ELGI 2021 Virtual Spring Events
19th – 27th April 2021
ELGI-STLE Tribology Exchange Workshop; Working Group Meetings; Grease Symposium
www.elgi.org

Maintaining safe and quiet railways with “top of rail materials”

Author: Marc Ingram - Ingram Tribology Ltd
Co-Authors: Matt Smeeth - PCS Instruments Ltd.
Anup Chalisey - Rail Safety and Standards Board UK
marc@ingramtribology.com

Marc has over 10 years of experience working in Tribology. He has a master’s degree in Chemistry and a PhD in Engineering (Tribology). He has had a successful career at Imperial College, PCS Instruments and Afton Chemical. Marc has extensive knowledge of all tribology test methods including both standardised and non-standardised lubricant tests. He has designed, modified and improved countless methods, to ultimately aid in the development of new lubricant products. Marc now works for his own company Ingram Tribology.

Key Words: Friction, top of rail, flange, creep curves, railway

Abstract

Lubricants are used on the rail/wheel interface to control friction, reduce wear and fatigue along with reducing noise. As a train proceeds around a curve its wheels (which are fixed) travel different distances and thus some sliding between the wheel and the rail is inevitable. This sliding at the wheel /rail interface can cause an unpleasant high pitched noise. The noise is generated by an unsteady dynamic where the sliding wheel alternates rapidly between two sliding speeds. This unsteady dynamic can be suppressed and controlled using lubricants which are added directly onto the rail or wheel. It has been found that to reduce noise, the friction between the wheel and rail should increase as the percentage of slip (creep) increases. This friction characteristics can be evaluated using “creep curves” in controlled test machines. A benchtop test method has been developed which can generate creep curves under realistic conditions of speed and contact pressure. This method was found to differentiate 11 different railway products. An inter-laboratory study/ round robin was then conducted using this new method. We report on the results of the round robin with a statistical analysis of repeatability and reproducibility.

Introduction

Lubricants are used on the rail tracks for numerous reasons including: ensuring safety, reducing wear and noise and improving fuel economy. Lubricants can be found on two sections of the wheel/rail interface (Figure 1). Top of rail (TOR) materials are used on the wheel tread/ rail crown area, whilst flange products are used on the wheel flange face/rail gauge shoulder interface. Flange products have traditionally been used on railways to control wear at the wheel/rail interface. Whereas the use of “top of rail materials” (friction modifiers) has become prevalent recently.

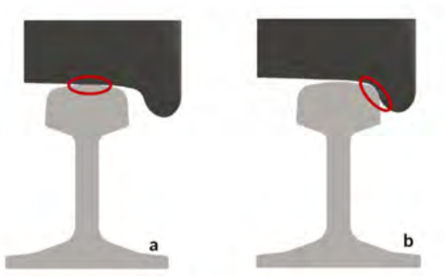

Figure 1 – Cross section of a wheel and rail, showing the contact between (a) the wheel tread and rail crown and (b) the wheel flange face and rail gauge shoulder

Flange products

Flange products are similar in composition and appearance to traditional greases. The flange products evaluated here are those applied to the rail via trackside applicators or trainborne equipment. These can be petroleum based with mineral or synthetic base oils. They can also be based on biodegradable oils for environmentally sensitive areas.

TOR Materials

The formulation of TOR materials is considered confidential by their manufacturers so exact compositions are not available in the public domain. Water based TOR materials are most common in Europe, these contain:

- Water
- Glycols
- Thickener/stabilisers (e.g. clays, PVA styrene copolymers, latex and silica)
- Solids (e.g. graphite, calcium carbonate and metal powders)

Some TOR materials are designed to work with a carrier system, which evaporates once the material has been deposited leaving a thin film of the active friction controlling substance. Oil based products are common in America, where axle loads are much higher. Oil based TOR Materials have a lower friction coefficient and generally not used in Europe.

Dual/hybrid systems

Dual/hybrid products aim to do the job of both the TOR materials and the flange product, having acceptable performance on both the rail crown and rail gauge shoulder.

Wheel/rail traction

Traction between railway lines and train wheels is paramount for the safe and effective operation of trains. High traction is required to allow the controlled acceleration and braking of the train.

The level of traction available for the safe operation of the train can be affected by environmental conditions (rain water, falling leaves) and also any material present at the interface.

In the railway industry it is customary to describe the friction forces in the wheel/rail interface as adhesion. This “adhesion” term is synonymous with the term friction coefficient or traction coefficient. Adhesion can be used to define the traction available to transfer tangential forces between a driving train wheel and the rail. If the driven wheel applies a tangential force larger than the limit (defined by the traction coefficient) the wheel will spin causing severe damage to the rail. Hence the need to maintain high traction at the wheel tread/rail crown interface, for both performance and safety of the train, as well as the longevity of the wheels and the rails.

TOR materials act to condition the rail to providing a consistent friction/ traction value, while reducing both micro slip and sliding. A controlled level of traction is preferred, within a range of 0.25 to 0.4 traction coefficient [1]. If the traction is too high, it can increase the wear and fatigue processes on the wheel and rails. If the traction coefficient is too low, excess slips and slides can occur leading to wear and uneconomical operation of the train and potentially give braking problems.

