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A Review of Railway Sanding System Research: Adhesion Restoration and Leaf Layer Removal

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ABSTRACT

This paper aims to provide a comprehensive review into academic and industrial research concerning the use of particles as a means of recovering adhesion when low adhesion conditions exist within the wheel/rail contact. The most common particle used is sand, generally possessing a high silica content; usually between 0.85-1.4 mm in size. Sand is currently being applied in low adhesion conditions in two ways: firing the sand into the wheel/rail contact by means of a train-borne sanding system, or by suspending it in a gel and applying it to the rail head with either a train-borne system or using a wayside applicator. Sanding has been used for a long time, but very little research has been conducted into the sanding system with research shortfalls surrounding particle properties and models of the mechanical behaviour of the particles' effect in the wheel/rail contact. This paper includes a gap analysis method whereby previous research has been categorised based on seven criteria, designed to help assess the papers. The research was then graded as either "A", "B", or "C" with "A" grade research representing peer reviewed work conducted across a range of scales or with an aspect of modelling. Most academic research was of "B" grade due to the lack of multiple scales or modelling, which was also lacking in industrial research, but due to the lack of peer review most industrial research received a "C" grade. The review also found there was evidence to suggest a lack of linkage between academia and industry with regards to taking sanding research findings forward. Additionally, this review helps clarify what future work is needed to optimise the sanding system to best recover adhesion and remove lubricating layers in the wheel/rail contact.

Keywords: Sanding; Traction enhancement; Leaf layer removal; Wheel/Rail Interface; Rolling/Sliding Contact

1 INTRODUCTION

Low adhesion in the wheel/rail contact leads to both performance and operational issues in the UK railway system. Performance issues arise as a lack of adhesion leads to reduced traction, therefore it takes longer for trains to accelerate up to a desired speed, thus leading to delays [1]. Safety issues occur due to the presence of low adhesion increasing braking distance, potentially leading to SPADs (signals passed at danger) or in the worst case collisions [2]. The minimum accepted adhesion values are 0.09 and 0.2 for braking and traction respectively [1], with problems occurring under this limit; adhesion values have been found to go as low as 0.05 in poor conditions [1]. Low adhesion conditions exist when a third body layer is present on the track, such as: oil [3], water [4], water and oxides [5], and leaves on the line which bond tightly to the rail [6].

Sanding as an adhesion recovery method has been in use since the early days of the railways in the UK. Over the last few decades research has been conducted to examine the effect particles have when applied to the wheel/rail contact. Experiments have been undertaken across a range of scales and have investigated both dry particles (mostly sand) and traction enhancers (traction gels).

Typically sanders are train borne systems that apply dry sand particles into the wheel/rail contact by means of an air stream running through a hose directed at the contact [7]. Figure 1 shows a typical sander set-up for a train-borne system.

[Figure 1 near here]

There is a lack of knowledge concerning the breadth of sanding research that has been conducted, in both industry and academia, as well as a lack of understanding of what conclusions can ultimately be drawn from previous research. This knowledge would allow future work to be focussed on important aspects of sanding and stop the repetition of old work.

The aim of this paper was to review both academic literature and industry reports for both dry particles and traction enhancers and provide a summary of what has been done and what conclusions can be drawn.

The objectives needed to achieve this aim were:

- Summarise the main testing methods as well as discuss their limitations and benefits.
- Review and discuss the effect particles have on adhesion and leaf layer removal.
- Review some different particle application methods and experiments.
- Conduct a gap analysis to better understand what future work is needed.

The research into the negative effects of sanding such as the impact it has on train detection and wheel/rail surface damage is covered in another paper [8]. This paper also reviews the research conducted looking at particle application into the wheel/rail contact.

2 TEST METHODS

When investigating something as complex as a wheel/rail contact, careful consideration needs to be taken to ensure any experiment is as accurate a representation of the contact as possible, whilst being simple enough to infer reliable conclusions. Field tests give real world results, but it is hard to control all the possible variables, whereas a simple test rig simulating the contact in lab conditions allows these variables to be controlled and therefore specific variables can be isolated and tested.

For significant conclusions to be drawn from testing a range of scales is needed, starting small and simple and then becoming larger and more complex. In this way results can be corroborated and correct conclusions can be drawn. For the wheel/rail contact there are generally three types of test: twin disc, full-scale rig, and field.

2.1 Twin Disc Set-up

A typical twin disc set-up uses two discs rolling against each other to simulate a wheel running over a rail, with one disc representing the wheel and the other the rail. This testing method has been used extensively in many investigations [9–13]. A typical schematic of such a machine is shown in Figure 2 (Top). The twin discs are usually cut from actual wheel and rail sections to achieve as close to the same surface material as possible, though obviously the geometries of the disc are very different to that of actual wheels and rails; all of the twin disc set-ups discussed in this review had smaller geometries than an actual wheel/rail contact. The actual geometries of the discs are very small compared to an actual wheel and rail with an example included in Figure 2 (Bottom).

[Figure 2 near here]

The actual contact between the discs is a line contact, again differing from that of an actual wheel and rail; the line contact has a width of 10mm. The actual geometry of the contact will not be stable, due to the curving rail head and wheel profiles, this cannot be modelled using twin-disc methods. However, the contact pressure between the discs is similar to those of an actual wheel/rail contact; mean contact pressures of 900-1500MPa can be achieved. Another limitation of the twin disc tests is the lack of realistic velocity between the surfaces, with speeds typically only reaching ~2mph.

When sanding is being applied to the twin-disc contact the results garnered for adhesion, isolation, and damage will all be exaggerated due to several factors [9].

- *Twin-disc geometry.* As mentioned above the geometry of the actual contact will be smaller than a realistic wheel/rail contact. As the sand is not scaled down it will be artificially large and therefore have a larger effect on the contact.
- *Sand application.* Whilst the application method uses a similar principle to that of a real-world sanding system, the hose is much closer to the contact. This will result in

more particles being entrained into the contact and subsequently affecting the mechanics of the contact. A typical example of the application set-up can be seen in Figure 3.

[Figure 3 near here]

- *Lab conditions.* Whilst the indoor conditions of the lab offer control over the testing procedure, the realism of the experiment is the necessary trade off. There is no way to account for: crosswinds, air turbulence, curves etc. What can be accounted for will only be in an artificial way; contaminants, moisture, temperature etc.

2.2 Linear Full-Scale Rig

Linear full-scale rigs use actual wheels and rails with realistic contact pressures (900-1500 MPa) and geometries. The limitation to this machine is the lack of realistic wheel velocity, due to the truncated length of rail used (600mm for one such rig [14]) and safety issues; the top speed of the wheel is <1mph for the rig used by British rail and the University of Sheffield [14]. The rig is especially helpful for studies concerning the actual application of particles [14,15] into the contact due to its realistic geometries. Even the effect of prevailing winds and cross winds can be taken into account with the use of large fans. An example of a full-scale rig (as used by Lewis et al. [14]) is included in Figure 4; *(1)* denotes the wheel and *(3)* is a 1010mm length of rail which is moved by a linear slider bed *(4)*, the sand is fired from the hopper *(10)* into the contact via the hose *(12)* and nozzle *(14)*.

[Figure 4 near here]

2.3 Field Tests

A large portion of industry field tests that have been carried out have been qualitative in nature [16–20], in large part due to the difficulty of running experiments on working lines. Most quantitative work there is comes either in the form of tribometer trains [21] (providing actual adhesion values), actual train performance [22–25] (journey time, slip detection, braking distances). Whilst there is inherent realism in field tests, the lack of any control of variables leads to results that could be misleading, therefore many of the field test conclusions come with caveats.

3 CURRENT INTERNATIONAL SANDING STANDARDS

Currently in the UK, the only dry particles applied to the wheel/rail contact are sand particles that meet the sanding equipment standards set by the Rail Safety and Standards Board (RSSB) [26]. The criteria for sand particles to be used in braking and traction in the UK are summarised in Table 1.

