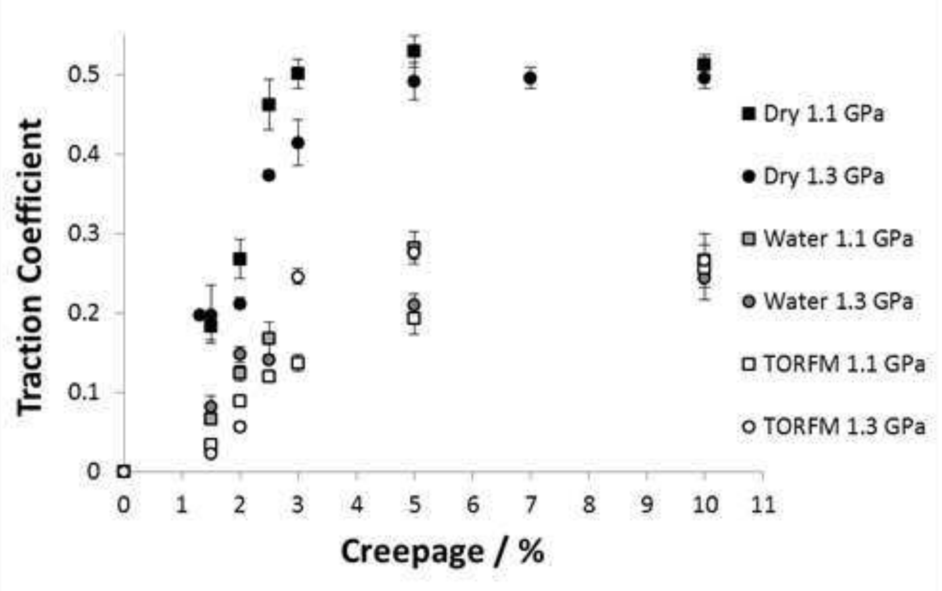

Figure 7 Creep curve for hardened R400HT rail

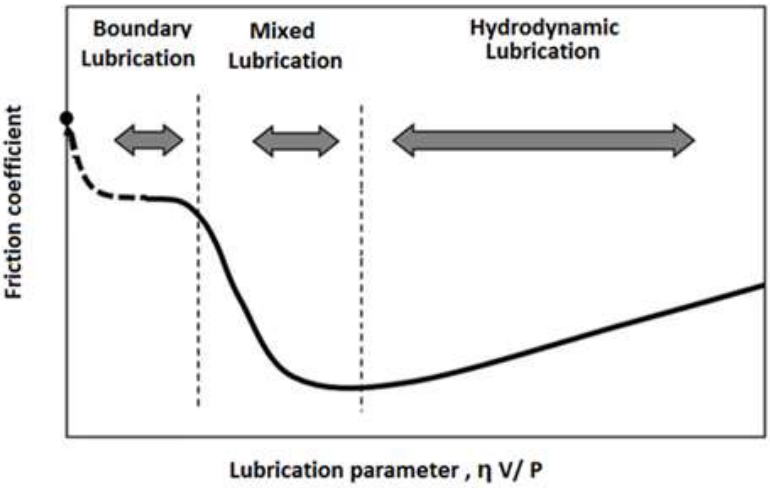

Figure 8 Stribeck curve, where η is the dynamic viscosity of the fluid, V is the speed in the contact and P is the normal load in the tribological contact

Figure 9 shows a creep curve comparing R260 and R400HT for dry and TORFM conditions using the FSTF. It clearly shows that R260 had a higher traction coefficient for both interfacial conditions at all creepages.

