Article:

Skipper, W., Chalisey, A. and Lewis, R. orcid.org/0000-0002-4300-0540 (2020) A review of railway sanding system research: wheel/rail Isolation, damage, and particle application. Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit, 234 (6). pp. 567-583. ISSN 0954-4097

https://doi.org/10.1177/0954409719851634

ARTICLE TYPE:

Review Article.

CORRESPONDING AUTHOR:

William A. Skipper, University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD, UK.

Email: waskipper1@sheffield.ac.uk

A Review of Railway Sanding System Research: Wheel/Rail Isolation, Damage, and Particle Application

W.A. Skipper[1]*, A. Chalisey[2], R. Lewis[1]

*waskipper1@sheffield.ac.uk

[1]Centre for Doctoral Training in Integrated Tribology, The University of Sheffield, Sheffield, United Kingdom

[2]RSSB, The Helicon, One South Place, London, United Kingdom

ABSTRACT

This paper reviews the academic and industrial research conducted into practical aspects of using abrasive particles in the wheel/rail contact, such as: wheel/rail isolation, surface damage, and the application of the particles into the contact. Abrasive particles are applied to the wheel/rail contact to restore traction when low adhesion situations exist on the rail head, this process is referred to as "sanding" due to sand particles being the preferred particle type in the railway industry; this aspect of sanding was covered in another sanding review.[1] Currently, particles are applied either by firing dry particles into the wheel/rail contact via an air stream or by suspending them in a gel which can be applied using train-borne or trackside methods. The papers looked at in this review were scrutinised using a gap analysis method which grades each paper based on seven criteria: whether the papers had been peer reviewed, whether the conclusions matched the results, the range of testing scales used, and the presence of fundamental modelling work. When the findings of the research in this review were analysed it was apparent that the negative effects of sanding (damage, isolation) have not been researched in much depth compared to its positive effects (adhesion restoration, leaf layer removal). In addition, the academic research that has been conducted has not been taken forward by industry and industry research has not been studied in more depth by academia, suggesting a communication gap between the two branches of research; this was also the case for research into application methods.

KEYWORDS: Sanding; Wheel/Rail Isolation; Wheel/Rail Damage; Sand Application.

1. INTRODUCTION

Sanding has long been used as a means of countering loss of traction when low adhesion conditions are present in the wheel/rail contact. Sand particles have the ability to break up the contaminant layer that causes low adhesion conditions and aids the transfer of traction from wheel to rail, though sanding can also have negative results, namely wheel/rail isolation and surface damage. A previous paper[1] has reviewed the research regarding traction restoration, whereas the purpose of this paper is to review the research surrounding the aforementioned negative effects of sanding. In addition, research concerning the application of particles into the wheel/rail contact will also be reviewed.

A safety feature of the railways is the use of train detection. Track sections are bounded using insulated rail joints and along the track section an electrical signal is sent from one end and received at the other end, this is a track circuit. If a train is present the track circuit is shorted out and the train is detected, this set-up is summarised in Figure 1~~Figure 1~~. Wheel/rail isolation or wrong side track circuit failure (WSTCF) occurs when the trains wheels are insulated by a contaminant layer, resulting in no short circuit occurring and the appearance of no train on the track section which can lead to safety issues. The relationship between sanding and the prevention of isolation will be studied in section 3.

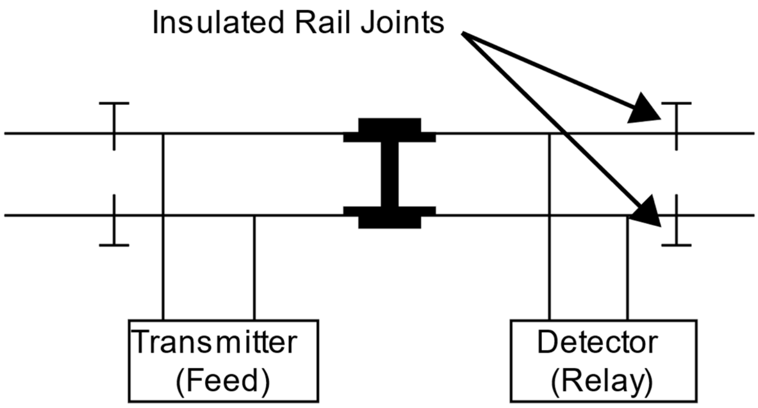

Figure 1 – Track Circuit Schematic.