[Table 1 near here]

Braking sand is used in multiple units with combined braking and traction sanding systems; this is done to simplify the design.

Both France and Germany have separate standards relating to the sand particles' characteristics. The French standard [27] differs from the UK standard in a few places: the sand origin must be alluvial as opposed to from a quarry; sand must be round and unbroken and not sharp, contradicting the UK standard for traction sand; French sand must be free of any additives whereas UK sand can be contaminated up to 2%; and the specified grain size distribution is more strict and calls for smaller grain sizes than is seen in the UK (see Table 2 for more details).

[Table 2 near here]

The German standard [28] surrounding particle characteristics is much closer to the UK standard than the French version. The German standard also specifies that the sand must be sharp, that it must be ≥90% quartz and does not specify a particle size distribution though it does recommend the distribution included in Table 3). The German standard also specifies that the moisture content of the sand must not exceed 0.5%wt and similarly to the French standard specifies that no contaminants can be present.

[Table 3 near here]

Australia also has standards [29] pertaining to sanding but these do not cover the characteristics of the sand being applied.

Current sanding equipment standards also encompass the application of the particles onto the rail as well as the mechanical design of the sanders. The UK standards depend on whether the locomotive is undergoing braking or traction and in the case of the former whether the multiple unit has 8 or more wheelsets [26]. All of the British [26], French [27], German [28] and Australian [29] standards specifically outline that sand must not interfere with the track circuit, i.e. cause isolation.

4 THE EFFECT OF PARTICLES ON ADHESION

There have been multiple laboratory investigations that have found that the use of sand generally has an augmentative effect on adhesion between the wheel and rail when low adhesion conditions exist [9,10,37,12,30–36]. On top of this, it has been shown that sand improves adhesion levels in the field also [15,17,19,20,24,25,38]. The following sections will describe these investigations in more detail.

4.1 Dry Particles

4.1.1 Twin-Disc Set-up

A large amount of the work utilising twin-disc measurements of adhesion has been undertaken by Arias-Cuevas who has conducted multiple studies into the use of sand particles in the wheel/rail contact.

In dry tests, Arias-Cuevas et al. [10] found that sand reduced friction in the contact at all sand densities (0.75-7.5 g/m), particle sizes (0.06-2mm) and at all creep rates (1-10%). The results obtained from Arias-Cuevas also showed the effect particle size had on adhesion, it was found larger particles generally lead to better adhesion. The same work suggested that there is an upper limit on the discharge rate of sand from the hose after which the sand within the contact was creating a solid lubricant, reducing the adhesion between the wheel and the track further still. A summary of the particle size categories used throughout all of Arias-Cuevas' et al. work has been included in Table 4.

[Table 4 near here]

It was also found in dry tests that higher slip rates enhanced the interlocking action of the sand particles leading to much higher adhesion values. It should be noted that the effect of further increasing the slip at already high slip rates was minor in comparison to the significant increase in adhesion when increasing the slip at low slip rates, thus suggesting that there is not much benefit from increasing the slip rate past a certain point. The influence of both slip and particle size is summarised in Figure 5.

[Figure 5 near here]

Arias-Cuevas et al. [39] ran another twin disc study with more focus on the effect particle size had on improving adhesion in leaf contaminated track. In these tests, he found that for all the various particle sizes the leaf layer was being removed yet the adhesion values still increased with particle size as the sand started acting on the actual rail. This may have an impact on particle size selection as any sand remaining after the leaf layer removal could negatively affect adhesion, as sand in a dry contact has been shown to reduce adhesion values [10].

Omasta et al. [40] undertook twin-disc work concerning the effect sand had on various adhesion reducing contaminants. In a wet contact, it was observed that changing the application rate of the sand did not have a large effect on adhesion recovery at low slips and low surface speeds. As the slip rate and surface speeds increased so did the effect the application rate of sand on adhesion recovery. These results are included in Figure 6. Kumar et al. [35], found that the application of sand into oil contaminated contacts had the effect of restoring adhesion, again only at higher slips. Similar results have been found in work conducted on a full-scale rig by Zobel [41], who found that adhesion was improved in oiled contacts down to particles sizes of <100µm.

[Figure 6 near here]

The results obtained from the studies described above clearly indicate that there is a relationship between slip, particle size and discharge rate at which the adhesion between wheel and rail will be optimised.

More work assessing the performance of sand in different liquid contaminated contacts has been undertaken by Wang et al. [36]; it was found that sand had a positive adhesive effect on wet contacts, but less so when oil was present perhaps due to the higher viscosity of the oil preventing entrainment into the contact; these results were summarised in Figure 7. They also found that sanding was most effective at restoring adhesion at lower speeds and higher normal loads.

[Figure 7 near here]

Wang et al. [37] studied the effect alumina particles had in recovering adhesion in contaminated contacts. They found evidence that suggested alumina performed better than sand in oiled and wet contacts, possibly due to the Alumina being harder and according to

Zobel's research [41] harder particles are more effective at restoring adhesion. However, in the leaf layered contact Wang et al. found that the alumina underperformed compared to sand; as the sand particles ranged from 0.5-1.3mm compared to an alumina particle size of 0.1mm this may have been due to the alumina not being sufficiently large enough to penetrate the leaf layer and break it up; this would be an interesting area to conduct further work into.

4.1.2 Linear Full-Scale Rig

Lewis et al. [30] focussed on the effect application rate had on improving adhesion in a full-scale rig; the low adhesion situation was created using wetted paper tape. They found that the minimum sand density needed on the rail (in this context sand density refers to the amount of sand per metre of rail) to remedy low adhesion situations was 7.5 g/m. In tests run with sand densities of 106 g/m there was still adhesion recovery, but the peak adhesion reached was lower than the 7.5 g/m test. Lewis et al. summarised that this may be due to the increased quantity of sand mixing with the low adhesion layer thereby creating a lubricating paste. Lewis et al. concluded that the optimal sand density will be somewhere between 7.5 g/m and 106 g/m and his results have been included in Figure 8.

[Figure 8 near here]

Zobel's full-scale tests [41] looked at different types of sand in an oiled contact, including research into the relationship between particle hardness and adhesion improvement. Zobel found that whilst harder particles generally offered higher adhesion there was a critical hardness after which there was very little adhesion improvement. The critical hardness seems to be between 6000-8000 kg/mm^2 in his tests, or around the same hardness of Quartz.

Both Lewis et al. [30] and Zobel [41] found that the amount of sand actually needed to improve adhesion is very small compared to the amount that is actually being discharged from the hose. This suggests that a focus on the accuracy of sanding system will have a beneficial effect on adhesion and waste less sand; this was discussed in another review paper [8].

In work done by Cooper [42], it was found that increasing sand particle size produced greater friction in an oiled contact, which reinforces conclusions from multiple papers in section 4.1.1. This relationship was especially pronounced for particle sizes below 53µm suggesting that particles may not be effective below this size. It should be noted that this test was run with a low quantity of sand on the rail (0.05-0.1 kg/m^2), so these results may be hard to compare to other results mentioned in this review as they mostly used a lower limit of 0.15 kg/m^2.

There has been some full-scale work looking at particles other than sand, Tanvir used a full-scale rig to measure the adhesion recovery properties of different types of unnamed “fines” in an oiled wheel/rail contact [43]. These fines differed from sand in that they were amorphous and crumbled very easily. Tanvir found that these fines did not improve the adhesion at all in the wheel/rail contact whilst the crystalline sand offered improvements, but not to the extent of completely recovering adhesion. From these results Tanvir surmised that amorphous particles gave lower adhesion values than crystalline particles.

4.1.3 Field Tests

Whilst there has been a lot of field work conducted looking at sanding in the wheel/rail contact, most of this has centred on qualitative research into the effect sanding has on improving adhesion [15].