For the wheel flange/rail contact a friction coefficient of below 0.1 is desirable [1]. This is achieved with flange lubricating products, which are known to reduce noise and wear at this interface.

The friction coefficient of a “dry” rail has been measured and is found to be between 0.4-0.6 [2]. At this level short pitch corrugations are found and sometimes referred to as roaring rails [3]. Very high friction forces can be achieved with the use of sand at the wheel/rail interface, but with the accelerated demise of the wheels and rails. This method can be used for example in areas with heavy leaf fall, which is known to reduce friction at the wheel rail interface [4].

Railway noise

An unpleasant high pitch noise can be generated from the wheel/rail interface as the train proceeds around curves. As the train moves through a curve the wheel pairs (which are fixed) travel different distances, and thus some sliding between the wheels and rails is inevitable. It is believed that the high-pitched squeal noise (in the region of 200 – 2000Hz) occurs at the leading inner wheels due to a lateral slipping at its natural mode [5]. When the friction characteristics of the wheel/rail interface allow it, the wheels can enter this unsteady dynamic. The unsteady dynamic is due to the wheels alternating between two sliding speeds, generating vibration. The vibration causes oscillation at the wheel web [6].

The noise can be reduced by controlling the friction characteristics at the wheel rail-interface. To reduce noise the friction at the wheel-rail interface should increase with the percentage creep [5]. Creep is defined as the percentage of sliding at the rail wheel interface relative to the speed of the train. Defined here as:

$$Creep\ (\%) = \frac{V_S}{V_T} \times 100$$

where V_S is the sliding speed between the rail and wheel (the slip) and V_T is the speed of the train.

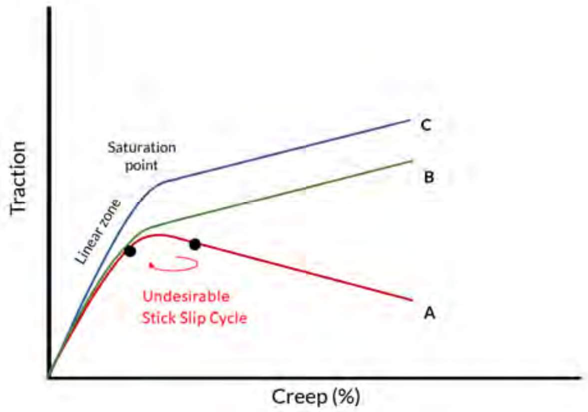

Figure 2: Representation of an idealised creep curve. Curve "A" would indicate noise generation in the field. "B" with a positive slope would suppress noise. Curve "C" with high overall traction and a positive slope is the ideal system.

A representation of a creep curve is shown in Figure 2. At lower levels of creep the traction increases linearly. This linear zone is due to more and more of the contact become sliding as opposed to rolling. At a certain percentage creep the contact becomes fully sliding, sometimes referred to as “saturated”. The traction forces are then dependent on the metal surfaces and any third body material. Three possible scenarios are shown in Figure 2:

- Curve “A” shows a traction force falling with increasing creep. Where the creep curve has this negative gradient, the wheels can enter an unsteady dynamic, where the speeds can quickly alternate between the two points of same traction either side of the saturation point. This produces a highly undesirable stick slip cycle, which will lead to the development of vibration and ultimately noise.
- Curve “B” will suppress the noise, due to the removal of the negative damping effect of the system depicted in Curve “A”.
- Curve “C” depicts the ideal system for a TOR material with high overall traction and a positive slope after the saturation point.

Despite the widespread use of TOR materials and flange products they are not yet covered by any international standards, although their use is accepted and practiced by many railway operators around the world.

The aim of this work is to develop a test method for TOR material and flange products to ensure performance in the field. This method would then be added DIN EN (possibly ISO) Standard “Railway applications – Wheel/rail friction management – Lubricants for trainborne and trackside applications” (EN 15427)
As all the railway lubricants and high traction products used in this study are approved for use in the field in Europe, the friction characteristics of these products can provide a benchmark on which to compare other formulations.

This paper details the development of the test method, followed by a inter laboratory study to evaluate its reproducibility.

Method development

A standard PCS Instruments Mini Traction Machine (MTM) was used to develop this new test method. The MTM uses a ¾ inch ball, loaded against a 46 mm diameter disk. Both ball and disk are manufactured from AISI 52100 steel and have a surface finish of approximately 10 nm Ra. The hardness of the ball and disk is 760 HV. The loads of between 5 and 75 N on the instrument allow the application of a contact pressure between 0.5 and 1.25 GPa. Both the ball and the disk are independently driven using accurate DC motors and encoders, allowing the application of controlled slippage at the contact. The slippage is defined with a slide/roll ratio. This definition is similar but not exactly comparable to the “creep”, more commonly used on railways:

$$SRR\ (\%) = \frac{U_S}{U_E} \times 100$$

Where, $U_S$is the sliding speed and U_E is the entrainment speed given by:

$$U_E = \frac{[U_A - U_B]}{2}$$

Where U_A and U_B are the linear speeds of the ball and the disk.
Thus in sliding/rolling tribometers such as that used in this study the slide/roll ratio is slightly lower than the equivalent quoted “creep” values from the railway industry.

