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Top of Rail Friction Modifier Review Paper

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Abstract

The aim of this paper was to review the current state of research for top of rail friction modifiers. In the railway industry friction modifiers is a catch all term for a wide range of products applied for different purposes which has led to confusion. It is hoped that recently published definitions will aid industry to a better understanding of the different products and how they function. The benefits of friction modifiers are well understood with a large body of research supporting the benefits. Comparatively, there is a lot less knowledge of the optimum amount of product to achieve the benefits or how far down the track from an application site the benefit will be seen. Modelling of the products is another area where there is little research, with most of the modelling papers found focussing on dry wheel-rail contact due to the complexity of introducing a third-body layer to a friction force model. Furthermore, only one paper was found which relates how friction modifiers are affected by contaminants or other applied products such as lubricants. With many different products applied to wheels and rail for different purposes, understanding their interaction is key. At the time of this review there are currently no standards that prescribe how top of rail friction modifiers should behave although the European Committee for Standardisation (CEN) is currently developing them at the moment. This review has also attempted to appraise the research against a set of criteria. Depending on how many of the criteria the piece of research filled, it was categorised as A, B or C. It was found that most of the research was of category, this was mainly due to only one test method being used or the scale presented. Category A research incorporated modelling or multiple test-scales to support the results presented.

1 Introduction

1.1 Wheel-rail contact

The wheel-rail contact is required to carry the load of the train, as well as transfer the traction and braking forces within the small area of contact between the wheel and rail, often approximated to 1 cm^2. The contact is further complicated by being an open system, which means there are many sources of contamination that can affect it. Differences in trains such as difference axle weights, suspension properties and wheel profiles also change the contact conditions. Maintaining an optimum level of contact conditions leads to industry wide benefits as passenger safety is increased and running costs reduced.

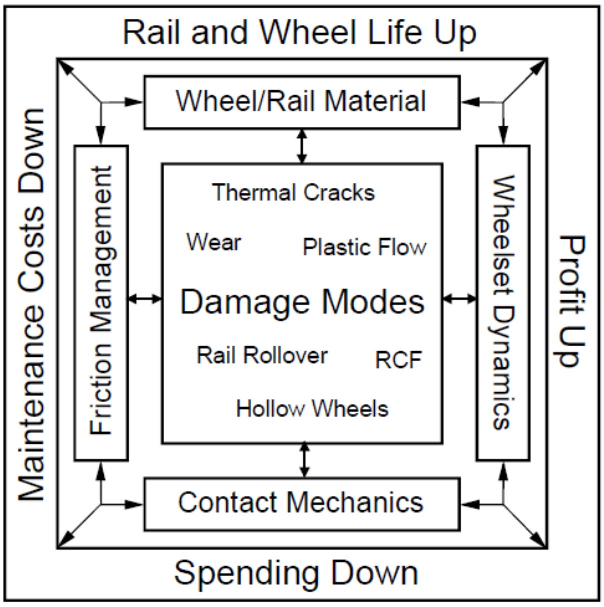

Figure 1- Wheel-rail interface systems diagram [1]

Figure 1 [1] highlights how the diverse aspects involved in the railway influence each other and the importance of considering the entire system when making a change to one aspect. For example, when introducing a new wheel material to reduce wear and increase time between reprofiling, the effect of this new material on Rolling Contact Fatigue (RCF) has to be taken into account as well.

1.1.1 Aim of Paper

This paper will focus on reviewing research that is currently published with regard to Top Of Rail Friction Modifiers (TORFM). Initially a short overview of the wheel-rail contact will be presented in order to put the research into context. Then all third-body substances will be discussed as the rail will rarely (if ever) be clean in the field and so the interaction between any applied product and what is on the rail already is an important aspect to consider. During the review of existing TORFM research, any gaps in knowledge and ideas for further work will be identified and explored. Friction modifiers were originally developed to overcome squeal and corrugation issues in Vancouver during the 1980's [2]. They have since been shown to have a number of other benefits, but how to optimise these benefits still needs to be investigated. An overview of different testing scales, from small-scale bench top rigs through to field trails, will also be discussed as understanding the suitability and limitations of different testing scales is an important area when assessing the results of any experimental research.

1.2 Friction, Creep and Damage Mechanisms

Friction is the force that resists two bodies in relative motion and therefore occurs everywhere in the world around us. The coefficient of friction is the ratio between the friction force and the normal force holding the surfaces together. The term traction is given to the force that generates motion between a wheel and a surface, and the coefficient of traction is the ratio between traction force and normal force.

According to shakedown theory (described in section 1.2.3) as friction increases in the wheel-rail interface, plastic deformation increases, leading to a greater rate of strain accumulation and greater RCF/wear. This is shown clearly in the shakedown plot (Figure 7) which will be discussed further in a later section. Life of components can be extended by introducing lubricants (often liquid but solid lubricants do exist) which provide a low shear strength layer to reduce friction between two surfaces in motion. There are three distinct regimes that occur in liquid lubrication [3]:

- Boundary Lubrication- constant contact between surfaces despite the lubricant being present. This means the laws of dry friction apply
- Mixed Lubrication- partially separated surfaces with some asperity contact
- Hydrodynamic Lubrication- surfaces are fully separated by the lubricant layer

Figure 2 shows a standard stribeck curve which shows how the three different regimes have clear differences in the coefficient of friction.

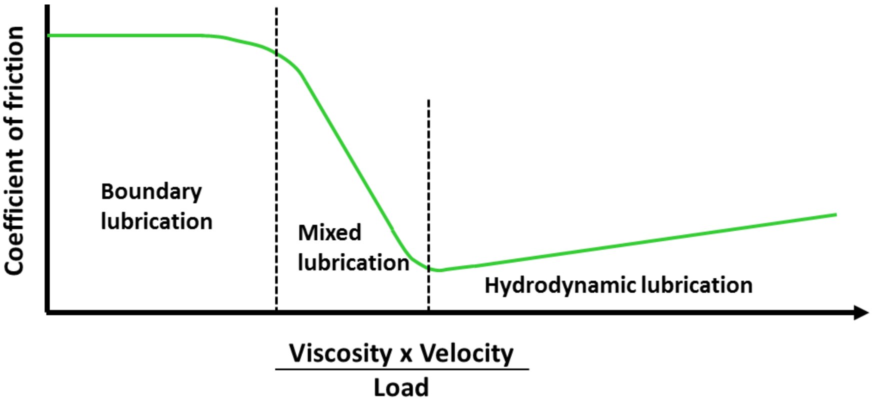

Figure 2- Stribeck curve showing the different lubrication regimes [4]

When the rail is contaminated by oil or is fully lubricated with grease it typically operates in the hydrodynamic region with the level of friction determined by the shear stress of the lubricant [5]. When the rail is wet it is in the boundary lubrication with an associated high coefficient of friction caused by asperity contact. Understanding which lubrication regime the contact is operating in can aid in understanding the results from testing, and how to change the contact properties to optimise friction. For example, the fact that oil contaminated contacts operate in the hydrodynamic region explains the creep curves in Figure 4. This is particularly important in top of rail products, where sufficient levels of adhesion are required for traction and braking, so alternative solutions to traditional lubrication are required.