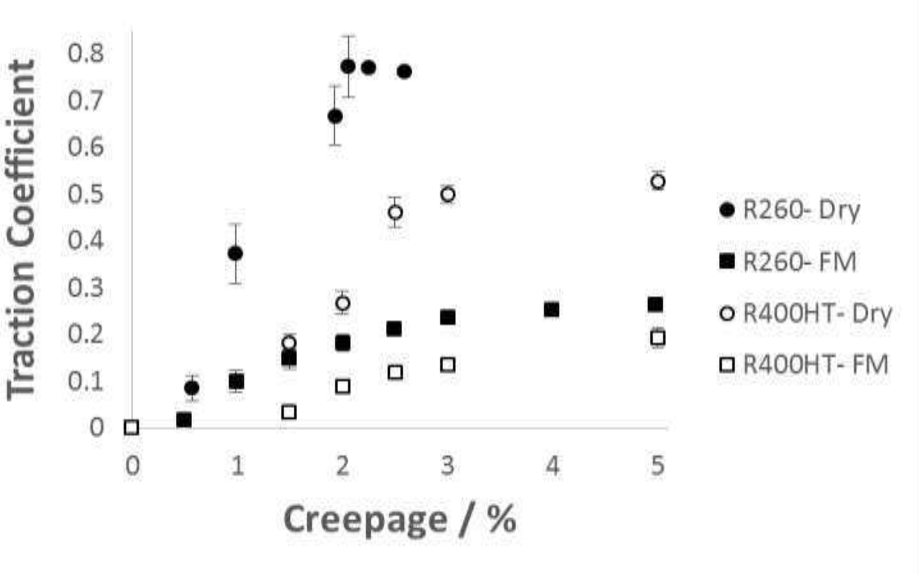

Figure 9 Creep curve for R260 and R400HT using FSTF

Figure 10 shows creep curves generated using the SUROS twin-disc machine. It clearly shows that R260 has a higher traction coefficient than the two harder rails. This is the same result as seen in Figure 9. R350HT and R400HT have very similar traction coefficients, with R350HT being slightly lower.

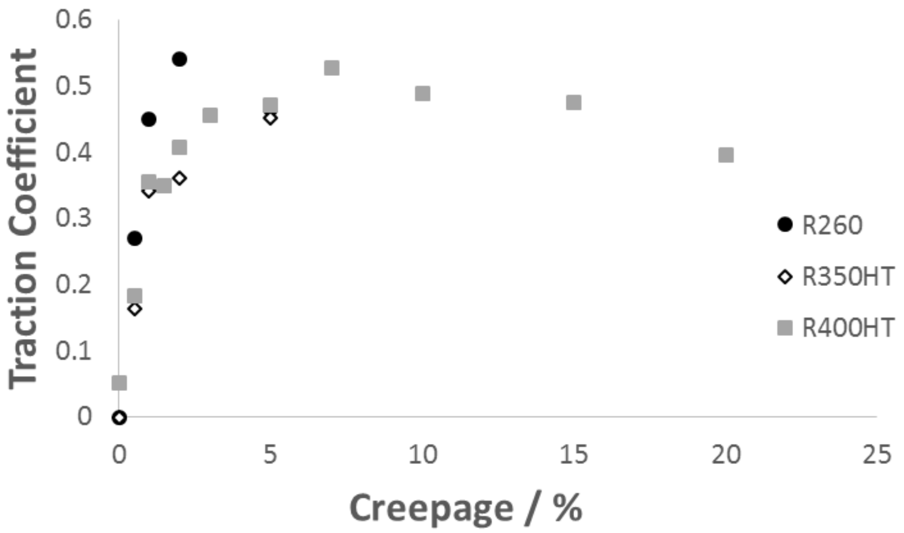

Figure 10 Creep curve for different rail materials using the SUROS twin-disc machine

Figure 11 compares the creep curves generated using the FSTF and the creep curve generated using the SUROS twin-disc machine. There is a clear overlap between the results from the two different test rigs, showing that both test scales produced similar results. The SUROS data was generated at a higher contact pressure which had the effect of decreasing the relative traction coefficient (according to Figure 7). This means that if the equivalent contact pressure was used as in the FSTF tests, the SUROS traction coefficient would be higher. Regardless of small changes in traction coefficient, the shape of the curve was the same for both test rigs.

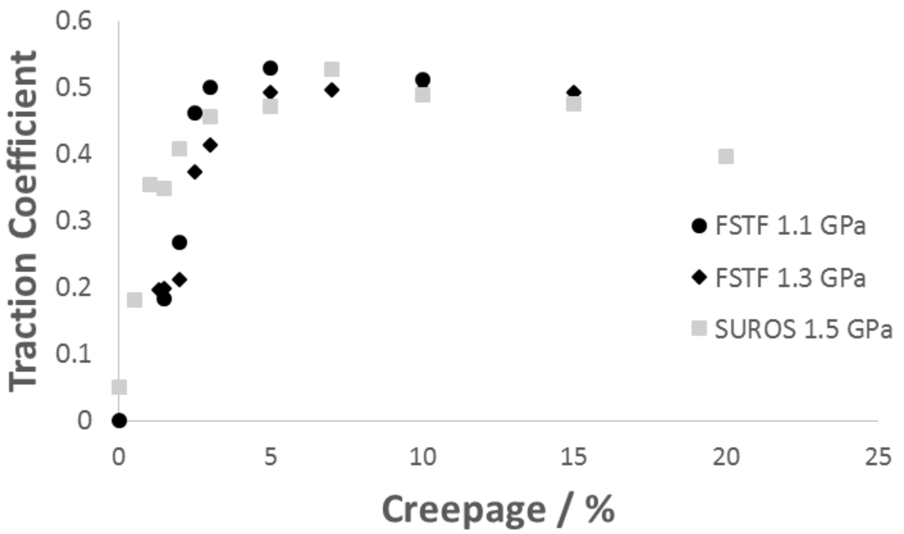

Figure 11 Creep curve comparing the SUROS twin-disc machine and FSTF

The results of the measurements using the pendulum in the laboratory showed that the Coefficient of Friction (COF) for the dry conditions was between 0.62 and 0.87 for the different rails (Figure 12). The values were slightly higher for the R400HT than R260 rail. Clad rails produced the lowest values for dry tests. When water was added to the contact, the resulting, COF was very similar for both R400HT and R260 rail. An interesting result was obtained when water was added to a rail with a dry layer of FM; the coefficient of friction became very low with values similar to those obtained with wet and contaminated rail in the field (as seen in Figure 18).