Both steel specimens were cleaned prior to testing to remove any corrosion inhibitor product from their surface. The cleaning procedure consisted of 20 minutes immersion in Heptane (analytical grade) with ultrasonic excitation. Followed by 20 minutes immersion in propan-2-ol (analytical grade) with ultrasonic excitation.

Figure 3 shows a photograph of the ball and disk test specimens attached to the MTM, before the application of a TOR material or flange product. A small quantity of TOR material or flange product is applied to the top of the disk using a clean mask. The quantity of material is higher than would be typically applied on the rails in the field, but as this is a non-conformal contact, much of the product is pushed from the contact zone. Only a very small quantity of TOR material or flange product remains in the running track during the test.

Figure 3: Photograph of the ball and disk attached to the MTM

An applicator mask was developed to help apply a controlled volume of material on the disk. The applicator contains 12 straight holes of 2.5 mm diameter and 1 mm depth. Thus each hole has a volume of 4.91 mm^3 and the mask will help deposit a nominal 58.9 mm^3 or 0.0589 ml around the running track of the disk in total. The semisolid substance is wiped over the mask, ensuring all the holes are filled. The substance is then made flush with the top of the mask with a flat spatula. This deposits 12 small dimples of material on the disk when removing the mask. This procedure is shown stepwise in Figure 4.

Mask clamped to the MTM disk

Apply TOR Material through the holes

Remove excess

12 small dimples of semisolid material remain on the disc

Figure 4: Photographs showing the step-by-step application of semisolid product onto the surface of a MTM disk.

Once the product has been applied to the disk, the disk and the ball are added to the MTM instrument as normal. The ball is loaded against the disk at 30 N. The temperature of the pot is not controlled. A run-in is used to spread the material evenly over the test specimens and condition the steel specimens. A speed of 100 mm/s and SRR of 50 % is used for the run-in for 30 minutes in total. At 15 minutes the speed is increased to 4000 mm/s and sliding stopped for 1 minute. This high-speed step is used to “fling” any loose material from the steel samples, to prevent any excess material being re-introduced into the contact during the high-speed traction curves, which occur later in the test. This step was found to be beneficial for repeatable creep curves in early experiments.

Creep curves are generated at two entrainment speeds, 1 m/s and 3.8 m/s. These correspond to train speeds of 3.6 km/h and 13 km/h respectively. Traction measurements are taken at slide/roll ratio values of 0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 %. Table 1 shows the speeds of the samples for each point of the creep curves at 1 m/s. Traction forces are measured in both directions and their average reported.

Table 7: Speeds of the ball and disk during the measurement of friction

Entrainment Speed (m/s)	**SRR (%)**	**Disk speed 1**	**Ball speed 1**	**Disk speed 2**	**Ball speed 2**
1	0.25	0.99875	1.00125	1.00125	0.99875
1	0.5	0.9975	1.0025	1.0025	0.9975
1	0.75	0.99625	1.00375	1.00375	0.99625
1	1	0.995	1.005	1.005	0.995
1	2	0.99	1.01	1.01	0.99
1	3	0.985	1.015	1.015	0.985
1	4	0.98	1.02	1.02	0.98
1	5	0.975	1.025	1.025	0.975
1	6	0.97	1.03	1.03	0.97
1	7	0.965	1.035	1.035	0.965
1	8	0.96	1.04	1.04	0.96
1	9	0.955	1.045	1.045	0.955
1	10	0.95	1.05	1.05	0.95

The test proceeds alternating between a measurement creep curve step and a 2 minute pure rolling step. This allows the steel samples to cool between each measurement.

Table 2 shows the test profile used on the MTM. All steps were carried out at 30 N load (~1 GPa contact pressure) and ambient temperature.

Table 8: Test conditions used on the MTM instrument

Step No.	**Description**	**Speed (mm/s)**	**SRR (%)**	**Duration (min)**
1	Run-in	100	50	15
2	Run-in	4000	0	1
3	Run-in	100	50	15
4	Creep curve medium speed	1000	0.25 - 10%	~ 1
5	Pause	50	0	2
6	Creep curve high speed	3800	0.25 - 10%	~ 1
7	Pause	50	0	2
8	Creep curve medium speed	1000	0.25 - 10%	~ 1
9	Pause	50	0	2
10	Creep curve high speed	3800	0.25 - 10%	~ 1
11	Pause	50	0	2
12	Creep curve medium speed	1000	0.25 - 10%	~ 1
13	Pause	50	0	2
14	Creep curve high speed	3800	0.25 - 10%	~ 1
15	Pause	50	0	2
16	Creep curve medium speed	1000	0.25 - 10%	~ 1
17	Pause	50	0	2
18	Creep curve high speed	3800	0.25 - 10%	~ 1

At the end of the test the disks were cleaned using the same procedure as the fresh specimens. The wear tracks are then analysed with a metallurgical grade microscope – (Brunel SP400 metallurgical). The width of the wear track is measured digitally using ImageJ software. The software is calibrated for each magnification using a calibration slide with increments of 0.01 mm, to relate each pixel on the camera to a length value.

Eleven materials were supplied by the ELGI Railway working group. The designation provided is noted here for reference in Table 3. The manufacturer or the type of material was not known during the development of the test method.