Schofield et al. [23], Marks [24] and Waring [25] ran tests with an emergency one shot sander system to understand how effective it would be when braking was critical and adhesion was low. Schofield et al. found stopping distance was halved when the emergency sander was applied, suggesting an increase in adhesion; Marks also found improvements when receiving feedback from drivers. Waring went into more detail and found the emergency sander, using a discharge rate of 5kg/min/rail, resulted in a train retardation increase from 2%g to 9%g, allowing full braking. In comparison, a typical sander with a discharge rate of 2kg/min/rail increased retardation from 1.5%g to 4.5%g considerably less perhaps due to the lower amount of sand going into the contact.

Recent field work carried out by the RSSB [44] has verified the findings of Waring i.e. higher discharge rates result in more effective braking. They found that two 4kg/min/rail sanders on a 4 car train comfortably achieved a train retardation of above 6%g even in very low adhesion conditions ($\mu<0.02$). There set-up was variable, in that the 4kg/min/rail rate was only active above 20 mph so as not to exceed the 7.5 g/m amount currently specified by RSSB standards [26], when slowing down between 10-20 mph the discharge rate ramped back down to 2kg/min/rail. It may be the case that even higher discharge rates at high speed are even more effective based on the field work conducted, however the upper limit may be decided by the chance of isolation and unwanted damage occurring.

4.2 Traction Enhancers

4.2.1 Twin-Disc Set-up

Traction gels are generally deposited on the rail in areas with low adhesion problems. Most enhancers consist of hard, abrasive particles suspended in an aqueous gel. Most traction gels will also have other chemical elements designed to improve its performance i.e. corrosion inhibitors.

Arias-Cuevas et al. [13] ran twin-disc experiments that investigated the effect two different traction gels had in a dry and a wet contact. In dry contacts, they found that adhesion was reduced in comparison with a clean rail, he did find that the gel with larger particles gave higher adhesion values than the other gel. These results seem to be very similar to the results found from research with dry particles, though the improvement could be for other reasons to do with the gel.

In wet contacts, Arias-Cuevas found that the traction gel with smaller particles had a stronger matrix between said particles and its polymers and had a longer lasting effect on adhesion than the traction gel with larger particles. This effectively meant the adhesion recovery in wet conditions was quicker for the smaller particle traction gel but was still lower than the peak adhesion reached in the bare rail. These results could either show that smaller particles had a greater effect than larger particles (unlikely when looking at the results garnered from dry particle tests), or the strength of the matrix between the particles and the gel has a large part to play in a traction enhancer's efficacy.

Lewis et al. [11] conducted experiments primarily designed to investigate traction gel's efficacy at removing leaf layers. They found that there was a drop in adhesion upon application of the gel followed by an increase in adhesion as the leaf layer was removed (see section 5.2.1 for more detail). A possible reason for this phenomenon was put forward and is explained using Figure 9; the timeline for the traction gel is: *(a)* the gel is entrained in to the contact but the particles are resisted by the hydrodynamic pressure of the gel, *(b)* as the gel evaporates particles begin to enter the contact, *(c)* the gel has fully evaporated resulting in crushed, embedded particles.

[Figure 9 near here]

4.2.2 Field Tests

Most of the field studies on traction gels centre around "Sandite", a mixture of sand and aluminium particles suspended in a silicate clay called Laponite, which becomes a gel when water is added. It is currently approved for use in the UK.

Tunley [22] conducted field work comparing the ability of sanding, Sandite and water jetting at restoring adhesion when a leaf layer was present. The Sandite was applied to the rail using train-borne applicators, which required a special train. In his work, he found that water jetting alone offered no adhesion improvements at all and that Sandite and water jetting combined offered the best adhesion recovery system, this was summarised into the graph shown below in Figure 10. It should be noted that Tunley does not go into any detail about methodology, so it is hard to draw any definitive conclusions about this work.

[Figure 10 near here]

Sandite was also used in a study by Marshall for Network Rail [45]. Using on train monitoring and recording it was found that the sandite restored adhesion when a Lignin mixture; a component of leaves that can bond firmly to the rail [6]. The amount of information that can be drawn from this finding is limited by the lack of repetition of results and the methodology used is unknown.

A now defunct traction gel, known as “slipmaster” was tested to find the adhesion improving properties. Zobel [41], conducted field work that found that after 20 wheelset passes the traction gel actually seemed to lower adhesion. Zobel conducted more tests using a twin disc set-up and concluded that the presence of ethylene glycol and the gel were responsible for lowering the adhesion as the gel was crushed and particles removed from the contact.

Fulford conducted an in-depth review into the use of traction gels in improving adhesion in the wheel/rail contact [1]. He found that almost all traction gels offered some improvement in adhesion when dry, but would cause a decrease in adhesion when freshly applied or too much gel was applied to the rail.

In addition to Fulford’s review, Garner [46] also found that traction enhancers were only beneficial in a limited climatic range. Garner’s study concerned two different traction enhancer products: U5® and Alleviate®; the study took place during Autumn and the products were applied every axle. Garner found that both products provided little benefit in

warm weather (~20°C) as the traction enhancers dried out quickly resulting in their quick breakdown and removal by subsequent wheel passes. Additionally, in freezing temperatures there was no improvement in adhesion possibly due to the applied gels freezing to create an icy layer though this was not verified in her thesis. Lastly, Garner found that the traction enhancers were at their most effective in dry conditions backing up the conclusions of Tunley and suggesting that applying traction enhancers directly after water jetting, whilst the rail head is moist, is detrimental to the efficacy of the gels.
It can be concluded that in ideal conditions (dry contaminant layer, time since application neither too short or long, cold but not freezing temperature) traction gel benefit adhesion levels. In future, more thought will need to be applied as to how and when to utilise traction enhancers in low adhesion conditions. In addition, the chemical structure of the gel is an important indicator as to how the traction enhancer will perform.

5 THE EFFECT OF PARTICLES ON LEAF LAYER REMOVAL

Leaves on the line have long been a problem for the rail industry as they dramatically reduce the adhesion between the wheel and rail whilst also forming a layer that bonds to the rail and that is very hard to remove [1,6,31]. Sand has long been a valuable tool, as it can indent into the leaf layer, breaking it away from the rail and restoring adhesion. The following sections investigate previous research to study the effect particles in the wheel/rail contact have on removing leaf layers.

5.1 Dry Particles

5.1.1 Twin-Disc Set-up

Particle size is critical when breaking up the leaf layer. Laboratory work undertaken by Arias Cuevas et al. [33] and operational experience [26] have shown medium size sand grains (<0.6mm in size) have been the most effective at removing leaf layers in braking. This is possibly due to:

- The grain size being larger than the contaminant thickness, thereby penetrating the leaf layer to provide a mechanical link between the wheel and rail.
- The particles being more easily entrained thereby increasing the number of particles affecting the layer.

The amount of sand actually applied to the contact will have an influence on leaf layer removal. Arias-Cuevas et al. [33] found that the number of sanding axles being used has proportional relationship with adhesion recovery, suggesting that one train pass with enough sanding axles may eradicate the leaf layer entirely. In a similar set-up with a 1:3 scale twin-disc, Omasta et al. [40] found that whilst the application rate of sand into the contact had an effect this was much less important than slip and disc speed at determining the amount of adhesion recovery.

Higher slip rates mean a particle embedded in the wheel will abrade the surface on the rail for longer. This means that high slip rates could be an effective way of removing the leaf layer, both with and without sand being present in the contact as shown by the Arias-Cuevas et al. [33] study; though they admitted this would need to be balanced with increasing wear and RCF at higher creeps. A complete summary of this paper has been presented in Table 5 and uses the number of cycles till adhesion restoration as the basis for the effect the particles have had in leaf layer removal.