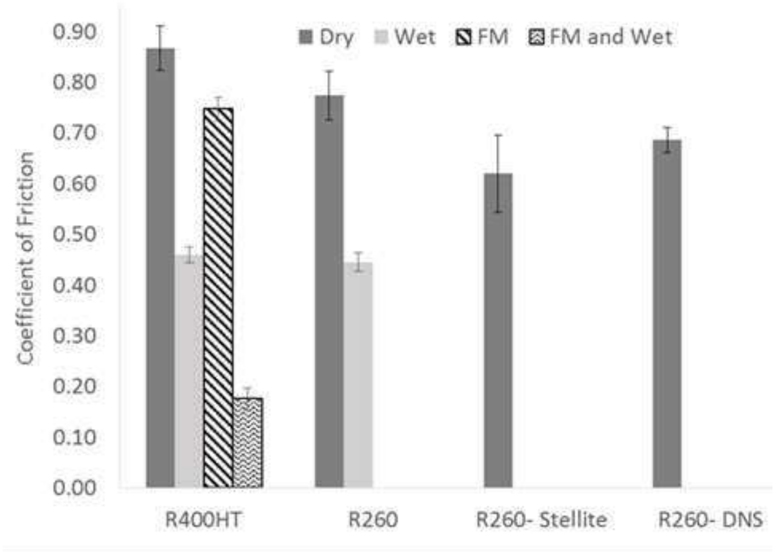

Figure 12 Coefficient of friction obtained with pendulum in the laboratory

Figure 13 shows the pendulum results carried out on two different days for 100 swings on R260 rail. For the dry tests, day one had a lower COF than day two. This could be caused by different environmental conditions in the lab between the two days. Both days showed a trend of increasing COF with swing number for the dry tests. The COF measured on dry day 2 was similar to the result seen in Figure 12. For the wet tests, both days were initially similar and lower than the value in Figure 12 due to more water being used (1.5 ml applied via syringe). After a period of time the COF started to increase. This is because the water was evaporating and being cleared from the contact with each swing of the pendulum. For day 2, the COF remained lower for longer and increased to a higher amount. The maximum COF increased above 1.0 in this case. This could have been caused by the conversion from PTV to COF (Equation 1); this equation was developed for flat surfaces where the whole pendulum pad is in contact with the surface, whereas this is not the case for rail (as seen in Figure 14) where only part of the pad is in contact with the rail.