Damage to the rail and wheel surfaces due to the presence of abrasive particles is a real possibility. Sand particles are mostly comprised of quartz,[2] which is harder than rail steel.[3] When hard particles go through a contact, they can abrade the surface causing damage.[4] The amount of damage caused by sanding is discussed in multiple papers which will be reviewed in section 4 of this paper.

Abrasive particles are applied to the wheel/rail contact one of two ways; they can be applied to the contact using a stream of air or they can be suspended in a gel, for the purposes of this review the former will be referred to as dry particles and the latter traction enhancers. Both are applied to the wheel/rail interface or rail using train-borne equipment, but traction enhancers can also be applied using a track-side set-up called a Traction Gel Applicator (TGA). The bulk of the application work that has been conducted is included within section 5 of this review.

Currently, the extent of the accumulated research into sanding is not fully known. This review aims to remedy this issue and summarise the findings of the research and look at what work has been conducted into the negative effects through a gap analysis.

The objectives to achieve this goal are as follows:

- Review the current research into the impact dry particles and traction enhancers have on wheel/rail isolation and damage.
- Review the research into application methods of dry particles and traction enhancers, as well as new application methods.
- Conduct a gap analysis and find conclusions and areas where further work is needed.

The testing methods used in the reviewed papers can be categorised into: twin disc set-ups, linear full-scale rigs, and field tests. As the realism of these methods increase there is generally a reduction in the control of variables, this was outlined in more detail in the review of sanding tribology.[1]

2. CURRENT SANDING STANDARDS

The rail safety and standards board (RSSB) are an independent body, working with industrial partners to drive improvements in the British rail system, which includes managing the GMRT2461 standard for sanding operations.[2] The standard specifies the necessary criteria for sand application under braking which has been summarised in Table 1.

Table 1 – Sanding System Standards under Braking.

	≥8 Wheelsets	<8 Wheelsets
Feed Rate (kg/min/rail)	2	2
Minimum Number of Wheelsets between Sanders	6	4
Location of First Sander	To the rear of the second wheelset in direction of travel	In front of the leading wheelset in direction of travel
Location of Last Sander	>6 wheelsets before rear of the train	>4 wheelsets before rear of the train
Minimum Train Speed (mph)	10	10

The traction requirements are much less complex, the standard requires the sand to be fed at 2kg/min/rail for a pure traction system. It should be noted that this discharge rate does not need to be continuous e.g. a discharge rate of 4kg/min/rail for 30 seconds followed by 30 seconds of inactivity would meet the standard.

The absolute minimum sanding requirements, set out by GMRT 2461,[2] state that the sand should be applied by the leading vehicle after the third wheelset in the direction of travel.

Though the sand is normally applied automatically, the standard[2] states that the driver can override the automatic application in certain areas such as through switches and crosses to avoid damaging bearer surfaces. It should be noted that the application of sand is not used in anticipation of low adhesion, as there are no benefits and in the worst case can cause train isolation.

The standard also deals with mechanical aspects of the sander. These mostly focus on achieving a steady sand application rate directed just in front of the wheel/rail contact. Included in section 5 is more research looking into the optimum sander set-up for maximum particle entrainment.

The guidance from the RSSB concerning sand boxes encompasses the following:

- The sand box should not consist of shallow angles, this is a way of avoiding blockages.
- Sand boxes that operate on the Venturi principle should have adequately sized breathers that are positioned away from areas where contamination is rife.