1.2.1 Creep

Creep (γ) is used as a measure of how much slip there is in the contact usually expressed as a percentage of the vehicle velocity. Slip occurs due to tangential forces in the trailing area of the contact. Creep curves which plot traction coefficient against creep can be used to evaluate different contact conditions. Full slip usually occurs in a dry contact at creep values of 1-2%, but there are many factors which can affect the creep curves such as humidity, contamination etc. Figure 3 shows that as the tractive force increases the slip region in the contact increases, and the stick region reduces until a maximum value where there is no stick region at all and the contact is in full slip.

Figure 4 displays data from experimental work carried out in 2008 which used a twin disc machine to simulate different contact conditions [6]. This work shows the effect of different contaminants on the creep curves and illustrates the dramatic effect that these contaminants can have on the traction coefficient and hence the traction level.

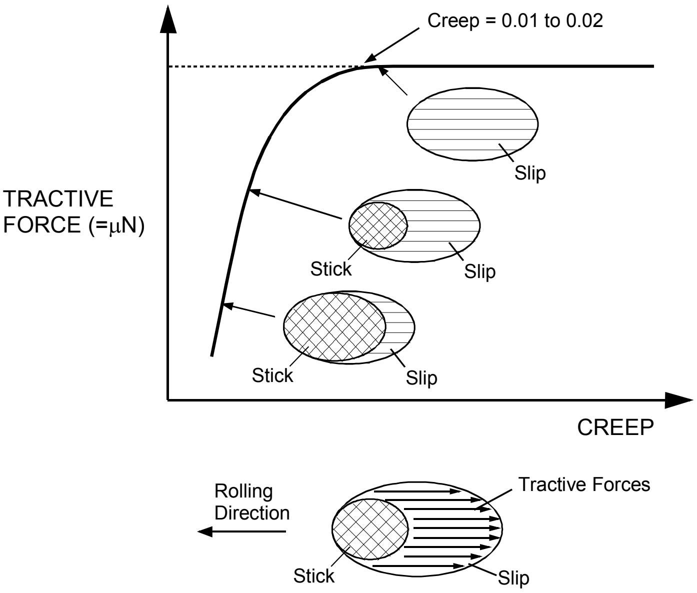

Figure 3- Relationship between traction and creep [7]

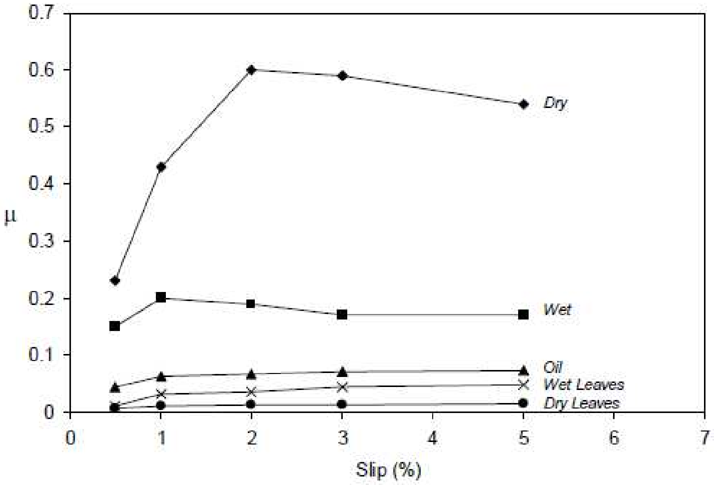

Figure 4- Creep curves for simulated contact conditions [6]

1.2.2 Wear

The wear of a material depends on the tribo-system as a whole. The system not only includes the material properties and stresses the contact is under, but also other factors such as environmental conditions and contamination of the contact. Wear can occur by a number of different mechanisms, the main mechanisms which can cause wear in the wheel rail contact:

- It is an open system which means there is a plentiful supply of oxygen to cause oxidative wear
- Contamination by hard, solid particles such as sand can cause abrasive wear
- Thermal wear occurs due to the rise in temperature caused by friction in the contact. This can increase the severity of the other mechanisms by causing a reduction in hardness.

Wear maps for a material can be created which help in the analysis of wear data. The maps are usually defined using slip or contact pressure. They are mainly used to define further areas of testing as the data used to create them is usually limited [8]. Figure 5 shows a wear map with typical contact conditions overlaid onto it. It shows that rail gauge/wheel flange contact results in more severe wear which matches field observations.

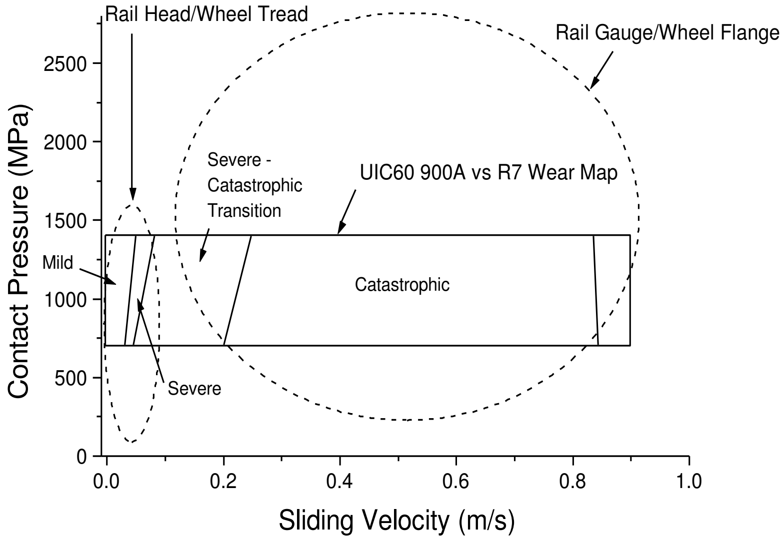

Figure 5- Wear map displaying wheel/rail contact regimes [8]

1.2.3 Rolling Contact Fatigue

Rolling contact fatigue (RCF) is the accumulation of fatigue damage caused by many passes of wheels, resulting in cracking on wheels and rails. Each wheel that passes a particular point on the track exerts a load cycle as the wheel approaches, passes over and continues down the track from the particular point. RCF leads to maintenance requirements (rail grinding, regular Non-Destructive Testing) which is costly but prevents safety issues, as missed cracks can grow quickly and lead to rail breaks. Figure 6 shows a typical head check defect (a form of RCF) on a real rail.

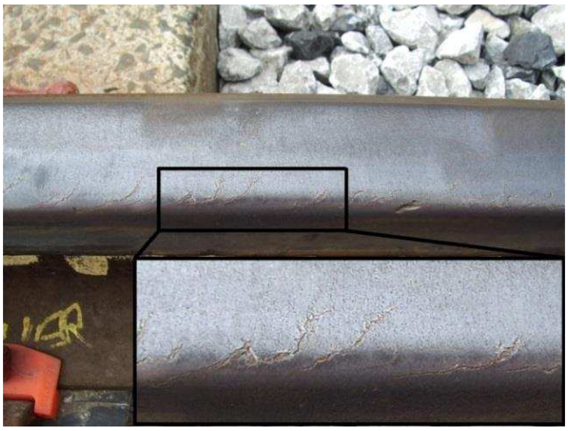

Figure 6- Visual appearance of head check defect type[9]

In pure rolling the maximum shear stress occurs below the surface of the material. As a tractive force is applied then shear stress increases and the location of the maximum stress moves towards the surface. At the surface there is less material surrounding the maximum stress to dissipate the stress and so more plastic deformation occurs here. Due to the rolling/sliding nature of the contact a cyclic build-up of plastic deformation occurs which is the origin of RCF and wear. The shakedown map (Figure 7) shows reducing the friction can lead to an increase in load factor without the material entering the dangerous ratchetting region [7]. Ratchetting can lead to large strains accumulating until a crack is initiated if the stress is subsurface or wear debris is created if the stress is at the surface.