[Table 5 near here]

Arias-Cuevas et al. [39] also conducted sanding tests on the twin disc which used a continuous application of sand into the contact, as opposed to the tests described above which used a set amount. Here they found that all particle sizes would remove the leaf layer eventually though under continuous application it seems like large particles gave the highest adhesion after recovery, probably due to the particles actually acting on the rail itself thus their conclusions from his research into a dry contact, that larger particles give better adhesion [10], hold true.

Sanding equipment standards [26] recommend that small grain sizes (the sizes specified in Table 4) should be used in traction as it forms a paste between the wheel and the rail that is more effective at transferring tractive effort from the wheel to the rail. This seems to run counter to the results gained from Arias Cuevas et al. [33], who found fine particles generally were not as effective as medium particles for adhesion recovery and in the worst case seemed to lubricate the contact; they found fine particles tended to mix with the leaf layer creating a lubricating paste.
It can be concluded that whilst there is a given amount of sand that will remove a given leaf layer, any extra sand will not aid in increasing adhesion and may cause unwanted effects e.g. damage and wheel/rail isolation). In addition, high slips aid the sand in the removal of the leaf layer. It should be noted that, due to the nature of twin-disc tests, sand embedded in the leaf layer will stay in the layer throughout the twin-disc test, possibly giving an unrealistic view of what one application of sand will do over multiple cycles.

5.1.2 Full Scale Rig

In more recent times some quantitative comparisons of sanding techniques have been carried out. In 1999, Tunley [22] conducted work comparing sanding with a variable discharge rate set-up and Sandite (traction gel); These results were summarised in Figure 11. He found that sand alone was enough to remove a significant amount of the leaf layer as multiple wheel sets passed over. Tunley also found evidence that whilst Sandite had an immediate impact on the leaf layer, the layer quickly rose back to pre-treatment levels. There are limitations as to what conclusions can be drawn from this testing: Tunley does not explain how he measured the percentage of leaf contaminated rail or explain the specifics of his test methodology. The only real conclusion that can be drawn from his work is that both sanding and Sandite can remove the leaf layer under the correct conditions.

[Figure 11 near here]

5.1.3 Field Tests

Most of the field work investigating leaf layer removal is qualitative [15–17] with most research occurring in the 70's when measurement techniques were not as advanced as they are now.

In recent field tests Arias-Cuevas & Li [38] looked at the influence of particle size at removing leaf layers; these tests used actual sanders and actual leaves. They found that sand was much more effective at removing leaf layers compared to without. They also saw that the optimal particle size (0.3-0.6mm) for removing leaf layers was the same as in his laboratory work [33], adding credence to the twin disc method. Another interesting finding was that the sanding was effective for the wheelsets after the sanding axle, showing the sand was staying indented into the leaf layer.

5.2 Traction Enhancers

5.2.1 Twin-Disc Set-up

The effects of an unnamed traction gel in removing the leaf layer has been studied by Lewis et al. [11] in a twin disc set-up, the results of which are included in Figure 12. He found that the traction gel eventually removed the leaf layer and increased adhesion. Initially they reduced the adhesion due to the lubricating effects of the gel; however, once the gel had evaporated the particles started to have an effect in removing the leaf layer.

[Figure 12 near here]

More twin disc work was undertaken by Li et al. [32] looking at the effectiveness of two types of traction gel on removing the leaf layer and restoring friction. The two types of traction gel can be summarised thusly:

- "FMA"- small particles with relatively strong bonds between its abrasive particles and its polymeric matrix.
- "FMB"- a mixture of gelling agent, stainless steel and sand particles of a larger size than those in FMA.

They found that when low slip conditions were present the friction modifiers were more likely to mix with the leaf layer, keeping adhesion levels low when this occurred. FMB was shown to recover adhesion better than FMA, probably due to the greater particle size. These results can be seen in Table 6.

[Table 6 near here]

The same research also took some Vickers hardness measurements: the leaf layer was 47-68 HV_{10g}, the stainless steel 320 HV_{10g}, and the sand was 1500 HV_{10g}. It can be inferred that the FMB particles were successful at removing the leaf layer because they could more easily indent the leaf layer due to their hardness and size.

Again, higher slip values seem to more easily remove leaf layers. It may also be possible that the gel can have a negative effect on adhesion under the wrong conditions. As with dry particles, the continued presence of traction gel during the cycles may exaggerate the effect on removing a leaf layer over a number of cycles.

5.2.2 Field Tests

McEwen [19], conducted field research into the effects of Sandite in recovering adhesion in leaf affected sections of track. Overall, he concluded that the Sandite did improve the adhesion, but due to limitations in his testing method he did not expand any more than this. He did report that he saw an increase in adhesion level of about 0.03, but qualified this with reports that sometimes the Sandite reduced the adhesion level and that these adhesion increases were not much more than that seen on an untreated rail.

Work by Garner [46], found that Alleviate® traction gel, applied every axle, was effective at removing a leaf layer. Traction enhancer carried down on the wheel was creating clear patches with spacing between each clear patch being equal to the circumference of the wheel. It should be noted that Garner did not see any wheel slips or slides during her testing period suggesting the leaf layer was not built up enough to cause low adhesion which means the leaf layer Garner observed is not fully representative of "problem" leaf layers.

McEwen et al. [20] also investigated the effect entrained sand in a water jetting system had on removing leaf layers. They found that whilst the water-sand system was detaching the leaf layers from the rail, it was leaving a paste on top of the rail which could be rubbed away with a finger. This paste however could be recompacted, thus not solving the adhesion problem completely.

Further field work on this water-sand system carried out by Pollicott and Taylor [16–18], found that whilst the system was effective at removing "thick" leaf layers it was less effective at removing tightly bonded "thin" leaf layers. In most of their work the system did not consistently remove all leaf layer.

These field studies corroborate the findings from the laboratory, previous traction gels may be partly effective, but could be counter-productive if not applied correctly or under the right conditions.

6 GAP ANALYSIS

6.1 Paper Grading

To successfully identify the current knowledge gap present in sanding research a paper grading system proposed by Harmon & Lewis [47] has been employed in this review. The aim of this paper grading system is not to assess a paper's quality but to understand what areas research has been conducted into and whether the conclusions have been validated by testing at multiple scales or through modelling work.

The papers have been graded according to seven criteria, summarised below in Table 7. The first two criteria have been chosen to assess whether they have correct conclusions and stand up to scrutiny, the last five indicate how much the conclusions or hypotheses are backed up by the weight of results.

[Table 7 near here]

Each graded paper was marked out of 7 and split into three categories: "A" papers had a score of 5/7 or higher; "B" papers had a score of 4/7; "C" papers had a score of 3/7 or below. The papers with higher grades have conclusions which are validated across a range of scales and/or modelling; this does not mean lower grade papers have no useful conclusions but that future work is needed to assess the validity of their conclusions.

Each paper was put into a primary category and a secondary category so the knowledge gap areas could be more easily identified. The primary categories were adhesion and leaf layer removal with the secondary categories "dry particles" and "traction enhancers". There were multiple papers which overlapped into various categories, in these cases the papers will be entered separately into each category.

6.2 Outcomes

The outcome has been included as a schematic, as can be seen in Figure 13. The majority of papers focussed on adhesion, with the bulk of these concerning dry particles. Most of the papers reviewed presented either grade B or grade C work with only two papers receiving a grade A. The conclusion that can be drawn from this is the lack of in-depth research into almost every field, most industrial research was below 3/7 (mostly due to the lack of peer review) and almost all the academic research focussed on one testing scale (twin disc, full-scale, field) without corroborating findings with modelling or testing at different scales. The scarcity of modelling work reinforces the lack of understanding of the physical mechanisms occurring when particles enter the wheel/rail contact.