Table 9: Top of Rail Material Codes - as supplied

Sample	Lubricants Designation	Application
A	18-03125	TOR Material
B	18-03126	Flange
C	18-03192	Flange
D	18-03127	Flange
E	18-03128	Flange
F	18-03129	Dual product
G	18-03130	TOR Material
H	18-03131	TOR Material
J	18-03132	TOR Material
K	13-03133	Flange
L	Supplied by ProRail	Dual

Data processing

For each test, eight creep curves are generated. Four at medium speed (1 m/s) and four at high speed (3.8 m/s). The first two creep curves (steps 4 and 6) and the last two creep curves (steps 16 and 18) were not used in the analysis. Although care was taken to run the samples in and ensure the TOR material is distributed evenly across the disk, the first creep curves sometimes showed variation. This could be due to the material still settling. At the final creep curves the samples may begin to wear and heat up, causing variation. The traction curves from step 8 to 14 were used in the analysis. Each material was evaluated at least twice using this method.

Results

The results of the creep curves at 1 and 3.8 m/s are shown in Figures 5 and 6 respectively for all the materials.

Most of the creep curves show a positive gradient, this might be expected as all these products are known to be approved for use in the field and are expected to have a good performance. The test method can also distinguish between the overall friction range of the different products groups, with TOR Materials demonstrating the highest overall friction, flange products the lowest and dual products middling. Sample A, J and G show creep curves with a greater gradient that the other samples. Sample H showed the highest overall traction throughout all creep values. The samples mostly show similar friction characteristics at 1 and 3.8 m/s. Although some, such as Sample A and B show higher overall friction characteristics at the higher speed.