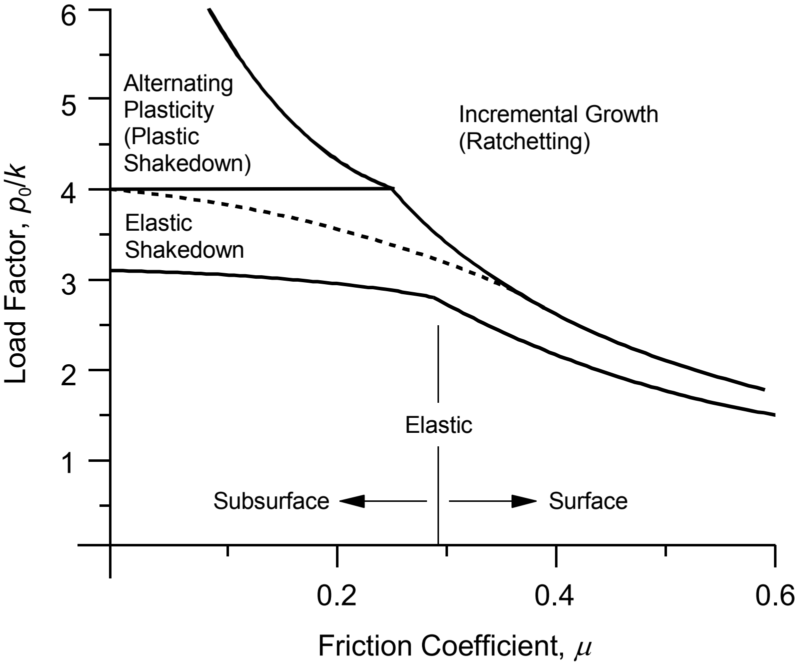

Figure 7- Shakedown Plot [7]

Wear and RCF are both caused by the gradual accumulation of plastic deformation. Depending on material/wheel combination will lead to different rates of wear and crack growth; if a particular train causes severe wear but has a small effect on crack growth then the length of cracks in the rail will actually decrease. Currently, all relationships between RCF and wear are experimentally based with the typical wear depth per wheel pass is 1nm. Figure 8 illustrates how wear truncates a crack.

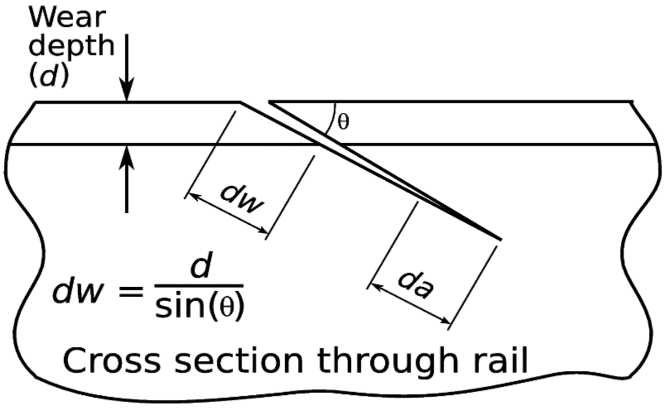

Figure 8- RCF/wear interaction [9]

1.3 Third-Body Materials

In most engineering applications contact areas are in closed systems where the sources of contamination can be carefully controlled. This is opposite to what occurs in the wheel-rail interface where the open system means there are many different sources of contaminant and environmental conditions can vary in relatively short temporal or spatial intervals. In this paper contaminants mean any material that is unintentionally present on the rail or wheel. The contaminants mix with the oxide layer found on top of rails to create a third-body layer and so depending on what contaminants are present can lead to different third-body layers being present. Track circuits detect a train when the train's wheelsets 'short' the track circuit by providing an electrical path between the two running rails; if the third-body layer isolates the wheelset then train detection can fail, resulting in a potential dangerous situation [10].

This paper has split the most popular materials into two distinct categories: naturally occurring substances and applied substances to manage the friction level. If the friction level becomes too low, the safety of the train network can be compromised by trains passing signals at danger or overshooting station stopping points and can also lead to wheel slippage. If the friction level increases too much then the efficiency of the industry decreases due to factors such as an increase in fuel consumption. Friction is a system parameter so what works on one area or operating conditions may not be applicable across the network.

1.3.1 Naturally occurring substances

The main substances generally considered are leaves, oxides, solid particles and water from rain or dew.

Leaves can fall directly onto the track or be sucked onto the track by the aerodynamics of passing trains [11]. Once on the rail the crushing and compression of the leaves results in a black lubricant strongly adhered on the rail resulting in issues with braking, accelerating and track circuit isolation [12]. This black layer is the product of a chemical reaction between the bulk rail material and the leaves [13]. Often the effects of the leaf layer is counteracted by applying sand which helps remove the layer improving electrical contact as well as providing more traction [14]. Wheel slip can also lead to an improvement in adhesion when a leaf layer is present as the wheel slip helps to remove the layer without some of the negatives of applying sand [14].

Solid particles will initially be crushed into smaller fragments by the contact pressure as a wheel passes over it, then some of the particles will be ejected from the contact whilst others will form a particulate agglomerate with steel wear debris and even become embedded into the rail or wheel [1], [15]. The solid contaminants can be a variety of things: sand, crushed ballast, soil debris. Particles such as grit salt which is used to prevent ice formation on the roads during the winter months can find its way into the contact [16]. This grit increases the formation of the oxide layer (increasing the severity of its effects), in dry conditions the salt acts as a solid lubricant to reduce traction and in wet conditions can increase corrosive pitting.

A thin film of moisture is often present on the rail either through rain or from dew. A wet rail has been shown to lower the wheel-rail adhesion level, an example is displayed in Figure 4 [6]. This low adhesion has a negative effect to train operation, data from 2014 has shown that there is an increase in the number of station overruns during the hours when dew is expected to be present on the rail (early morning and late evening) [17]. Another detrimental effect of this layer is actually through an increase in RCF. This is because the water is forced into a crack, lubricating the faces and the compression of the crack causes the water to be forced into the tip creating a widening (mode 1) of the crack [15]. There have been studies to investigate if using a hydrophobic top of rail product would reduce the effect of this contamination [18]; however, it concluded that there was not a convincing case for applying hydrophobic products although there may be some benefit in further investigating their role in suppressing the formation of an oxide layer.

Oxides can form a layer on top of the rail as discussed earlier. This process is heavily dependent on the ability of the material to oxidise, the availability of oxygen and the contact conditions (temperature and humidity). The oxide layer has the effect of reducing the traction coefficient in the contact; the reduction is small in dry conditions but the effect is much greater in wet conditions (a reduction of up to 4.5 times from the reference value). Additionally the oxide layer is removed after many cycles in the dry condition due to abrasive wear, but in wet conditions the layer is removed at a much lower rate [16]. There is great variety in an oxide layer that is formed on the rail due to a variety of environmental conditions that the rail can face from location to location. Therefore it is very difficult to characterise exactly how an oxide layer will behave in a laboratory setting. A recent paper [19] has analysed the third-body layer after performing twin disc testing and found it to consist of iron and iron oxides. Figure 9 shows the optical results of the testing with a 50µm thick layer of oxide on the surface of the disc. The third-body layer in this case is thicker than would be found on the wheel or rail in service use which has been seen to be 15µm thick [20].