- Care should be taken to keep the sand dry, this includes preventative measures such as using adequate seals or curative measures such as heating within the sand box.
- Sand box storage capacity should be adequate for the journey being undertaken, a sand level monitoring system can assist with this.

The same standards also provide guidance on the hose and nozzle sand delivery system:

- The hose length should be as small as possible.
- The sand needs to applied to both rails, this means two hoses are needed per sander.
- The combining of a large diameter hose with a smaller diameter nozzle can increase the amount of sand going into the wheel/rail contact, though small bore sizes can reduce the flow rate.
- The nozzle should be straight and made of stainless steel.
- The discharge nozzle should be kept at an angle of 10-15° relative to the rail.
- Sags in the hose should be eliminated to keep up the discharge rate.
- The discharge nozzle should be as close to the wheel/rail interface as possible.
- The nozzle should be aimed at the centre of the rail head.
- Non-corrosive materials should be used as much as possible to maintain performance.

It should be noted that an RSSB report into sander set-ups[5] found that many sanding systems were not dispensing the required amount of sand out of the hose. The report specified the lack of regular maintenance and ineffective design as the root causes with the current sanding standards detailed in this section being a response to this.

3. THE EFFECT OF PARTICLES ON ISOLATION

Trains on the line are sensed via an electronic current running through sections of rail known as track circuits. If these rails are short circuited by the wheels of a train then detection has occurred, when the wheels are insulated from the rail by a contaminant then the train cannot be detected and isolation has occurred. As sand is insulating, too large a quantity between the wheels and the rails could result in the loss of train detection potentially leading to accidents.[2]

The sanding equipment standards supplied by the RSSB[2] state that the factors affecting isolation include:

- The position of the first sander on the locomotive.
- The number of wheelsets between sanders.

- The number of wheelsets after the last sander on the locomotive.
- Sanding feed rate.
- Properties of the sand being used.
- Axle load.

It should be noted that in work conducted by the RSSB,[6] using field data, the viability of applying sand during braking was assessed using RSSB's Network Modelling Framework Safety Module. This approach calculated that reduction in risk of SPADs was 170 times greater than the risk of isolation occurring, in fact it was found that only 3% of isolations were caused by sanding with the rest coming from contamination. These findings suggest that whilst it is important to consider isolation when designing a sanding system, the ability of the system to remove contaminants is of much greater importance.

The following sections detail the research that has previously been carried out to assess the effect particles have on isolation in the wheel/rail contact.

3.1. Dry Particles

3.1.1. Twin-Disc Set-up

The laboratory tests studying isolation have mostly been conducted on twin-disc set-ups, such as the study by Arias-Cuevas et al.[7] The investigation showed that sand size plays an important part in the likelihood of isolation occurring in the contact, with fine and medium sized sand particles (0.06-0.3mm and 0.3-0.6mm respectively) being more likely to cause isolation, this was shown in Figure 2.