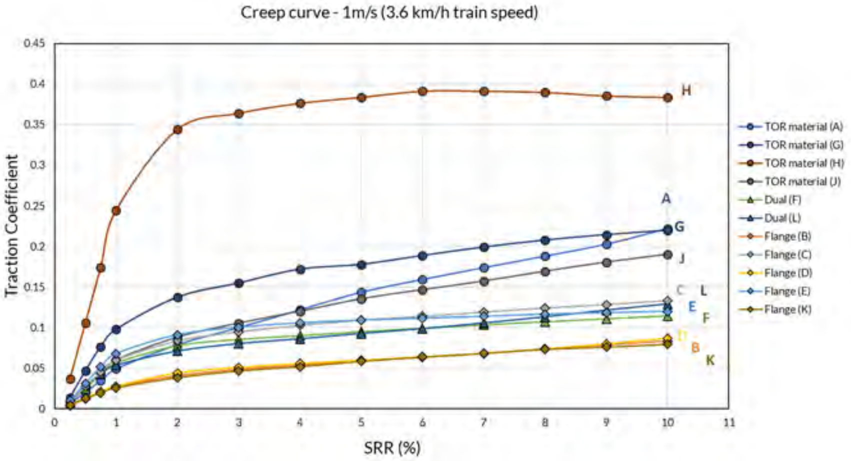

Figure 5: MTM Creep curves at 1 m/s for materials A through L

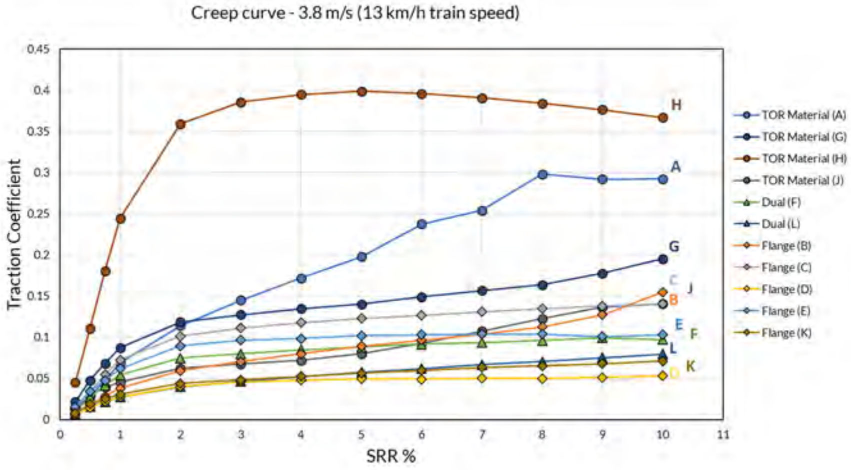

Figure 6: MTM Creep curves at 3.8 m/s for materials A through L

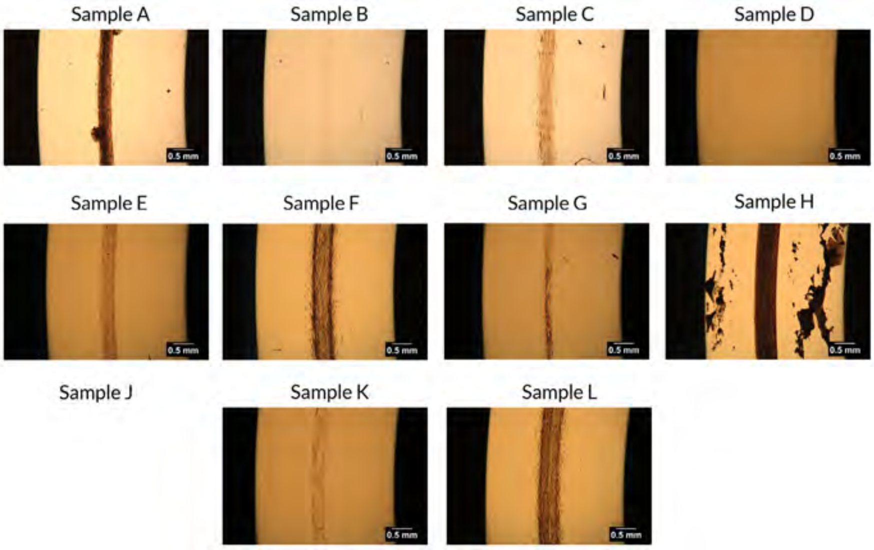

Figure 7: Micrographs of the disk surface after the MTM tests for all 11 samples

Images of the disk surface after the tests are given in Figure 7 for all 11 samples. Showing a large variation in the nature of the deposited material of wear to the metal surface. Sample B and D show a barely visible wear scar, whereas samples A, F, H and L have deposited solid particles on the disk surface. Sample G has deposited a thick, viscous residue. The wear track width was measured digitally using the photographs from the microscope. The results are given in Figure 8.

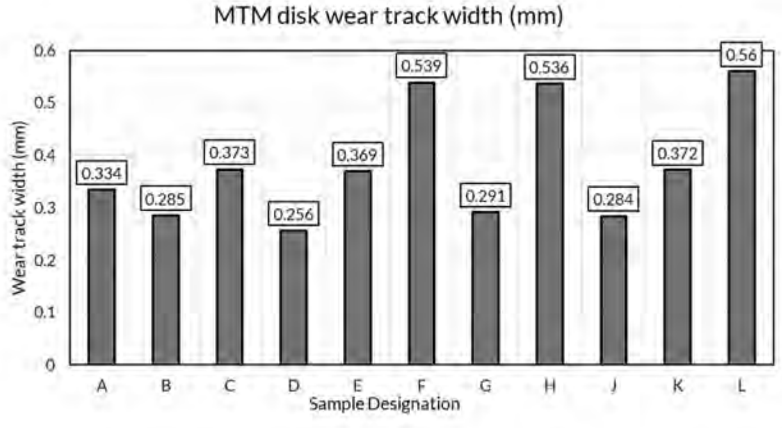

Figure 8: Wear scar width as measured on the MTM disc after the test

The variation in the wear track width at the end of the test show the formulation style used to achieve TOR materials with Sample J and G having significantly lower wear compared to sample H.

Test Method development summary

The MTM creep curves method is shown to measure the friction characteristics of high-pressure steel contacts, such as those found within rail/wheel interface. This method was found to differentiate the performance of TOR materials, flange products and dual products, to an extent expected by railway engineers. This method was adopted by the ELGI railway working group and a inter laboratory study was initiated – detailed below.

Inter laboratory study (Round Robin)

An inter laboratory study (ILS)/ Round robin was set up by the members of the ELGI Railway working group in 2019. 12 laboratories volunteered to participate in the ILS. The participants are to remain anonymous, but it can be said that the ILS was conducted by a group of international oil companies, lubricant additive manufacturers, instrument manufacturers and test houses.

Four test samples were selected for the ILS and are detailed in Table 4.

Table 10: Details of the four materials used during the ILS

Sample A	TOR material
Sample D	Flange product
Sample F	Dual product
Sample H	TOR material

The test samples were provided to each participant along with a reference oil and the grease applicator. The reference oil was used to check the performance of each MTM instrument before starting the testing of the railway products. If this qualifying test was satisfactory, the participants were asked to conduct 3 tests on each railway sample, following a defined method. The test method was changed slightly for the ILS, with the applied load being reduced from 30 N to 20 N. This was to reduce the chance of the instruments exceeding their maximum force and tripping out or causing damage.

Results – ILS

The creep curves generated on the four samples during the ILS are shown in Figures 9 and 10. Eleven of the twelve labs submitted data back to the group. This gives the entire spread of the results. Where the mean of the results is given for the entire population (every test from every lab). The error bars denote the spread of the data (showing the highest and lowest recorded result)