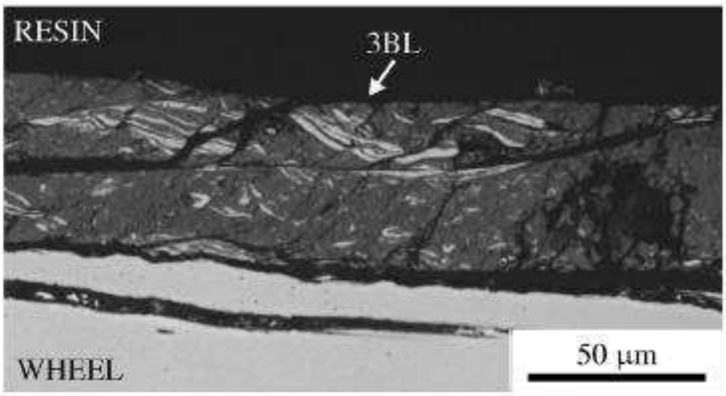

Figure 9- Optical investigation of oxide layer [19]

1.3.2 Applied Substances

Applied substances include anything that is applied to control friction and/or wear in the wheel-rail contact. This substances can broadly be split into grease/lubricants, friction modifiers and traction enhancers. Within these categories there is often confusion in the industry and in academia about what to call certain products, in particular Top Of Rail (TOR) products. A recent paper [4] has attempted to define terms to bring clarity to this issue. From the paper TOR products are classified according to their drying behaviour with non-drying products called *TOR lubricants* and drying products called *TOR friction modifiers.*

Traction enhancers are used solely to improve traction in low slip conditions. Sand is the oldest traction enhancer and is still used all around the world but there are products, often in a gel form, which are also used as traction enhancers. Sand can have a detrimental effect on wear, increasing wear by at least a factor of two via abrasive wear mechansims, and the effect can be even more severe if the sand is wet [21]. Therefore, traction enhancers are only deployed to recover traction if wheel slippage is detected. Modern traction enhancers use steel shot or alumina rather than sand to reduce issues with wear and track circuit isolation [21–28].

Greases and lubricants on the rail reduce the coefficient of friction usually to a level below 0.1, the exact level of friction is extremely sensitive to the film thickness between the wheel and rail, but even small amounts can cause traction loss [29]. Often grease acts in the boundary lubrication regime which means some asperity contact still occurs. Lubricants can be found on top of the rail due to deliberate application to achieve a perceived benefit, migration from gauge face lubricants onto the rail head and even oils dripping from passing trains. The positive impact of lubrication is illustrated by Eurostar estimating that lubrication saves £1,000,000 per year in maintenance and wheel replacement, additionally the American Association of Railroads estimates that wear caused by ineffective lubrication costs in excess of $US 2 billion per year [30].

TOR lubricants provide friction through mixed lubrication regime and can be oil based, grease, or hybrid (a mixture of oil and water) [4]. These products stay ‘wet’ over a long period and have constant transfer between wheel and rail. The products still allow contact between the surface of the wheel and rail and so a slight change in quantity applied dramatically changes the friction level. Oil also has the same effect on RCF as water provided that there is enough time for the oil to seep into the crack, causing it to grow. Additionally it has been shown that in the presence of water and oil mixtures the oil is dominant and traction coefficients are the same as having only oil present [31].

2 Top of Rail Products

A friction modifier differs from a lubricant as it aims to deliver a targeted friction coefficient without negatively affecting the train operations when braking and accelerating or causing surface damage. In top of rail friction modification (TORFM) this is often 0.3-0.4; the upper limit of a friction modifier is so that rolling resistance is not significantly increased, improving energy efficiency of the railways. Current products are water based with a solid suspension; as the water evaporates, the solid particles are left behind in the third-body layer on top of the rail delivering the required friction level. The products are wet near to the applicator and material transfer takes place between the wheel and rail, once the product is dry, there is little material transfer [4]. Solid friction modifiers do exist as well which are made of an easily sheared material to aid material transfer. There can be issues with increased wear due to indentation and scratching if the solid particles are too large which means extensive analysis is required in order to optimise toughness, hardness and size of the friction modifier's solid particles [50, 51]. There are two products that are called friction modifiers that are used on the top of rail on the UK rail network. They are Keltrack, which is a water based product and as such is a TORFM and Railguard which is an oil based product and so is a TOR lubricant.

Friction modifiers eliminate the negative gradient on creep curves; this is because if a negative gradient exists then for a given adhesion level there are two separate creep levels. This creates an oscillation between the two creep levels which leads to increased damage and squealing.

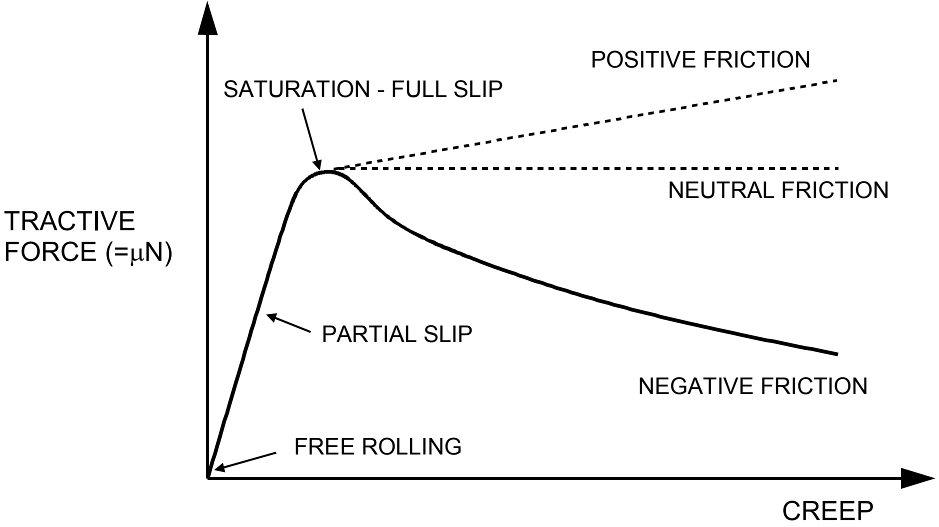

Figure 10- Behaviour of Friction Modifiers [1]

Figure 10 illustrates the effect that different products can have once full slip has been reached:

- Friction modifiers, sometimes called high positive friction modifiers (HPF). These substances provide neutral friction creep characteristics [34]
- Traction enhancers, sometimes called very high friction modifiers are used to increase adhesion in the contact especially when braking and display positive friction creep characteristics

It is important to define different levels of adhesion in order to better understand the effect of different contaminants. The following definitions have been taken from recent work [35]:

- Medium low: $0.1 < \mu < 0.15$
- Low: $0.05 < \mu < 0.1$
- Exceptionally low: $0.02 < \mu < 0.05$

2.1 Application, amount required and carry-down

Friction modifiers can be applied via trackside applicators or from train mounted systems [36] which are popular as no access to the tracks is required and the amount of friction modifier used can be more easily controlled. Trackside applicators have issues associated with environmental conditions (temperature/humidity) which could affect the product (e.g. separation of product in storage tank). The solid stick versions are applied via a spring loaded device on the train and form a film on the wheel which is then transferred to the rail. Currently the practice of how best to deliver the friction modifier to the contact is often based on experience and judgement rather than a theoretical basis supported with experimental evidence. This is starting to change as more experimental research is published and the industry seeks to optimise it’s processes.