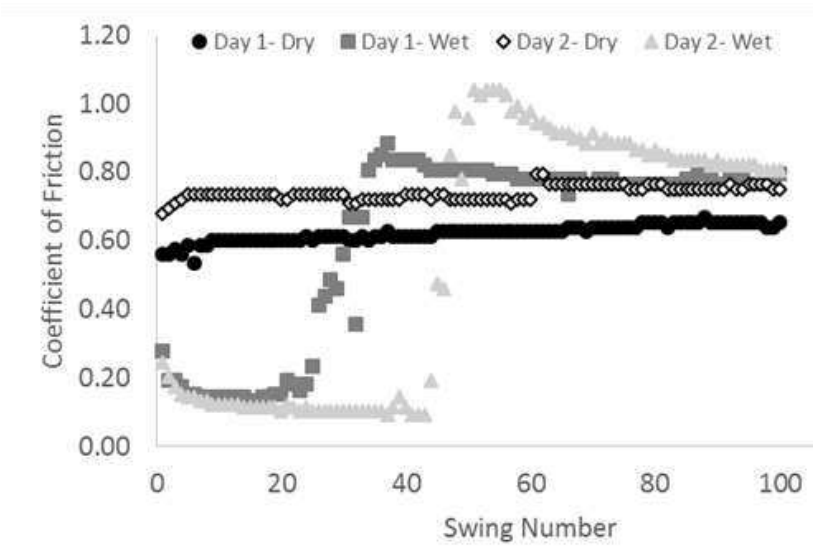

Figure 13 Pendulum tests on two different days for dry and wet conditions

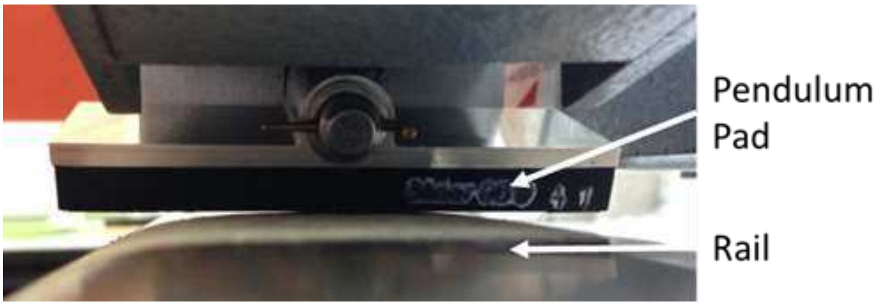

Figure 14 Pendulum and railhead contact

Figure 15 shows the results from pendulum tests of different amounts of TORFM applied at the start of the test and not reapplied during the test. Increasing the applied amount increased the COF. For the amounts applied by brush, the COF increased with each swing after an initial decrease in the first 10 swings. The 0.2 g applied by roller had the lowest COF and was a similar value across all 100 swings. Figure 16A and Figure 16C show the difference between the two application techniques prior to the test starting. Figure 16B shows how the pendulum pad sweeps across a very narrow band of the railhead.

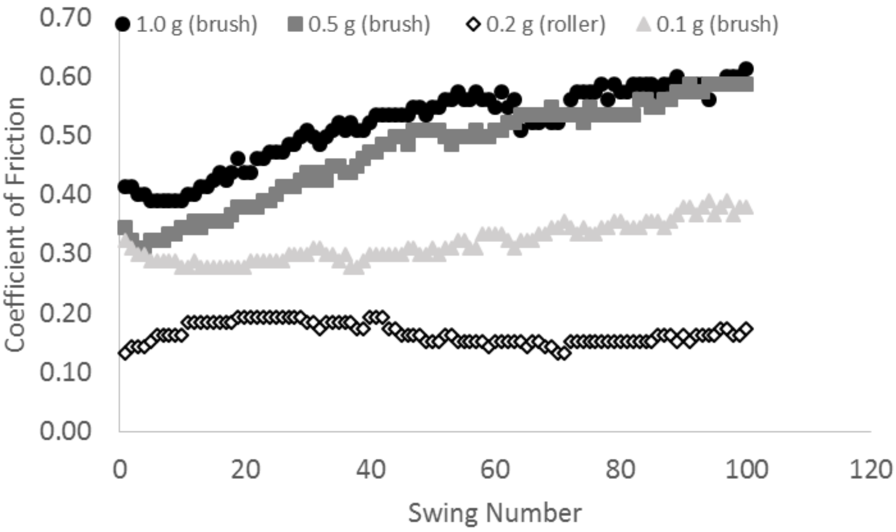

Figure 15 Pendulum tests using different amounts of TORFM and different application methods

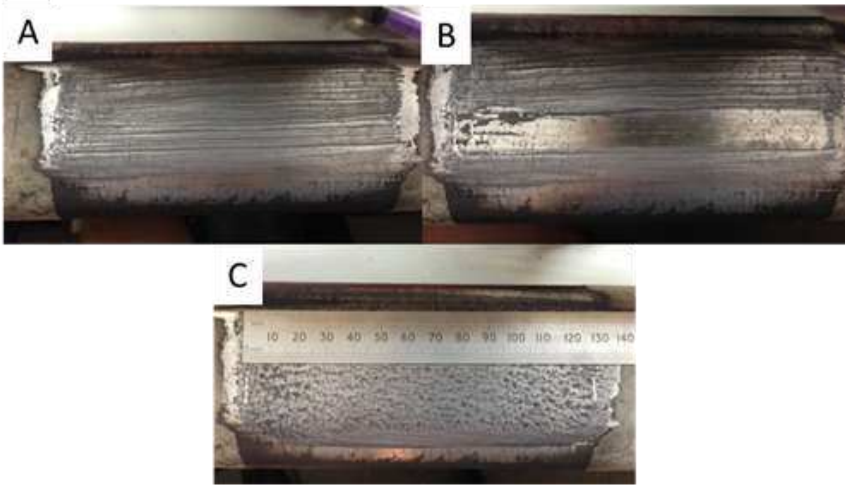

Figure 16 Photos of railhead during pendulum tests using TORFM A) 0.1 g applied by brush pre-test B) 0.1 g applied by brush after 60 swings C) 0.2 g applied by roller pre-test

4.2 Field test results

The coefficient of friction obtained with the pendulum in the field for the tested sites under dry conditions was between 0.65 and 0.88 (see Figure 17). The multiple readings for MDM and SVR in Figure 17 are for different positions in the curves. The results for the two UK sites were similar and slightly lower than the results from Colombia. This is thought to be due to the humidity being higher in the UK than in Colombia [19] as well as the different rail materials, but it is not clear which had the greater effect. From Figure 12, it would be expected that the R400HT rail would have a higher friction coefficient than R350HT, but this is not the case. However, the rail in the field will have hardened during service, so without hardness measurements from the sites it is difficult to fully analyse the differences between the rail materials.