[Figure 13 near here]

7 CONCLUSIONS

The results of the gap analysis show that current research lacks in both quantity and depth. It should be taken into consideration that whilst the gap analysis only covers individual papers it is perhaps hard to fully comprehend the testing methods used by a particular researcher across their research. For example, whilst there were only two "A" grade papers concerning adhesion, there has been quite a lot of research into both particle size, and slip rates over all testing scales [33,38,39,42], but over separate papers instead of one paper. Overall, a lot of work has been done looking at adhesion whilst there has been very little on leaf layer removal specifically; in addition, more work is needed to assess traction enhancer performance at a range of scales.

Another outcome of this review is the highlighting of the lack of linkage between fundamental academic research and applied industrial work. What work that has been conducted in academia has not been taken forward by industry, and industrial research outcomes have not been analysed in greater depth by the academic world; there was no discernible proof of this academic industrial link in any of the reviewed papers. Laboratory conclusions need to be tested in industry to quantify the real-world effect of academic findings. Additionally, findings from industrial work need to be explained through investigations into their fundamental physical mechanisms a role more suited to an academic environment.

Across the papers where sanding tests were conducted with a twin-disc set-up the methodology varied widely. Sand was applied into the twin disc contact in different ways: Some studies used actual sanding equipment to fire the sand into the contact [9,40]; other studies supplied sand via a gravity fed chute [10,31,33]. The measure of sanding rates was also varied across papers with some studies preferring a continuous stream of sand at a steady rate [35,36,39], whereas one study applied a fix amount to the contact whilst still maintaining a steady rate [33]. Additionally the adhesion lowering contaminant was applied in different ways, with different methods being used to simulate leaf layer methods [11,33,40]. These different methods being employed means it is difficult to make direct comparisons between their results and highlight the need to have a more consistent methodology when conducting twin-disc testing.

The gap analysis identified two papers with "A" grades, meaning conclusions drawn from this paper have been validated with supporting models. Both papers covered the effect sand particles have on restoring adhesion, whilst Lewis et al. [9] also studied the particle's effect on track isolation and Lewis & Dwyer-Joyce [12] looked at the surface damage caused by sand particles; these latter parts are reviewed in another paper [8]. Both papers found that sand lubricated in dry contacts and restored adhesion in wet contacts. As these conclusions have been included in grade "A" papers it can be said that they are more robust than other conclusions drawn in other papers. It can also be said that larger particles and higher slip rates are the most effective at restoring adhesion in wet contacts, this conclusion can be drawn because of the quantity of evidence in multiple papers supporting this claim [10,30,35,40,42].

It should be noted that all Arias-Cuevas et al. research combined would be grade "A" if combined into one paper, especially by uniting papers by Arias-Cuevas et al. [33] & Arias_Cuevas & Li [38] which were respectively laboratory and field investigations into the effect of particles in leaf layer removal. The main conclusions from his work were: that sanding aided leaf layer removal; higher slip rates and more sanding axles aided removal; and medium size particles (see Table 4) were most effective. Again, these conclusions can be said to be more robust due to the grade "A" nature of the work.

Particle properties have been massively under researched, with the exception of particle size. The influence of particle shape, density, toughness, and to a lesser extent hardness have either not been looked at or looked at very briefly. In addition, there is a miniscule amount of research on particles that are not sand. There is small amount of work concerning traction gels with particles aiding sand and one paper studying alumina particles but apart from this there is nothing.

In addition, the scarcity of modelling approaches highlights the need for work that tries to understand how particles are acting in the wheel/rail contact. This knowledge would give someone the ability to predict how effective a prospective particle may be at restoring adhesion.

The future work that is needed can be summarised thusly:

- An investigation into the effect different particle characteristics have on the contact would help to optimise the sanding system.
- The use of different particles other than sand and whether they can compete in terms of performance, ease of application, storage, ease of acquisition, and cost.
- A comprehensive modelling approach to further understand the actual mechanics of particles in a rolling sliding contact.

These areas will need to be properly investigated across a range of scales to validate any results and recommendations that arise from this research. If successful, this research will be able to identify the optimal sanding regime at which adhesion and leaf layer removal are maximised whilst limiting the negative effects of sanding.

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Table 1 - Sand Specifications Provided by the RSSB [26].

Parameter	**Sand Specification for Braking**	**Sand Specification for Traction**
Size	<5% of particles should be <0.71mm	100% of particles must be able to pass through a 1.25mm sieve
		≤15% of particles should be >1.18mm
	<5% of particles should be >2.8mm	≤15% of particles should be <0.15mm
		≤1% of particles should be <75µm
Shape	Rounded and Irregular	Sharp
Uniformity Coefficient	<1.5	N/A
Mineralogy	≥90% Quartz or some other silicate	Silicate
	≤2% Contaminant Particles	
Source	Quarry sands preferable	Quarry sands preferable

Table 2 – Specified Grain Size Distribution provided by SNCF [27].

Sieve Aperture Size (mm)	Maximum Percentage Passing Value (%)	Minimum Percentage Passing Value (%)
3.15	100	100
2.5	100	98.5
2	99	90
1.25	85	60
0.63	50	25
0.315	10	0
0.08	1	0

Table 3 - Specified Grain Size Distribution provided by German Operators [28].

Grain Size (mm)	Maximum Share (Mass %)
>2.5	0.1
>2	5
1.6-2	30
0.8-1.6	50
0.63-0.8	30
<0.63	5
<0.1	0.5

Table 4 - Particle Size Categories used in Arias-Cuevas et al. work.

	Particle Size Band (μm)	**Location of Particle Size Distribution Peak (μm)**
S sand	60-300	150
M sand	300-600	350
L sand	850-1600	1200
R sand	250-1400	600-1000

Table 5 - Number of Cycles Required to Reach Minimum Adhesion Levels at different slip rates, particle sizes, and application amounts [33].

Mass of Sand Applied (g)	1% slip	5% slip				10% slip
	R sand	R sand	S sand	M sand	L sand	R sand
0	880	418				308
1.108	1000	315	80	66	440	249
2.216	528	117	<65	<65	308	117
4.432	286	<65	<65	<65	117	<65

Table 6 – Number of Cycles Needed to Achieve Adequate Adhesion in a Leaf Contaminated Contact [32].

	Braking (μ=0.09)			**Traction (μ=0.2)**		
	0.5% slip	**1% slip**	**2% slip**	**0.5% slip**	**1% slip**	**2% slip**
Untreated	515	115	0	2255	982	667
FMA	245	207	220	N/A	1884	1151
FMB	187	35	70	1965	65	145

Table 7 - Paper Grading Criteria.

	Criteria
1	Peer Reviewed
2	Conclusions match with results
3	Theory supported by testing
4	Theory supported by modelling
5	Scaled test
6	Full size test
7	Real world test

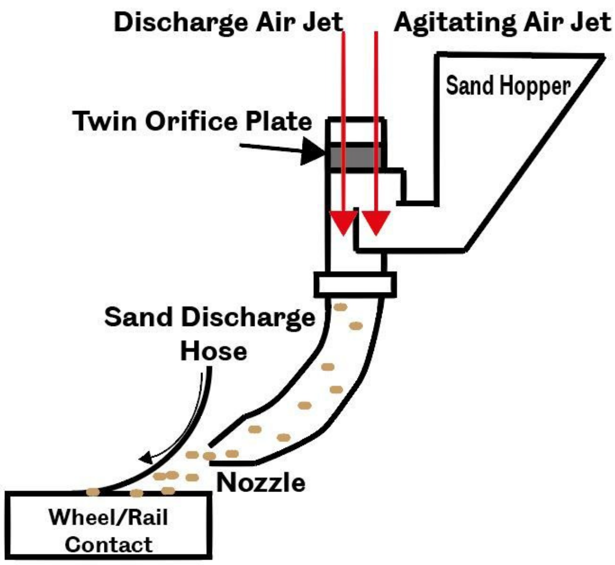

Figure 1 – Schematic of a Typical Sander.