A full-scale rig study which used Keltrack (a water based suspension) applied via a spray atomiser found that the FM applied every 250 wheel passes had the same effect as applying it every 50 passes and applying it every 500 passes only had a partial effect compared to the dry conditions [37]. This conclusion supports the earlier field test conclusion that there is an optimum amount of FM and also showed that increasing application of FM beyond this limit has no benefit. This conclusion is further supported by a Japanese paper which looked at subway lines in Tokyo and twin roller tests [38]. This paper found that during twin roller tests there was no difference in creep characteristics after a 0.4s spray and a 1.0s spray whereas there was a difference when compared to a 0.2s spray. The same paper made some observations based on a field trial. It concluded that both trains spraying friction modifier onto the low rail was the most effective configuration when changing between one or two trains spraying the modifier and between spraying either rail or both.

Carry-down can be defined as the distance from application point over which the product is found to have a noticeable effect on the friction characteristics of the contact. Field testing has shown that a TOR material can produce a 35% reduction in lateral force (with associated decrease in wear and RCF) at 2 miles down the track from the application point [39]. Additionally carry-down is affected by the amount of FM applied, however Eadie et al. [40] there is an optimum amount beyond which increasing the amount of FM has no effect on the carry distance. In North American heavy haul railways TOR friction control is already well implemented [40]. This paper describes implementation strategies as well as noting that in one traffic direction there is little evidence of product carry. This leads to the conclusion that the product mainly remains on the wheelset rather than being continually transferred between wheel and rail.

There have been papers looking at carry down of lubricants, how they are picked up by wheel, performance of different applicators [41–43]. Similar research for TORFM has not been carried out and is currently an area where there is scope for new research.

Water based friction management products have been shown to be vaporised quicker in high contact temperature scenarios (high axle loads, hot weather, tight curves etc.) [44]. This research was carried out on a pin-on-disc machine, but the effect of this quicker vaporisation on performance, carry down etc. has not been explored using more realistic conditions.

2.2 Testing Standards

Currently there is no testing standard for friction modifiers although the European Committee for Standardisation (CEN) are currently developing a standard to encompass all friction management products. BS EN 15427 [45] is a standard relating to application of flange lubricants, but there is no equivalent for application of friction modifiers. BS EN 16028 [46] is a standard for lubricants and within it, Annex L, there is a section for solid stick testing using twin-disc machine which could be used for solid stick friction modifiers although there is no mention of friction modifiers in the standard. There are also gaps in the standard, for example there is no specification for pre conditioning the discs or for cooling the discs during running. This means repeatability of results is hard to gain between different users using the same products and this standard.

There is a Network Rail standard which defines the minimum requirements for rail curve lubricants [47]. The standard details the properties of the lubricant as well as specifying two laboratory tests to analyse the lubricants pumpability and wear/retentivity properties. Although these tests and the minimum requirements are for curve lubricants, a similar process and testing philosophy could be applied to friction modifiers.

2.3 Effect on RCF and wear

Friction modifiers primarily aim to reduce RCF and wear, therefore reducing maintenance requirements and improving safety. Friction modifiers achieve this reduction by improving steering in curves and hence, reduce lateral forces. A study using a full-scale rail-wheel rig showed that after a small initial increase in wear, rails applied with a FM had no further wear compared to dry tests which wear continued throughout the test [37]. The same study found no cracks after running the tests in the rails applied with FM, compared to the dry rails which had cracks visible to the naked eye after half the running distance of the tests. The same conclusions have been found by field testing using a heavy haulage line in China [48] and in America [49].

Twin disc testing has shown that with gauge lubricants, increasing surface roughness decreases retentivity and decreasing retentivity leads to increases in wear [50]. It is thought these relationships are driven by crack pressurisation of the liquid lubricant and so TORFM should not have the same relationships once they have “dried” although there is currently no literature found which looks at his relationships with TORFM.

As RCF and wear has been shown to reduce with using a premium grade rail [47- 48] and using a FM reduces RCF and wear even further; optimising both of these parameters can produce very low wear rates and very little RCF.

2.4 Effect of the Third-Body layer on FM

Understanding of the effects of the third-body layer on the performance of FM is important as the rail will very rarely be clean in the field. A study on the effect of an artificially created oxide layer using a pin on disc and disc on disc apparatus concluded that a FM is still effective under wide range of oxide contamination on the rail head [53]. The same study also looked at the effect of grease on the performance of FM. It determined that grease affected the FM by disturbing the film adhesion to the surface and reducing the friction level; however, it did show that there was still an increase in friction coefficient with a FM present and so displaying that the FM can cope with light grease contamination. This study was the only work found which looked at FM’s interaction with other substances.

Another study using pin on disc looked at the temperature, humidity and oxide contamination on the performance of friction modifiers [54]. It showed that the humidity had an obvious effect on the retentivity and the friction levels of the FM. It also showed that the levels of oxide present made a difference as well.

2.5 Other effects

Almost all the field studies reviewed [55]–[60] showed that a TORFM reduced the noise of a train on straight track and also in subsequent curves due to a reduction in roll-slip oscillations by reducing lateral/flanging forces. The studies also concluded that FMs are an effective method of reducing all forms of rail corrugation and in particular rutting. There have also been reports of reductions in low frequency vibrations observed when a FM is applied. This suggests that the benefits of applying friction modifiers extends beyond simply the wear and RCF and also applies to the whole industry rather than specific vehicle types. This is supported by an evaluation of field trials in Europe and Japan [61] which looked at a variety of studies on the effect of FM on short pitch corrugation growth. It concluded that the studies had included a large variety of contact conditions that showed a universal reduction in corrugation when FM was applied when compared to no FM present. This infers that the effect of FM is not limited to just one type of vehicle or configuration but its benefits are universal across the industry.

Fuel consumption of a train would be reduced due to reduced rolling and curve resistance when using a TORFM [39, 61]. One study has estimated that 81 litres of diesel could be saved with an application of 1 litre of a TOR lubricant [60], this figure was attained via scaling from a laboratory test and so it is unknown how accurate this figure is. A passenger would also feel a benefit due to a reduction in the noise and vibration of the vehicle they are travelling on. These benefits are also apparent with gauge face lubrication [62].

A field study of a passenger transit system showed no negative effects of friction modifiers on traction or braking [63]; however, it has been noted that one German railway experienced braking issues at some application sites with a TOR product [64], it is unknown if this was an TOR lubricant or TOR friction modifier.

Friction Modifiers have also been shown to have no effect on track isolation [65]; this study used a twin disc tester and static test and neither showed a difference in measured impedance during the application of a FM. This is important as introducing new materials into the industry can cause questions about safe running of the trains and so the lack of effect of the FM on impedance is a positive factor.

Applied products have been shown to reduce the number of coarse particles into the air by up to 95% depending on which product is used [44] due to a shift from dry contact to boundary lubrication as well as some particles becoming trapped into the product. Grease and TOR lubricant were shown to also decrease ultrafine particles, but water based FM increased the levels of ultrafine particles. These tests were carried out on a pin on disc machine which is not wholly representative of wheel-rail contact, further tests should be carried out to confirm these conclusions.