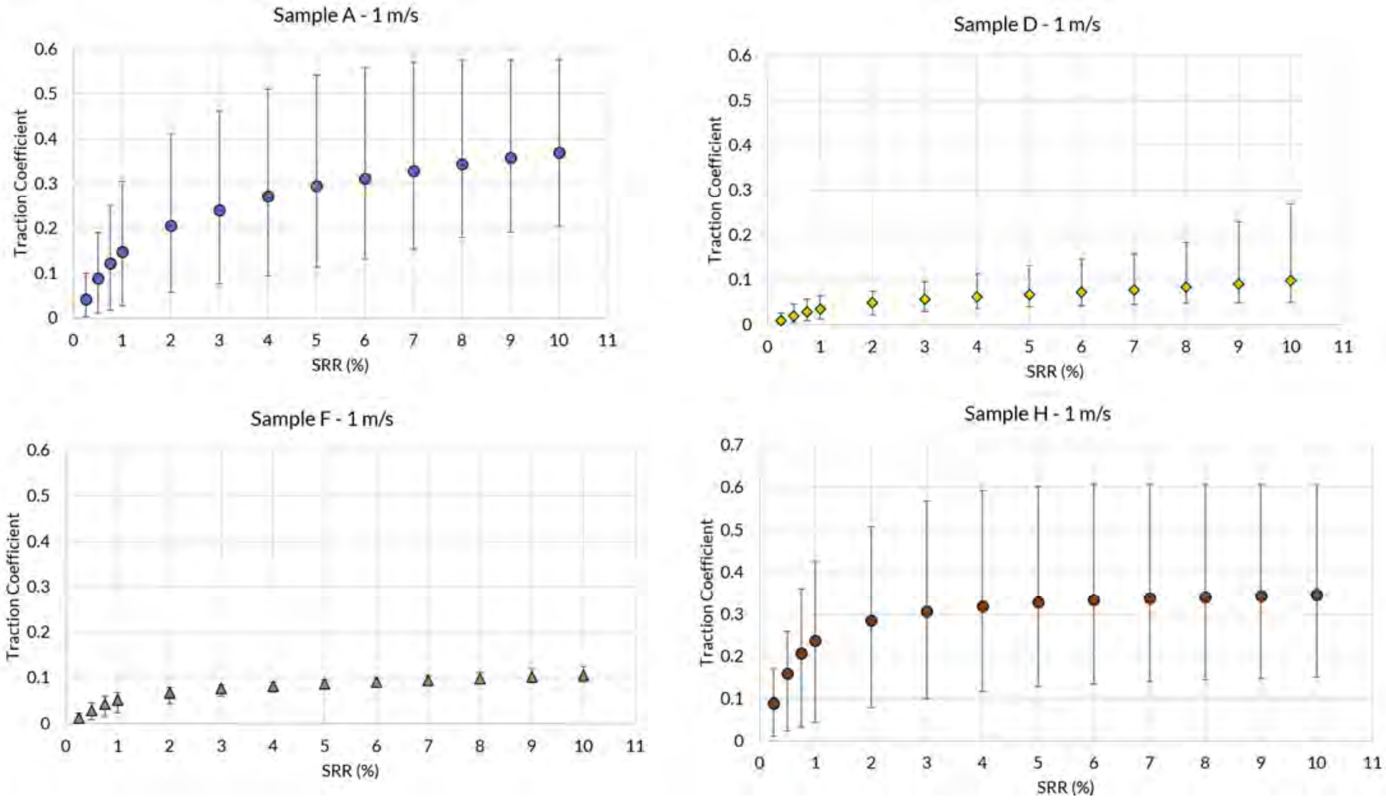

Figure 9: Raw data from the ILS – medium speed creep curves for each material

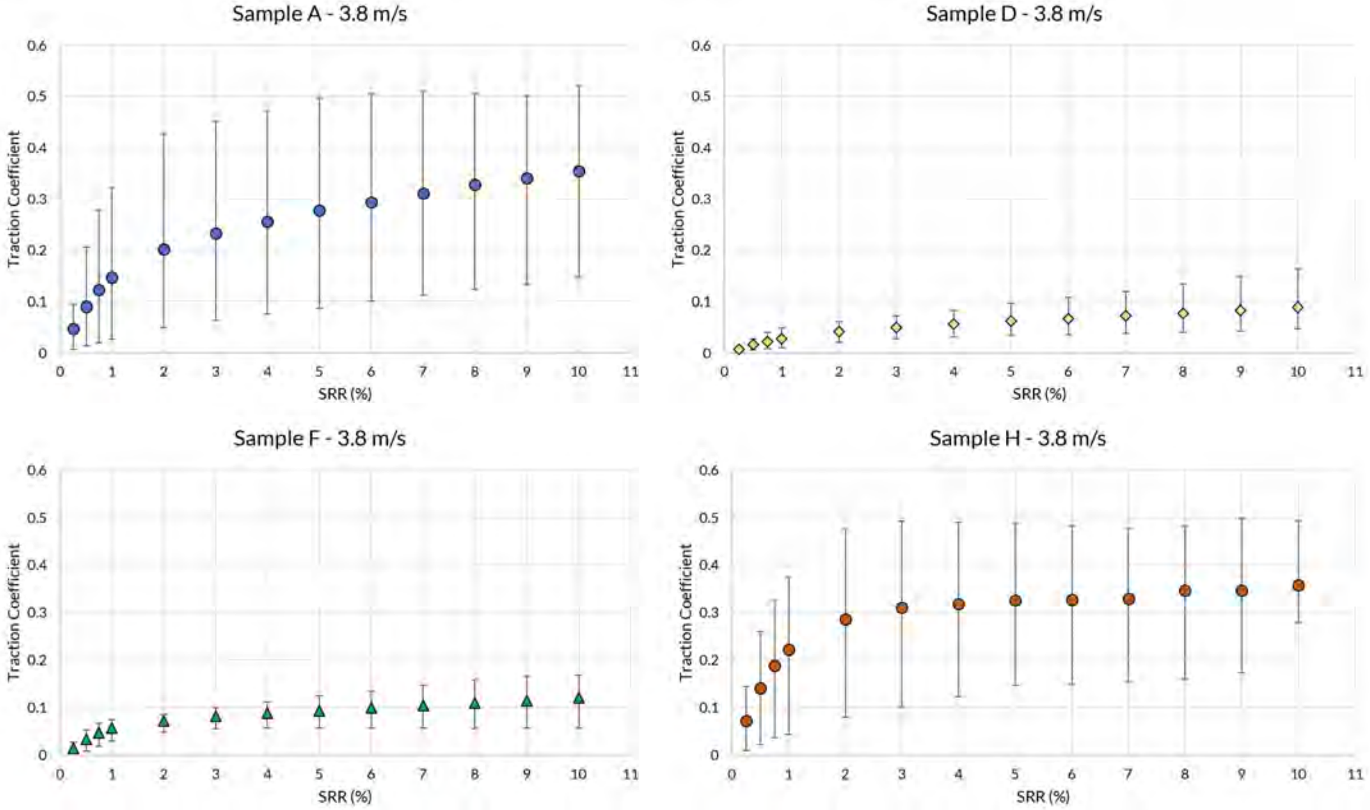

Figure 10: Raw data from the ILS – high speed creep curves for each material

It can be seen that Sample A and H have a greater variation across the 11 labs, than Sample D and F. This was attributed to the inhomogeneous nature of the TOR materials, leading to differences in the composition of the coating on the

MTM disk, leading to differences in the measured friction. It has also been noted in field trials that the friction coefficient measured on rails is variable when conditioned with TOR materials [7].

The data points at a speed of 1 m/s and 1 % creep are plotted in Figure 11 for each sample, along with the mean with the standard deviation denoted by the error bars. Table 5 gives the mean, standard deviation and number of data samples (n) shown in the plot.

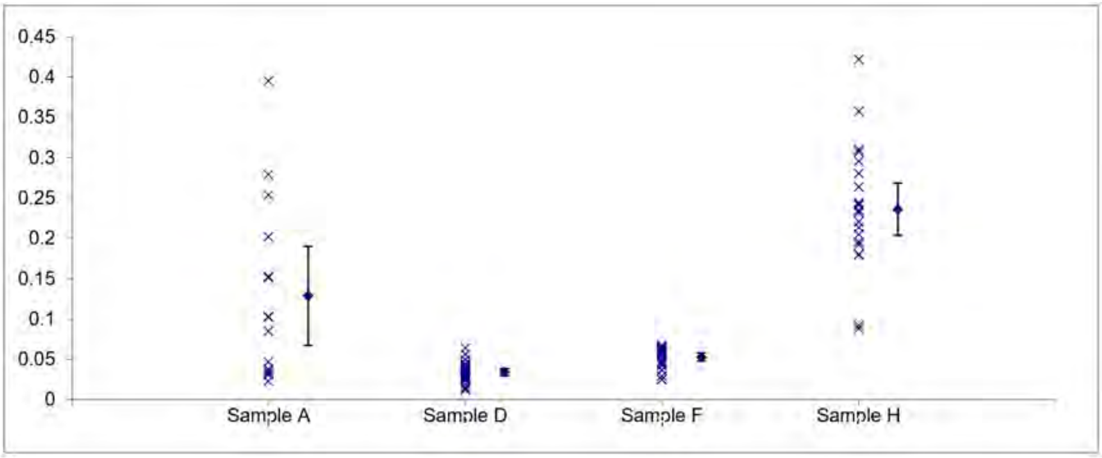

Figure 11: Plot showing the distribution of the measured traction coefficient at 1 m/s and 1 % SRR

Table 11: Population statistical values for the ILS

Multiple Blob Diagram	Sample A	Sample D	Sample F	Sample H
Mean	0.13	0.03	0.05	0.24
SD	0.111	0.012	0.013	0.075
n	15	31	31	23

Figure 11 shows that although the spread of the results is large for the TOR materials across the 11 different labs and operators, there is still a statistical difference measured between the different product types. Where samples D and F are clearly differentiated from Sample A and H using this method.

The data was analysed using the Analysis of variance method to ascertain the likely precision of the MTM test method. The measured traction coefficient at each SRR was treated independently in the analysis, to understand the variation across the creep curves. At 1 m/s the reproducibility (95% confidence interval) can be estimated as 0.02 for the flange/dual products and 0.2 for TOR materials. The repeatability (95% confidence interval) can be estimated as 0.02 for flange/dual products and 0.15 for TOR materials.

The variation of the measured traction within the laboratories is shown in Figure 12. This shows graphically the confidence interval for repeating this experiment on one instrument with one user. Clearly, variation in the measured traction can still be expected for TOR materials. The flange and dual products (Samples D and F) show a very narrow range of expected measured friction for repeat experiments.