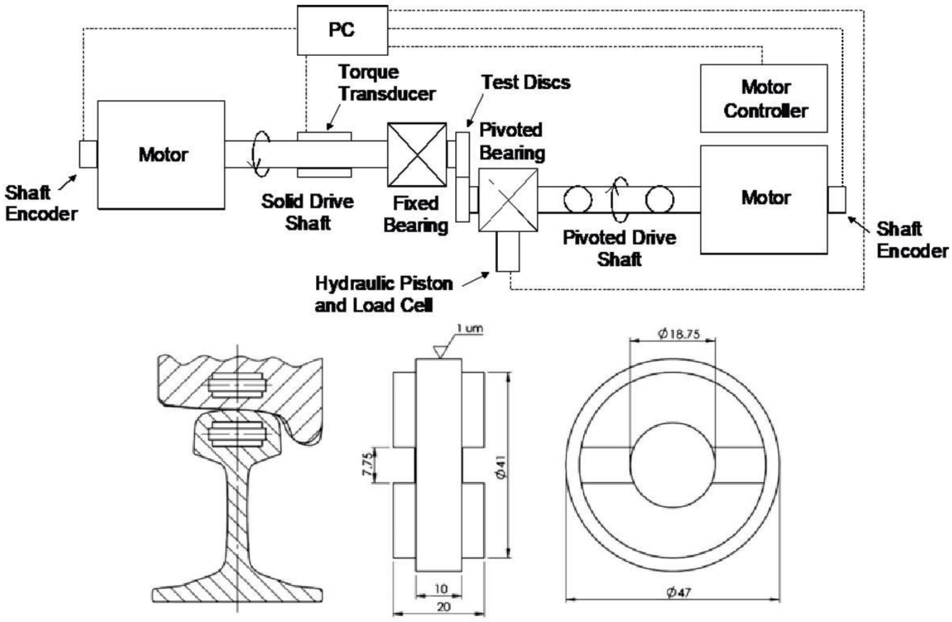

Figure 2 – Twin Disc Tests: *(Top)* Twin Disc set-up, *(Bottom)* Wheel and Rail Disc Geometry **[13]**.

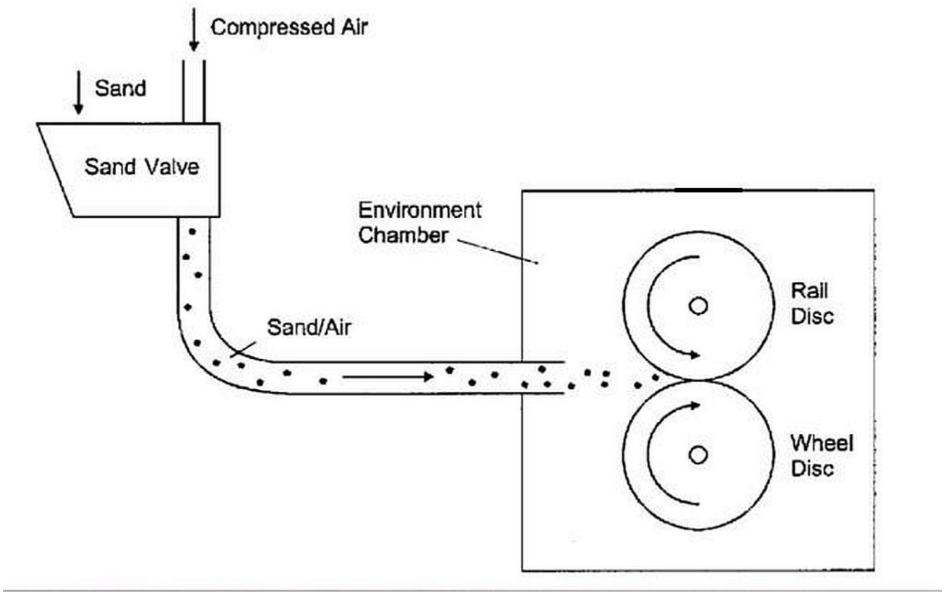

Figure 3 – Particle Application Set-up **[9]**.

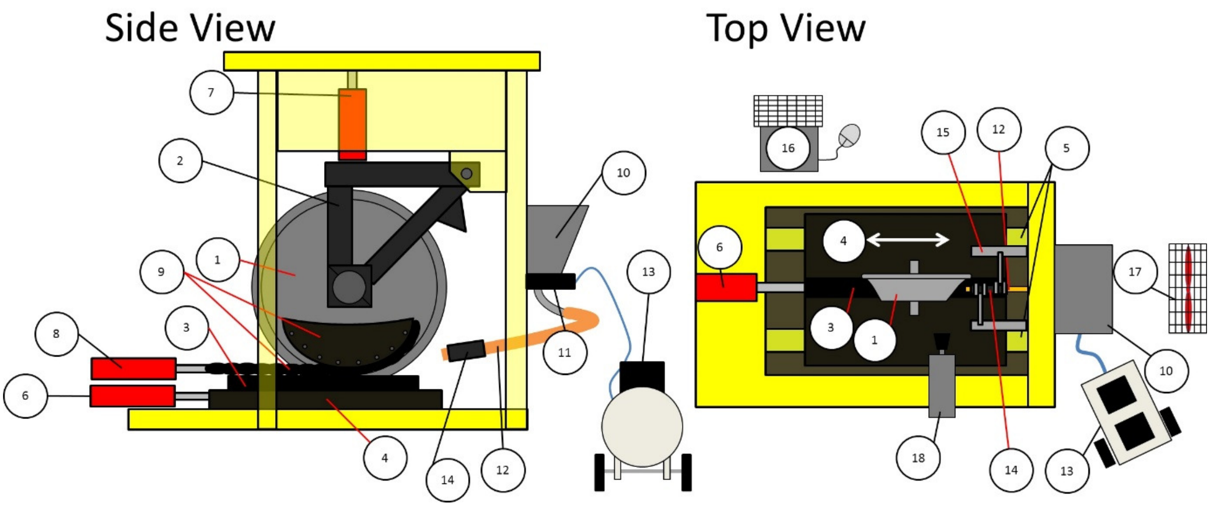

Figure 4 - Schematic of Full-scale Rig Sanding Set-up **[14]**.

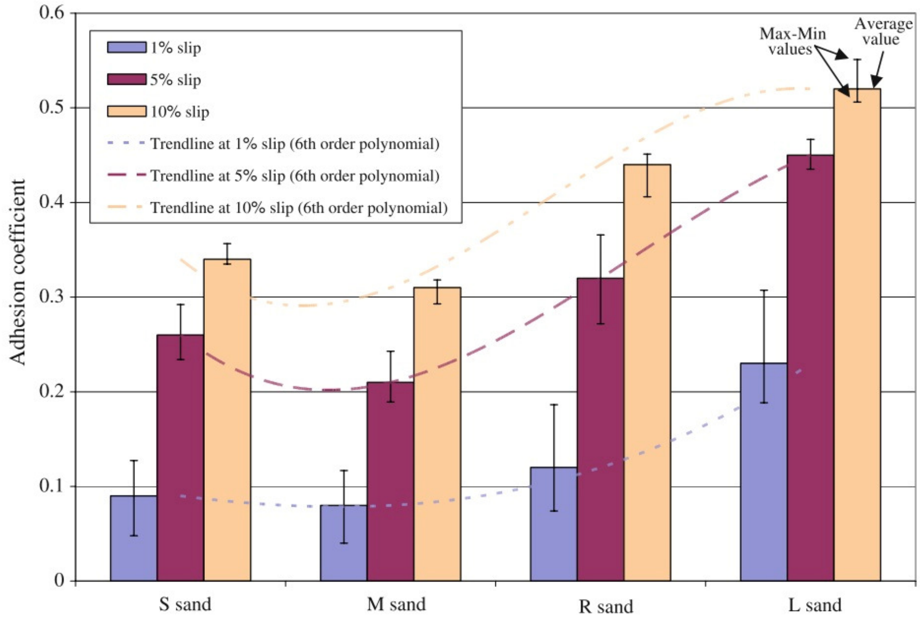

Figure 5 – Summary of Adhesion Results from Twin-disc Tests from Arias-Cuevas et al. **[10]**.