2.6 Modelling of Effects

One of the easiest ways of modelling the effects would be to use the T-gamma approach. This method has wear and fatigue combined in a single parameter referred to as damage. It also relies on correlations between certain T-gamma numbers and the wear/fatigue performance found on the track which can often be an issue if new rail steels are introduced for example.

The wear number is representative of the energy consumed in the contact patch but it does not differentiate between different forms of energy (wear, heat, noise etc.). The wear coefficients rely on experimental data from rolling/sliding tests which have been well researched for dry contacts, but there are some tests now which are using wet contaminated contacts [66]. However, there is still limited experimental data for friction modifiers. One paper which has produced friction modifier wear data [67] has published data for both small scale twin disc testing and full-scale rig tests.

Modelling the effects of friction modifiers on contact conditions is important when carrying out rail vehicle dynamic simulations. An evaluation of the NUCARS computer programme for simulating the effect of FM has been carried out [68]. NUCARS allows the user to specify a percentage of Kalker coefficient which best applies to their FM/lubricant characteristics. However, as creepage/force characteristics are difficult to obtain in the field due to current portable tribometers not producing reliable data, and the results of the simulation being very dependent on the kalker coefficient the results of the simulations cannot currently be trusted.

Within friction force modelling, the Extended Creep Force (ECF) and CONTACT models have the capability to model the effects of friction modifiers. There is also the Popovici model [69] which is able to model lubricants in the mixed lubrication region but adaptations would need to be made to handle solid interfacial products such as FM.

CONTACT [70] was originally a simple half space based model, but has been recently extended to include a third-body layer, the elastic properties of which can be adapted, and included a falling friction law. However, its computational effort is still high and is not as widely available or as suitable for multi body simulations as other models. Including a third-body layer is a recent development and therefore there is currently no research which validates how well the model predicts the effect of the third-body layer.

The ECF [28, 29] model is an extension of the Tomberger model [73] which itself extended FASTSIM [74] to make it more applicable to wheel-rail contact and UK conditions. However, it is not fully published, but has been validated against railway operations. It has High Pressure Torsion (HPT) tests built into the inputs to characterise the behaviour of the third-body layer [75] and has been shown to increase the prediction quality when compared to other creep force models [71].

3 Testing method and scales

There are many different scales of testing in order to analyse the wheel-rail contact ranging from simple table top simple tribometers to field testing. Choosing the appropriate test methodology is a trade-off between many factors including cost, complexity and control. It is usually the case that the simple test rigs are able to give results from specimens reasonably cheaply and quickly compared to more complex methods at the expense of accurately portraying the system being analysed. Increasing the complexity of the test methodology to representative test conditions not only leads to the increase in costs and time but control over the individual parameters being investigated is lost, introducing a source of error into the investigation. Using real rail material cut out to form specimens to put into smaller test rigs is one way of being able to compare full-scale field tests to smaller scale laboratory experiments [8]. The main differences between the different scales often becomes from the difference in environmental control.

An example of how different test scales can interact is a study that attempted to correlate ball on disc with full-scale rail performance tests using the Transportation Technology Centre Inc. (TTCI) test track loop [76]. One of the issues faced was that the wear data was reported using different units (depth of wear track for ball on disc and total area loss for full-scale test), once this was overcome by getting the wear data from ball on disc experiments in total area loss the two sets of data could be compared. It showed that there was a good correlation between the two scales with the ball on disc providing a pre-screening of rail performance to select the best materials to take forward to full-scale test.

Studies have started to look at the differences between the different scales used when evaluating rail contact conditions. It has been shown in a small study that there is a reasonable correlation between small scale and full-scale results [8, 63].

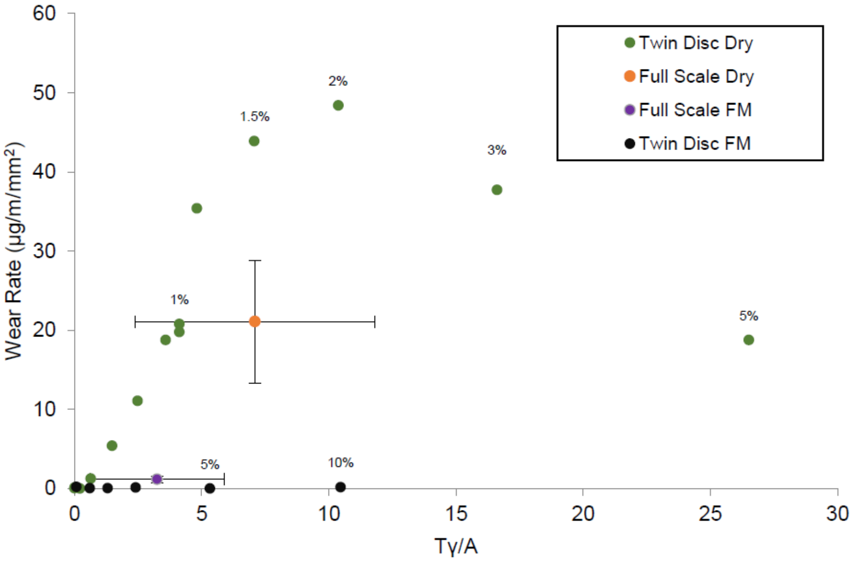

Figure 11- Tγ/A Wear Rate Data Twin-Disc / Full-Scale Comparison for Dry and Applied Friction Modifier Conditions [67]

Figure 11 is from a paper comparing two different test scales- twin disc and full-scale [67]. It illustrates a T-gamma approach can be used to compare different test rigs

Full-scale tests and twin disc tests have been shown to provide the same performance ranking of different greases [62]. This shows that even if the exact values are different, the small scale tests do provide useful qualitative data. Other studies have also found that whilst the same trends are observed the exact values can differ greatly between full-scale rig tests and actual field trials [52]; this could mainly be due to the lack of control over what is on the rail in field trails. It has been noted in one study [37] that the FM used was seen to build up on the test rail, something which has not been noted from field observations. This illustrates the difference between carrying out a test on the same short section of rail at similar contact and environmental conditions compared to what actually occurs in the field.

Adhesion levels in twin disc testing are within the range that are known to occur in the field as seen in Table 1 [6]. This shows that this approach is suitable to compare adhesion levels for a variety of conditions. Conversely twin disc tests involving contaminants, for example sand, are often more severe cases then would be met in real application. This is due to the contaminant being more easily entrained into the contact as there is no surrounding air current and the point of application is much closer to the contact [67]. This means that these sort of tests are only really useful as qualitive tests between different contaminants/products rather than investigation into real application values.