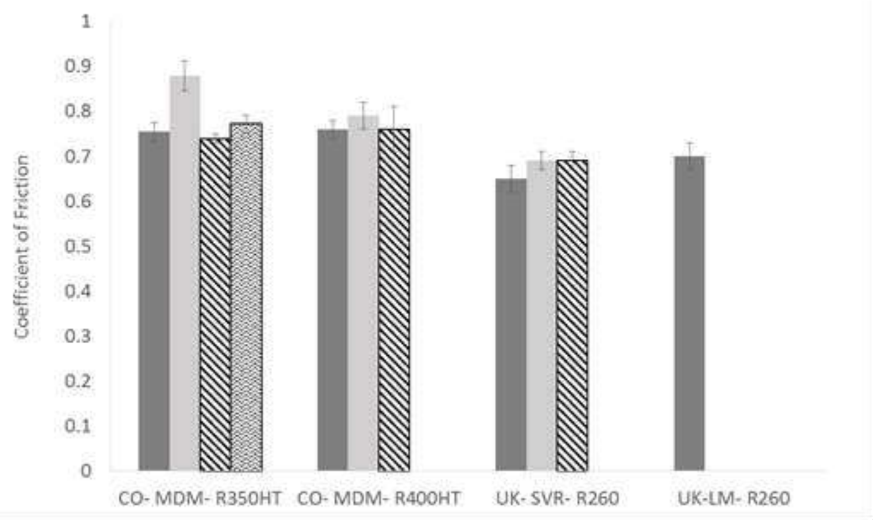

Figure 17 Dry coefficient of friction obtained with pendulum for the tested sites

Figure 18 shows the coefficient of friction measured using a hand-push tribometer on the gauge face at three sites around a curve at SVR (UK) for different interfacial conditions. The wet and contaminated values were obtained by testing the rail without cleaning it first. This means that there were unknown contaminants present on the rail during the test. The wet results are lower than the dry values due to water acting as a lubricant. Site two has a significantly lower COF for the wet tests compared to sites one and three. There was more tree canopy observed on this section of the curve, which led to greater leaf contamination which was impossible to clean off the rail by hand. This could explain the significantly lower value.

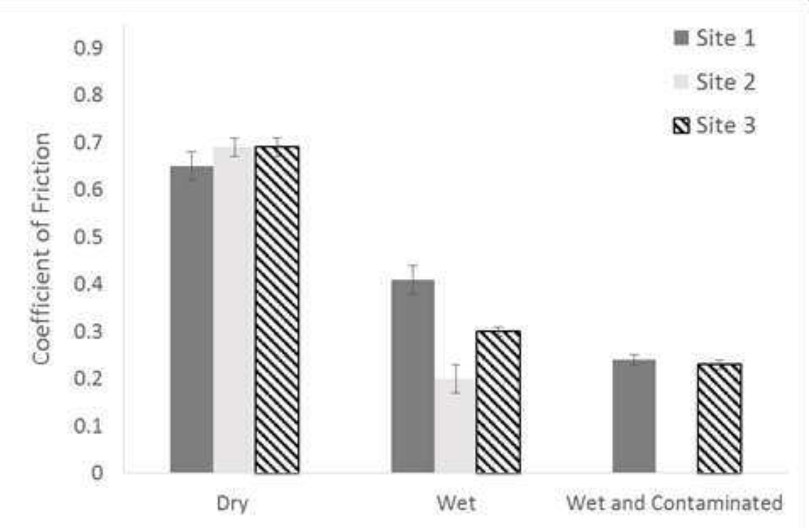

Figure 18 Coefficient of Friction obtained at SVR (UK) for different interfacial conditions using a hand-push tribometer

Figure 19 shows the COF obtained by the hand-pushed tribometer on the TOR under dry conditions. The value of the dry coefficient of friction was lower at LM (UK) than in Colombia (CO-R260). As with the pendulum tests, the lower coefficient of friction is thought to be due to higher humidity in the UK. In addition, the measurements in Colombia were done using a contact pressure of 1.1 GPa (TriboMetro FR-101 tribometer). The contact pressure of the Salient System tribometer used in the UK is around 0.7 GPa [3], and measurements with a lower contact pressure will report higher coefficients of friction (as seen in Figure 7 and [10]). This means that the values taken in the UK are higher than if tests had been done using the TriboMetro FR-101 tribometer. From the laboratory tests in Figure 12, the COF measured for the R400 HT rail material should be higher than that for the R260 rail, but the relationship is reversed in the results presented in Figure 19. These readings were all taken on different days and the different rail materials are in different places. This means that different environmental conditions as well as changes to the third body layer present on the railhead affects the results and a direct comparison is difficult to make. This highlights the differences between laboratory and field testing and illustrates the complexity in analysing field data.