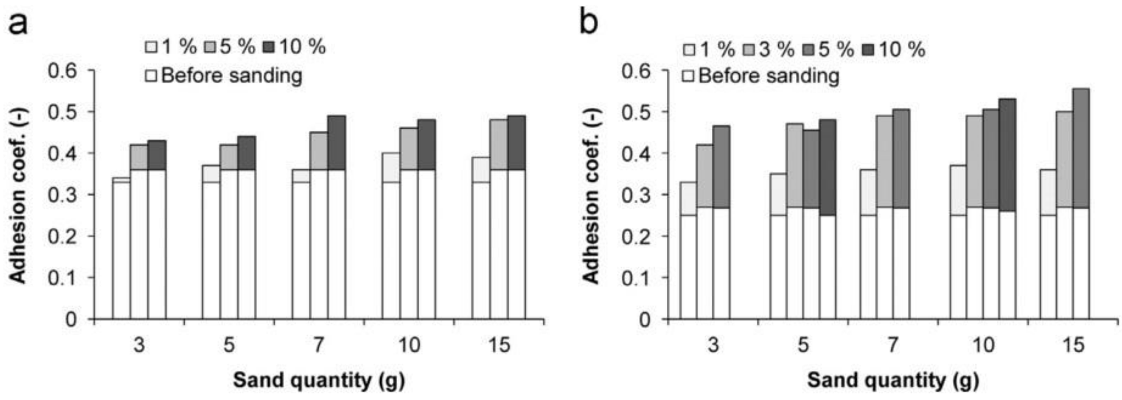

Figure 6 – The Effect of Sanding in a Wet Contact at Surface Speeds of: *(a)* 1m/s, and *(b)* 3m/s [40].

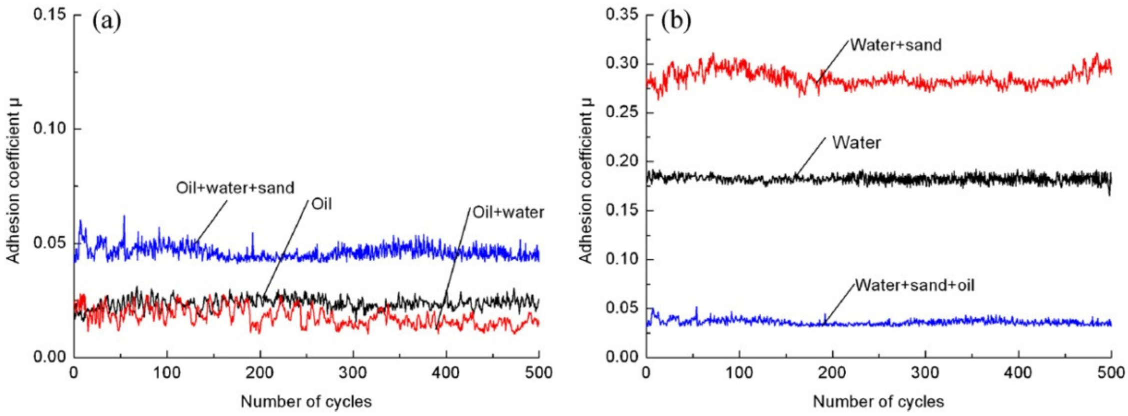

Figure 7 – *(a)* The Effect Sanding has in an Oiled Contact; *(b)* The Effect Sanding has in different Low Adhesion Conditions [36].

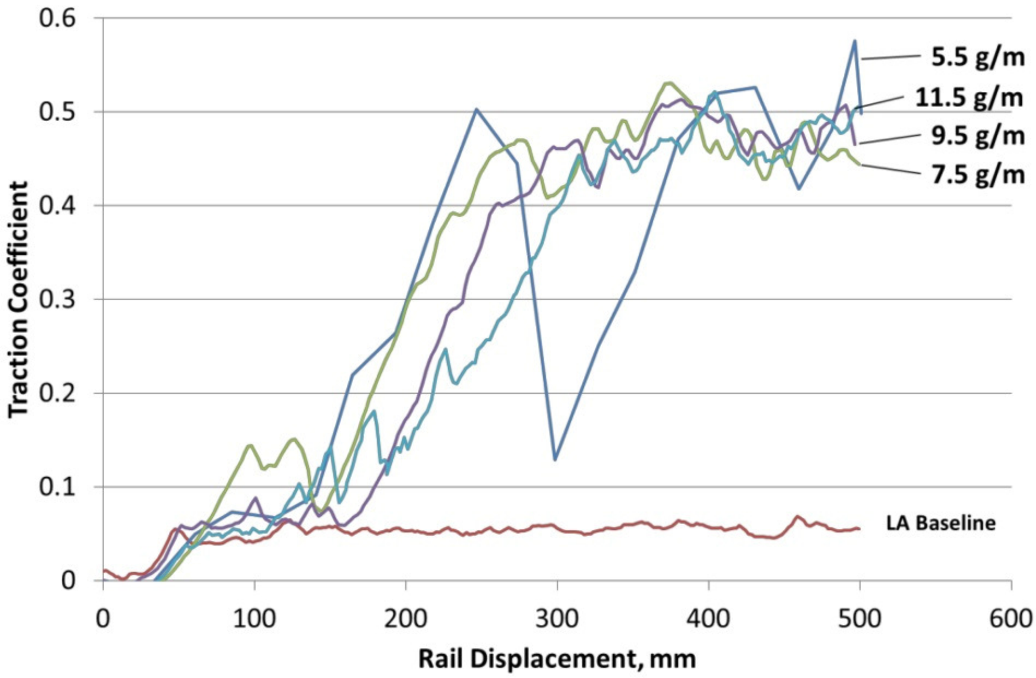

Figure 8 – Investigation of the Effect of Sand Density in Restoring Adhesion [30].

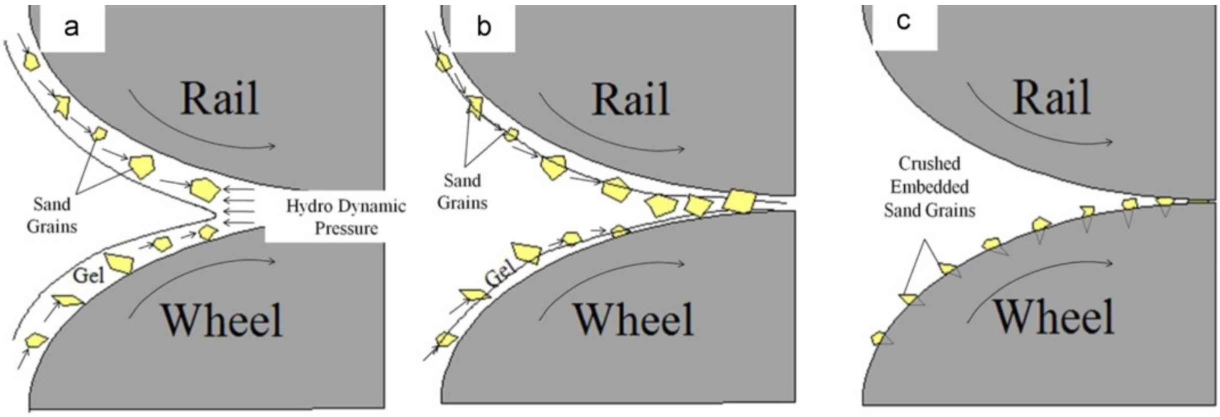

Figure 9 – Mechanism of Traction Gel Entrainment **[11]**.