Author	Test Apparatus	Load (kN)	Rolling Speed (km/h)	Test Condition	Peak μ	Slip at Peak μ (%)	Stable μ (5% Slip)
Zhang et al. (10)	Full-scale rig	44	10-70	Dry	0.5-0.57	2	0.5-0.57
		67	10-70	Dry	0.44-0.55	1-2	0.44-0.52
		44	120-240	Wet	0.07-0.13	0.5-1	0.065-0.12
		67	80-240	Wet	0.05-0.11	0.5-1	0.05-0.105
		67	140-300	Oil	0.045-0.055	1	0.044-0.052
Jin et al. (20)	Full-scale rig	135	140-300	Oil	0.04-0.05	1	0.037-0.048
Harrison et al. (21)	Push tribometer	Unknown	Unknown	Dry	0.52	1	0.5
				Dry	0.7	2-5	0.7
Nagese (7)	Instrumented bogie on test vehicle	Variable	Variable	"Dry"	0.2-0.4	Unknown	Unknown
				Wet	0.05-0.2		
				Oil	0.05-0.07		
				Leaves	0.025-0.10		
Present Study	Twin-disc	7.7	3.54	Dry	0.6	2	0.54
				Wet	0.2	1	0.17
				Oil	0.07	1	0.06

Table 1- Table showing comparison of traction coefficients derived by a variety of test methods [6]

4 Grading of Research

In order to gauge the current status of research in this area a grading system has been created, scoring each reference according to a set of criteria. This methodology has been used before in industry reports [77]. It is important to note that the criteria focusses on the research's validation and scaling from laboratory to the field, rather than a fundamental assessment of the research. Review papers and textbooks have not been included in this evaluation of the research. This review is focussed on TORFM but other products have been included to allow a comparison of research focus across the rail industry, although there is plenty of research not included with regards to general wheel-rail contact. The seven criteria are:

- *Peer reviewed publication.* This determines if the research is good enough to have been accepted by the author's peers.
- *Conclusions evidence in paper.* This determines if the conclusions in the paper is supported by results within the research.
- *Theory supported by testing.* This determines if the theory presented is supported by testing or modelling.
- *Testing supported by modelling.* This determines if the testing carried out has been supported by models and vice versa.
- *Scale test.* This determines if the testing has been carried out on small scale test rigs to simulate the contact and gain control over specific variables.
- *Full size test.* This determines if the testing has been carried out using a full-scale test rig to simulate the contact.
- *Real world measurements.* This determines if there has been testing carried out/measurements taken during live operation of the railways.

The research is marked against the criteria above and categorised into A, B or C. Category A research fulfils at least 70% of the criteria, category B research fulfils at least 45% of the criteria and Category C research fulfils less than 45% of the criteria. Each reference is also assigned a primary and secondary group according to the main focus of the research:

- *Wheel-rail contact* covers dry contact research. The *modelling* section covers research which deals with modelling of the wheel-rail contact and the *tribological effect* section covers research that has looked at the tribology of the contact using physical testing.
- *Traction enhancers* covers all research which has focussed on traction enhancers such as sand or traction gels. This category is further split into *modelling, practical considerations* (covers such things as track isolation, pick up of product, carry-down of product) and *product performance* (covers such things as retentivity, RCF and wear damage, friction performance etc.).
- *Friction modifiers* covers all research which has focussed on friction modifiers. This category is also further split into *modelling, practical consideration* and *product performance.*
- *Grease/lubricant* covers all research which has focussed on greases or lubricants. This category is also further split into *modelling, practical consideration* and *product performance.*
- *Contaminants* covers all research which focusses other things that effect the wheel-rail contact and aren't covered in the above categories. These things include oxide layers, leaves, oil etc. This category is further split into *tribological effect* and *modelling.*

Clearly this procedure will differentiate the well validated (using a number of different test scales) research, from research which has only been carried out on one test scale and could be an area for future work. A paper which is in a peer reviewed journal, presents conclusions supported by evidence in the paper, puts forward theory that is supported by modelling, includes a scaled test, a full-scale test and real world measurements would give industry confidence that the conclusions of the paper are accurate. Whereas a paper which only uses a scaled test to support a theory is less robust. It should be reiterated that research is categorised according to the criteria detailed above and is not a criticism of the research in general.

The full table detailing the grading of each individual reference is included in Appendix A. The chart displaying the results of the grading is shown in Figure 12. It is important to note that this paper has focussed mainly on friction modifiers and so there is a large body of research on lubricants and dry wheel-rail contact that is not included here. It is immediately obvious that most of the research is in category B with only two of the papers assessed being given category C. This is mainly due to only one scale of testing or one method used in each assessed piece of research. The research that is categorised A is mainly because it has used other scales or modelling to support the initial findings of the research. The small number of category A research illustrates that there is a lot of work to do to relate lab work to the field and vice versa. There are also a comparatively large number of papers that focus on modelling of the wheel-rail contact, but the modelling of contaminants or applied products is an area where there is a large gap in the research found. This is thought to be due to the complexity of including a third-body into the modelled contact and the associated computing cost involved.

For friction modifiers the research to date has mainly focussed on the performance of the products. Although more recently research has started to be published which focusses on the practical considerations involved, this is still an area where more work could be done to ensure the full benefits of these products are realised. Additionally, due to the number of different product philosophies (as discussed in section 1.3.2 above) there seems to be very little understanding of the fundamental properties behind how each of the different products work and produce the benefits described in the literature. Looking at Figure 12, it appears as though there are more papers that concentrate on friction modifiers compared to other products. Part of this is because this paper has focussed on friction modifiers more and so has covered this area more extensively, but this is also due to the variety in products called friction modifiers. This means there is more scope for research as the variation in products that work in different ways, requires more work to fully understand how the products function, and the benefits they bring. This can be compared to traction enhancers/lubricants which have a set of standards that any new form of these types of products must meet in order to be used on the rail network.