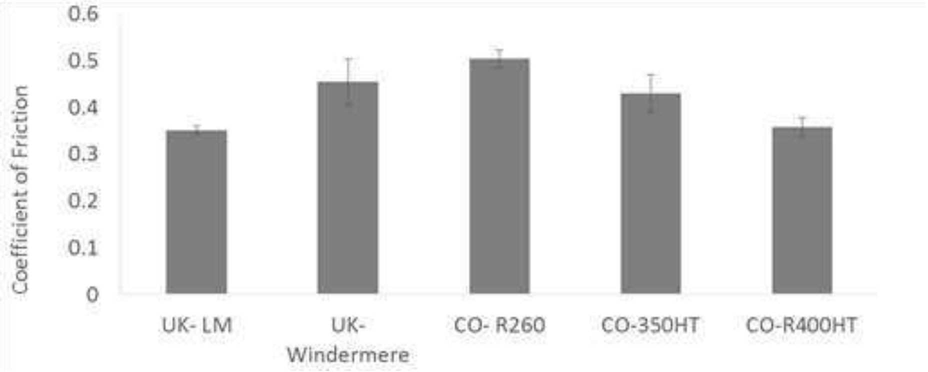

Figure 19 Coefficient of Friction obtained for dry TOR using hand-push tribometer

Figure 20 shows the results from hand-push tribometer tests at SVR and Colombia under wet conditions. The wet conditions were caused by rain and not controlled. SVR-Site 1- High Rail was located near to a lubricator (see Figure 5) and so the low friction coefficient was caused by grease migration from the gauge face to the TOR. Site 2 and Site 3 measurements took place on the high rail. The COF reduction at SVR site 2 that was seen in the wet tests in Figure 18 is also seen in the results here.

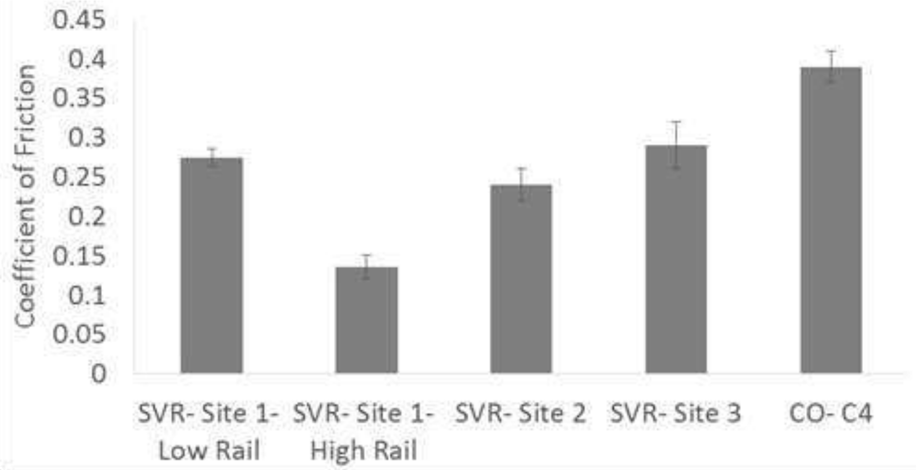

Figure 20 Coefficient of Friction obtained for wet TOR at SVR at different sites using a hand-push tribometer

Figure 21 shows the results from the hand-push tribometer tests on the gauge face in dry conditions. The COF values are the same for the TOR (Figure 19) and the GF for the sites at SVR. This is because, as the tribometer is pushed along the track taking its readings, it is possible for the measuring wheel in the tribometer to pick up contamination from the rail. If this occurs early in the test, the contamination stays on the measuring wheel throughout the test. This was observed at the end of each 'push' of the tribometer; a black viscous substance had built up on the measuring wheel. The black substance is likely to be composed of remains of grease mixed with sand (from soil) and oxides removed from the rail. The COF were higher at SVR than at Oxenholme and Windermere. As the tests took place on a curve and the rail was not cleaned before the test took place there was an unknown amount of grease present on the GF. This difference in amount of grease (and potentially other unknown contaminants) is thought to have led to the difference in COF. There was more grease observed on the gauge face at Oxenholme than at Windermere, causing the difference in COF.