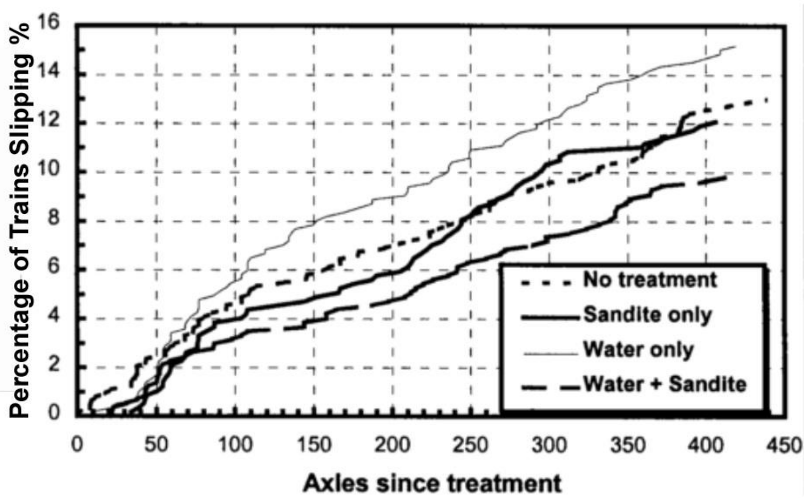

Figure 10 – Performance of Different Leaf Layer Removal Methods **[22]**.

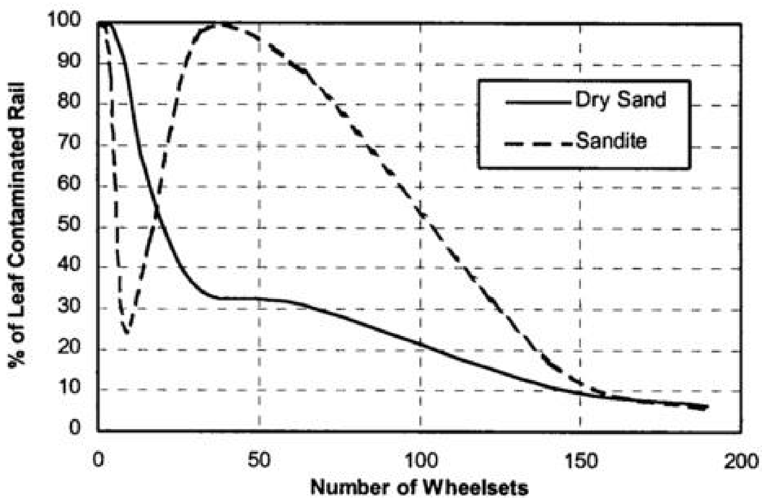

Figure 11 – Efficacy of sand vs sandite at removing the leaf layer **[22]**.

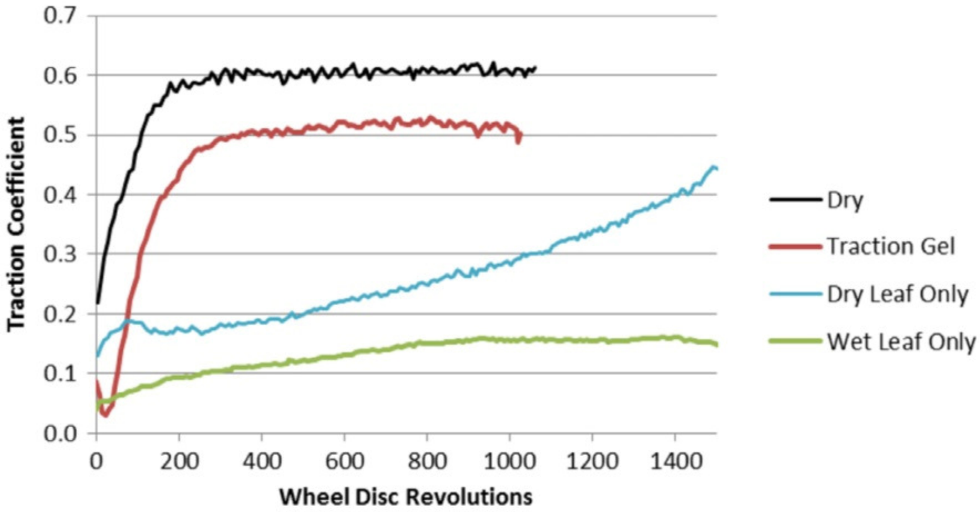

Figure 12 – Restoration of Adhesion in a Leaf Contaminated Contact **[11]**.

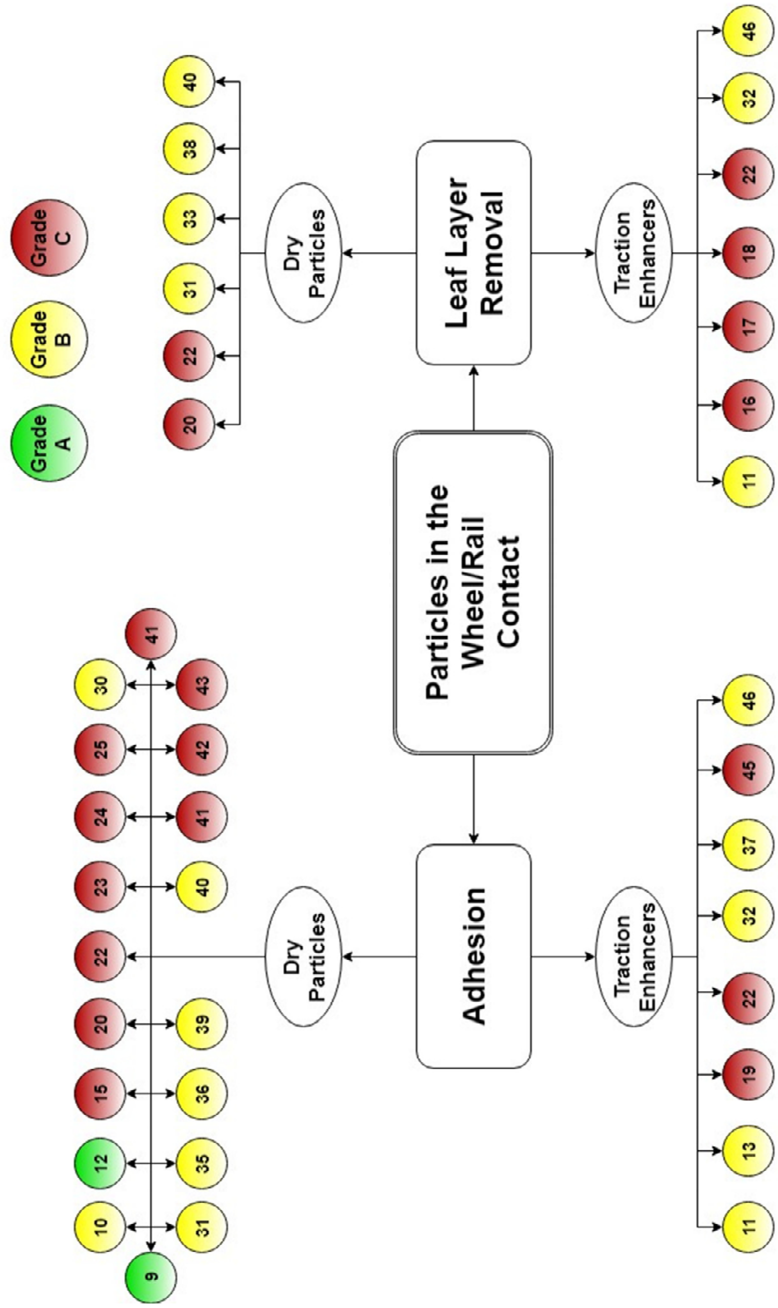

Figure 13 – Gap Analysis Visualisation of Reviewed Papers Represented by their Reference Numbers.