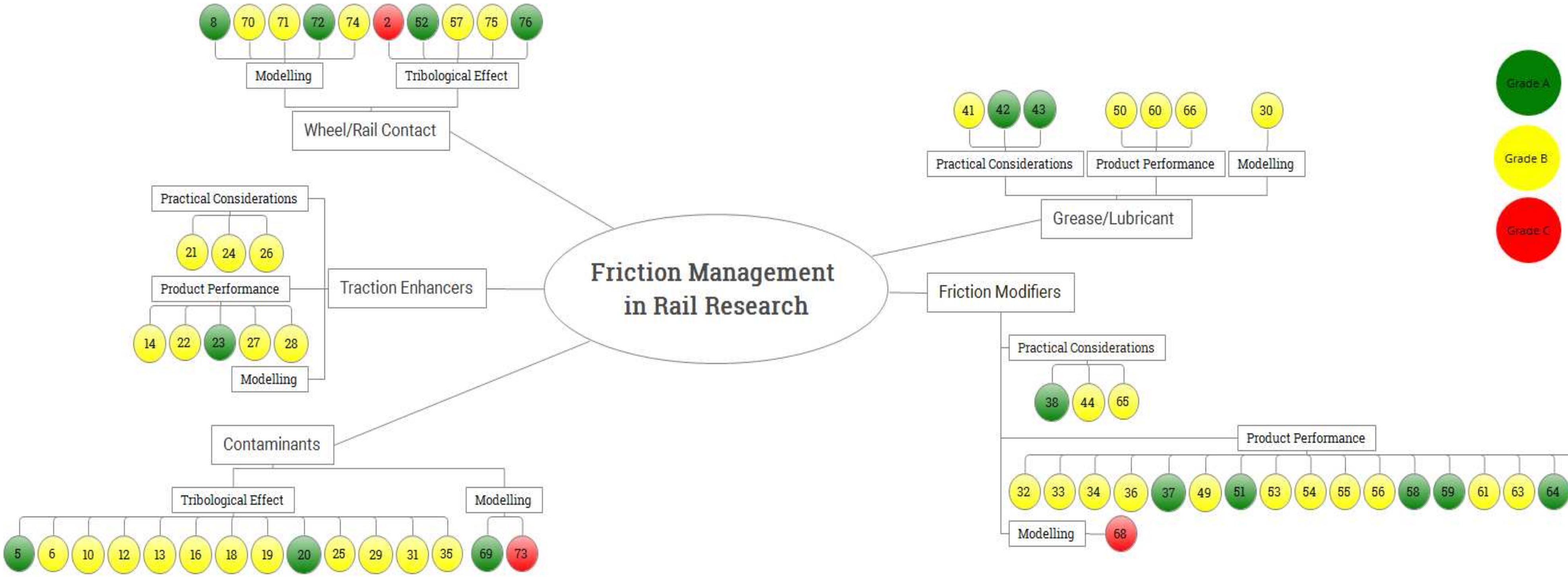

Figure 12- Summary of grading of research

5 Summary

A recent report by a Vehicle Track Systems Interface Committee (VT/SIC) [78] highlighted that an optimised coefficient of friction was a positive area of development and could start by better understanding of the conditions within the contact patch. The areas that affect this behaviour are many and include third-body layers, temperature and relationships between regions of stick and slip in the contact. The findings in the report are supported by the analysis of the quality of research in the previous sections which has highlighted that much of the research is of 'average' quality and that there is less research into the practical considerations of the products.

One criticism of the much of the academic literature on the subject of friction modifiers is that there are not many research studies which focus on how much product is required or where to apply it to achieve the benefits that much of the research has found. The main benefits of reducing RCF and wear as well as the secondary benefits of reducing noise and vibration are well documented; however, there are significant gaps in knowledge when trying to understand the behaviour of the friction modifier for use in the field. For example, understanding how far down the track the effects of applying the product lasts for is an important consideration when attempting to choose where and how often to apply a product. Another important consideration is the effect of contamination of the friction modifier. This review has only found one paper which looked at the interaction of FM with grease, but research looking at other forms of contamination such as sand or the interaction with different oxide layers is currently lacking. The most recent papers do start to tackle these issues which shows that the academic research is starting to focus on the gaps in knowledge. Friction modifiers is a term applied to a lot of different products which are fundamentally different and work in different ways. This has led to confusion and some papers claim to report results for friction modifiers when in fact the product that is tested is actually a top of rail lubricant. Recent publications [4] have attempted to clarify this issue and it is hoped that in the future the industry will have a clearer understanding of the different products and how they function.

How the different scales of testing compare to field conditions is another area which there is scope for more research in. If the relationship between the different scales is fully understood then it would help answer the questions in the previous paragraph as the representative, smaller, faster, cheaper tests can be carried out to ascertain certain factors and focus the more expensive, slower testing scales. This research into scaling would also help with the development of testing standards (there are currently no standards for how TORFM should behave, although CEN is currently working on developing them).

From the evidence presented in this review there are a number of areas to focus further research on:

- Understanding the mechanisms by which friction modifiers function
- Assessment of fundamental product properties and modelling of how they relate to product performance
- Understanding of transferability of laboratory results to the actual, real world contact
- Bench mark tests to assess performance based on available test platforms across a range of scales
- Optimum application methods and amounts for different operating scenarios

By linking all these areas of research together, recommendations can be made on appropriate use of products across a range of operating scenarios. Thus ensuring an optimum amount of the correct product to achieve the desired aim is delivered without negatively effecting other aspects of the industry. This would ensure a more efficient and reliable industry.

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Appendix A

Reference Number	Primary Category	Secondary Category	Criteria							Total Score
			1	2	3	4	5	6	7	
2	Wheel-Rail Contact	Tribological Effect	Yes	No	Yes	No	No	No	Yes	3
5	Contaminants	Tribological Effect	No	Yes	Yes	Yes	Yes	Yes	No	5
6	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
8	Wheel-Rail Contact	Modelling	Yes	Yes	Yes	No	Yes	No	Yes	5
10	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
12	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
13	Contaminants	Tribological Effect	Yes	Yes	Yes	No	No	No	Yes	4
14	Traction Enhancers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
16	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
18	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
19	Contaminants	Tribological Effect	Yes	Yes	No	Yes	Yes	No	No	4
20	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	Yes	5
21	Traction Enhancers	Practical Considerations	Yes	Yes	Yes	No	Yes	No	No	4
22	Traction Enhancers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
23	Traction Enhancers	Product Performance	Yes	Yes	Yes	Yes	Yes	No	No	5
24	Traction Enhancers	Practical Considerations	Yes	Yes	Yes	No	Yes	No	No	4
25	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
26	Traction Enhancers	Practical Considerations	Yes	Yes	Yes	No	Yes	No	No	4
27	Traction Enhancers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
28	Traction Enhancers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
29	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
30	Grease/Lubricant	Modelling	Yes	Yes	Yes	Yes	No	No	No	4
31	Contaminants	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
32	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
33	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
34	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
35	Contaminats	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
36	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	No	No	Yes	4
37	Friction Modifiers	Product Performance	Yes	Yes	Yes	Yes	No	Yes	No	5
38	Friction Modifiers	Practical Considerations	Yes	Yes	Yes	Yes	Yes	No	Yes	6
41	Grease/Lubricant	Practical Considerations	Yes	Yes	Yes	No	No	No	Yes	4
42	Grease/Lubricant	Practical Considerations	Yes	Yes	Yes	Yes	Yes	No	No	5
43	Grease/Lubricant	Practical Considerations	Yes	Yes	Yes	No	Yes	No	Yes	5
44	Friction Modifiers	Practical Considerations	Yes	Yes	Yes	No	Yes	No	No	4
49	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	No	No	Yes	4
50	Grease/Lubricant	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
51	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	No	Yes	Yes	5
52	Wheel-Rail Contact	Tribological Effect	Yes	Yes	Yes	No	No	Yes	Yes	5
53	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
54	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
55	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	No	No	Yes	4

56	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	No	No	Yes	4
57	Wheel-Rail Contact	Tribological Effect	Yes	Yes	Yes	No	No	No	Yes	4
58	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	Yes	No	Yes	5
59	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	Yes	No	Yes	5
60	Grease/Lubricant	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
61	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	No	No	Yes	4
63	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	No	No	Yes	4
64	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	No	Yes	Yes	5
65	Friction Modifiers	Practical Considerations	Yes	Yes	Yes	No	Yes	No	No	4
66	Grease/Lubricant	Product Performance	Yes	Yes	Yes	No	Yes	No	No	4
67	Friction Modifiers	Product Performance	Yes	Yes	Yes	No	Yes	Yes	No	5
68	Friction Modifiers	Modelling	No	Yes	Yes	No	No	No	Yes	3
69	Contaminants	Modelling	No	Yes	Yes	Yes	Yes	Yes	Yes	6
70	Wheel-Rail Contact	Modelling	Yes	Yes	Yes	Yes	No	No	No	4
71	Wheel-Rail Contact	Modelling	Yes	Yes	Yes	Yes	No	No	No	4
72	Wheel-Rail Contact	Modelling	No	Yes	Yes	Yes	Yes	No	Yes	5
73	Contaminants	Modelling	Yes	No	Yes	No	No	No	No	2
74	Wheel-Rail Contact	Modelling	Yes	Yes	Yes	Yes	No	No	No	4
75	Wheel-Rail Contact	Tribological Effect	Yes	Yes	Yes	No	Yes	No	No	4
76	Wheel-Rail Contact	Tribological Effect	Yes	Yes	Yes	No	Yes	No	Yes	5

Table 2- Table detailing the scoring results from the "quality" assessment