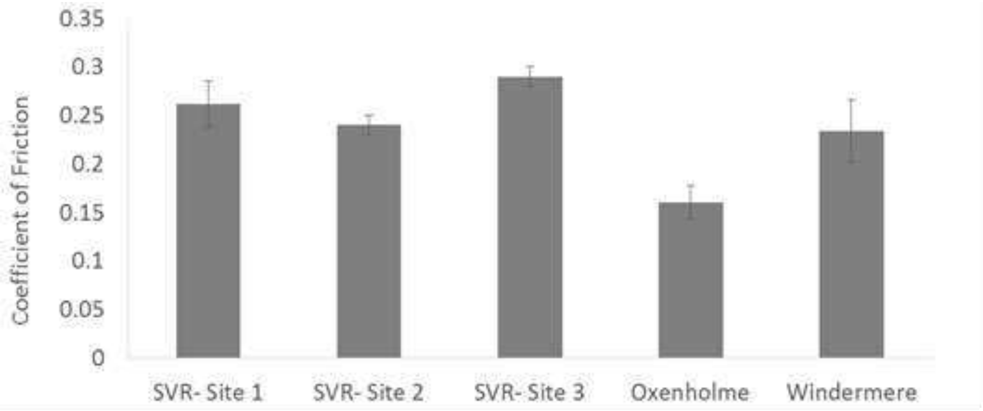

Figure 21 Coefficient of Friction obtained for gauge face using hand-push tribometer

5 Discussion

The results from the pendulum and hand-push tribometer show that the pendulum is more sensitive to different types of contaminants; the difference in values between the different interfacial conditions was larger. Pendulum measurements can also be carried out on a shorter section of rail (approximately 0.3 m in length). This means that the conditions being tested can be more carefully controlled. Additionally, measurements with the pendulum are more practical and quicker than those with the hand-pushed tribometer. However, extensive tests with the same pad could lead to it becoming unevenly worn and as seen in Figure 14, the contact is much smaller than the full pad width. A larger issue is that variation in rail profile changes the contact between pad and rail which could lead to different results in different areas. This could cause an error in the conversion from PTV to COF and these problems should be thought about when choosing which measurement device to use. A recently developed tribometer [20] aims to overcome some of the issues with the hand-push tribometer. This new tribometer only uses a 0.5 m section of rail and can measure anywhere on the railhead and for a range of contact pressures.

Figure 22 compares the COF measured by the pendulum for R400HT at 5% creep with the COF reported by the FSTF and SUROS. Clearly, the pendulum's measurements were higher for the three interfacial conditions tested. This was expected; the pendulum is a full sliding, rubber, rectangular pad on steel rail contact, whereas, the FSTF is a rolling/sliding, steel on steel contact. Additionally, the contact pressure that the pendulum reaches is much smaller than in the FSTF or the SUROS twin-disc machine. These differences also caused the change in values between pendulum and tribometer. What is important is that the methods produced the same ranking of interfacial conditions: dry had highest COF, water had the lowest COF, and TORFM was between the two levels. The SUROS twin-disc machine reported a similar but slightly lower COF compared to the FSTF results. However, the test was carried out at

1.5 GPa contact pressure which lowered the COF compared to the FSTF contact pressures. When this is taken into account, the COF levels are very similar which shows that, despite the differences between the SUROS twin-disc machine and FSTF, there is good agreement between the measurements.

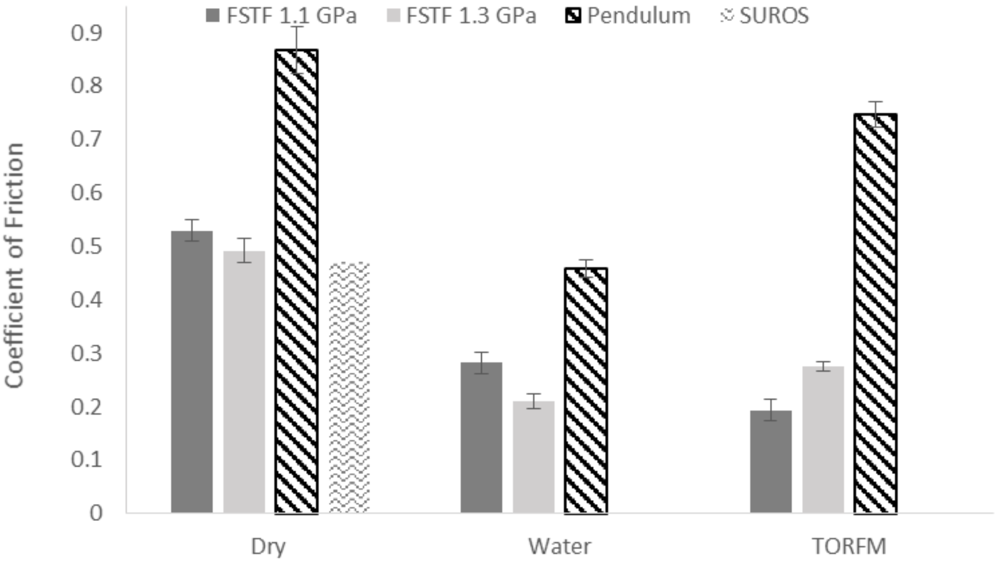

Figure 22 Comparison of FSTF to pendulum in the laboratory

Figure 23 shows the results from tests in the laboratory and the field. In all cases the COF was lower in the field than it was in the laboratory. This is to be expected as there will always be traces of contamination in the field that are not present in the lab (despite any cleaning that occurs prior to test).