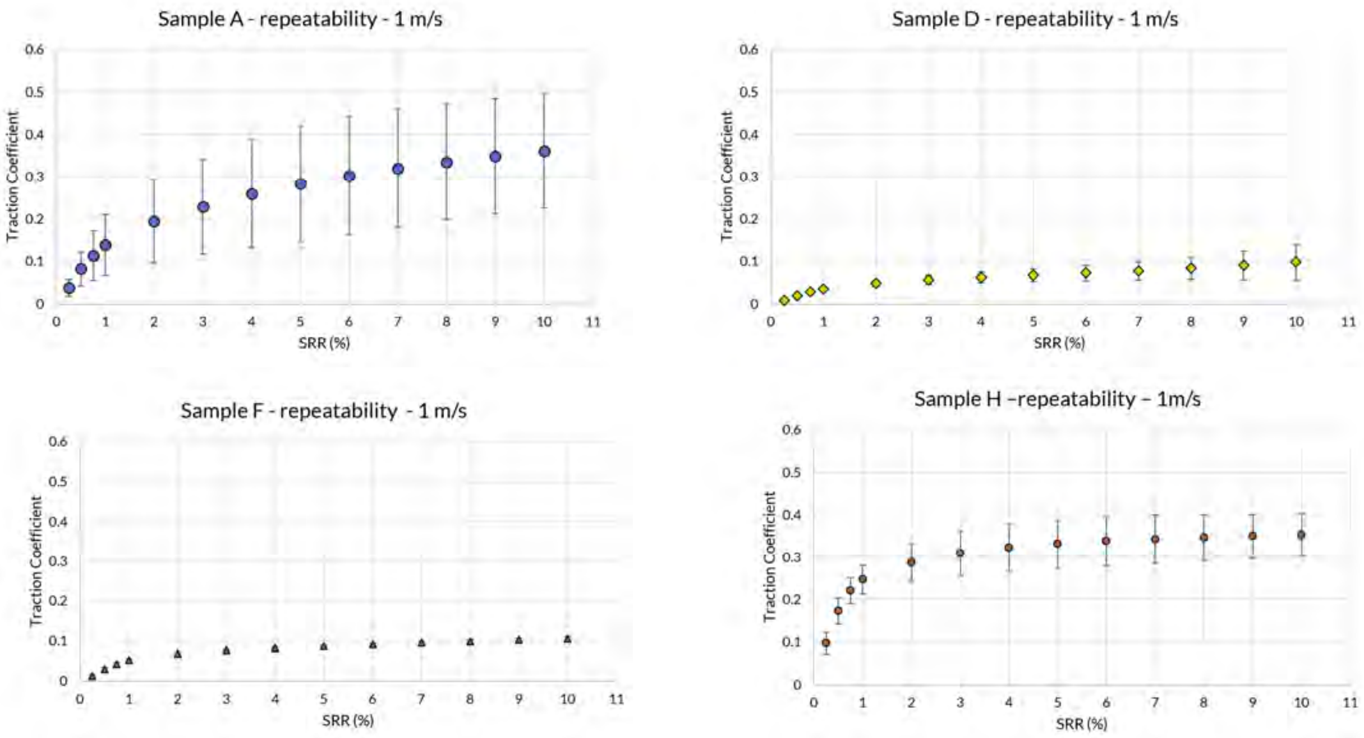

Figure 12: Average creep curves traction coefficient showing the expected confidence interval for a single user and laboratory

Standardisation

This method is currently included in the draft standard for TOR materials and flange products as an indicative test [8]. Meaning that this method can help in early stage evaluation of new candidate products for railways, before further full scale testing is required for qualification.

Currently flange products are specified to have a traction coefficient of below 0.13 over the entire range of the creep curve at 1 m/s (medium speed). TOR materials are required to have a traction coefficient of above 0.11 at 1 m/s and 10 % SRR using this method.

Summary

A new test method has been developed to evaluate the performance of TOR materials and flange products that are used in wheel rail interfaces. This method demonstrates the friction characteristics of the products through conventional creep curves, at 1 and 3.8 m/s linear speeds. These curves give an indication of noise generation and available traction at the wheel/rail interface.

An ILS has been completed using this MTM creep curve method with 4 railway products. The method is able to differentiate the performance of the products. The method is now being added as an indicative test to the European standards for TOR materials and flange products.

Declaration

The work described here was sponsored by the Rail Safety and Standards Board (RSSB) in collaboration with the European Lubricating Grease Institute (ELGI) working group on Railway grease.

References

[1] Sinclair, J., 2004, Friction modifiers, Vehicle track interaction: Identifying and implementing solutions, IMechE Seminar, 17 February.

[2] Kalousek, J., Hou, K., Magel, E., Chiddick, K., The benefits of friction management – a third body approach, in: Proceedings of the World Congress Conference on Railroad Research, Colorado Springs, Junes 1996, pp. 461-467.

[3] Eadie, D.T., Kalousec, J., Chiddick, K.C., 2002, The role of high positive friction (HPF) modifier in the control of short pitch corrugation and related phenomena, Wear, 253, 185-92.

[4] Cann, P.M., 2006, The "leaves on the line" problem – a study of leaf residue film formation and lubricity under laboratory test conditions. Tribology Letters, Vol. 24, No. 2.

[5] Thompson, D., and Jones, C., Noise and vibration from the wheel-rail interface. *Wheel-rail interface handbook*. CRC Press 2009

[6] Eadie, D.T., Santoro, M., Powell, W., 2003. Local control of noise and vibration with KELTRACK friction modifier and Protector trackside application: an integrated solution, Journal of Sound and Vibration, 267, 761-72.

[7] Testing the effect of friction modifier Product 1 on braking distance. Document No: 10-P-13664-TTZ213-102340-PR02-V02, RSSB, UK. Translated March 2011

[8] Railway Applications – Wheel/Rail friction management. EN 15427: 2019, CEN/TC 256 (in draft)