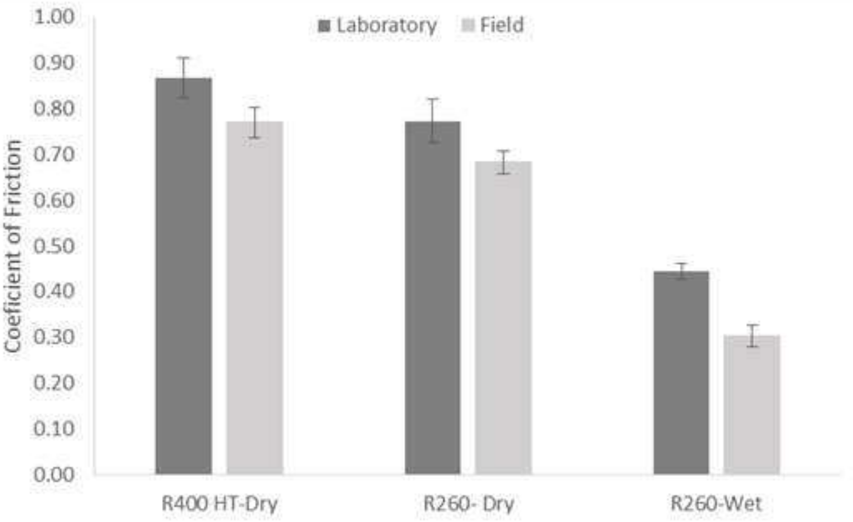

Figure 23- Pendulum tests in the laboratory and the field

For the FSTF (Figure 9), SUROS (Figure 10), and hand- push tribometer (Figure 19), the COF for R260 was reported to be higher than that for R400HT. However, for the pendulum (Figure 23). This relationship was reversed.

In the data presented in this work the dry and wet values fell into the ranges specified in Figure 1. Figure 24 shows work carried out with an instrumented train [21]. The data broadly matches the creep curves displayed in Figure 7- Figure 11 with some small differences. The steep negative gradient after saturation in Figure 24 is not present for any of the dry creep curves measured, but the location of the saturation point is the same. The fact that water lowers friction and shifts the saturation point to a higher creep level is seen in Figure 7- Figure 11 and in Figure 24. This gives confidence that the laboratory tests represented conditions seen in the field by real trains.

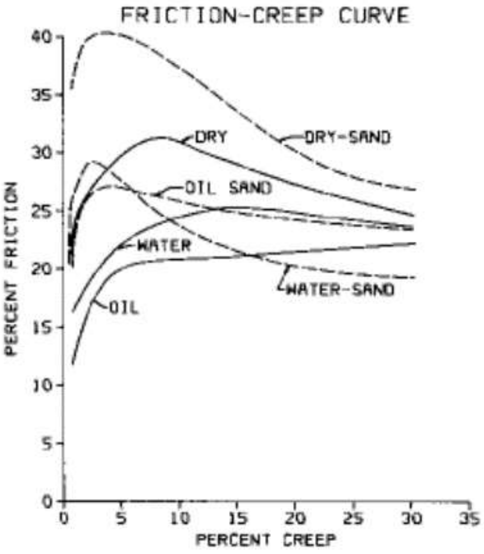

Figure 24- Creep curves measured with an instrumented train [21]

The tests performed in MDM showed that, in the field, the pendulum was not sensitive enough to measure the differences in friction in contacts with different rail materials. The same trend was observed in the laboratory. The curves C15 and C32 are on the same line and they are similar in terms of radius and the same trains are passing in both curves, but the rail in every curve is different.

On the other hand, the hand-pushed tribometer was more sensitive to rail material than the pendulum; the contact area would be reduced when the measuring wheel rotates against a harder rail. In the pendulum the contact area is controlled by the rubber and it is not affected significantly by the rail material.

6 Conclusions

The results from the Full-Scale Test Facility showed that the COF varies when the contact pressure is modified:

- For the dry tests, the COF was greater for the low pressure.

- The COF was reduced by 7% and 34% for the dry and wet conditions respectively, when the contact pressure was increased for a fixed value of creepage of 5%.

- The FSTF tests showed good agreement with the twin-disc tests, with the same relationships shown and similar COF (taking into account different contact pressures).

- The COF obtained with the pendulum in the field for the tested sites under dry conditions was between 0.65 and 0.88.

- The minimum COF obtained with the hand-pushed tribometer was at Severn Valley Railway when the rail was wet and contaminated.

- The pendulum and hand-push tribometer showed the same relationships for different interfacial conditions.

- The pendulum could differentiate between different contaminants better than the tribometer; the contact area is more controllable. However, the conversion between the PTV and COF may need adjusting to take account of the smaller contact area on the railhead compared to its original use, measuring COF on flat surfaces.
- Therefore the pendulum device is more advantageous to be used when comparing different contaminants.

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