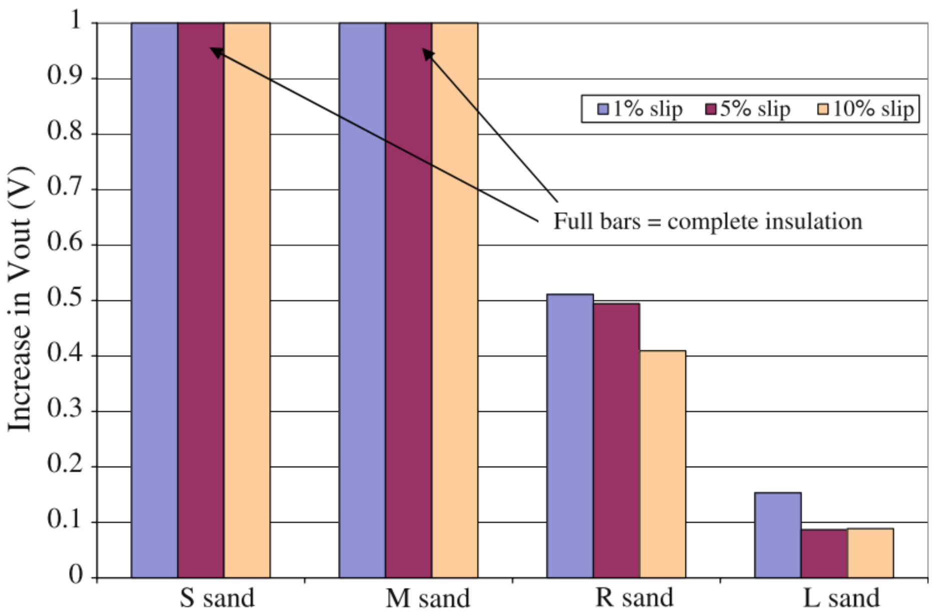

Figure 2 – Electrical Isolation Occurrence for Different Particle Sizes.[7]

Arias-Cuevas et al.[7] suggested this may be due to smaller particles not breaking up and being ejected upon entering the contact thus allowing a layer of sand to build up on the disc. The schematic Arias-Cuevas et al. used to illustrate this hypothesis is shown in Figure 3.

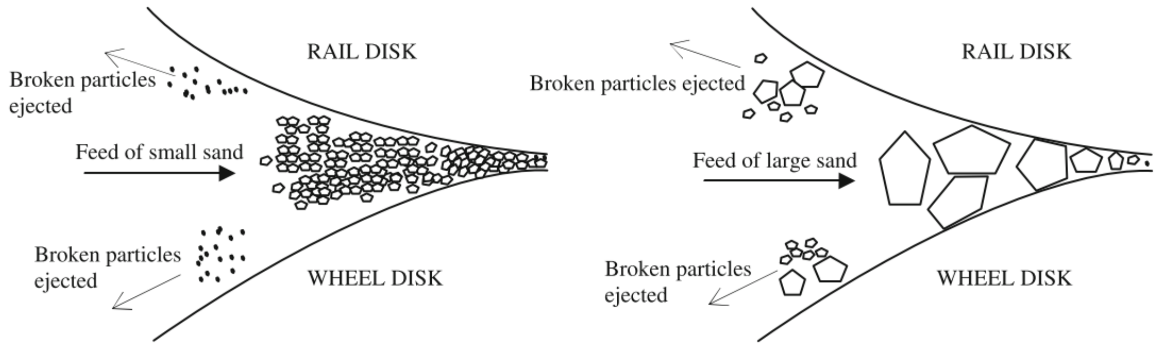

Figure 3 – Schematic of Sand Entrainment at Different Particle Sizes.[7]

On a similar test set-up Lewis et al.[8] conducted a more detailed and fundamental investigation into isolation caused by sanding. Their experimental work found that there was a critical discharge rate at which isolation would occur, the same conclusion that Arias-Cuevas et al. drew. Lewis et al. also formulated a simple model of isolation in the contact which was based largely on Bowden and Tabor's work.[9] This model predicts that the amount of contact points needed for effective conductance between wheel and rail is in the order of magnitude of 100 points, this is a tiny proportion of the nominal contact area and suggests that for isolation to occur there needs to be a complete separation of the surfaces by a sand layer. It also means that the voltage across the surfaces is effectively binary, the voltage being either at 0V or at the open circuit voltage.

A more complex isolation model, using discrete element modelling (DEM), was formulated by Descartes et al.[10] Their work principally studied the effects of contaminant layers, which they modelled as a large number of particles, meaning it could possibly be adapted to model individual sand particles.

Another isolation causing factor to consider is whether there is enough sand being applied. Previous field work[2] identified a critical sand density of 7.5 g/m above which isolation would occur. Lewis & Masing[11] and Lewis et al.[8] found that the amount needed to cause isolation was significantly higher than the 7.5 g/m mark. Their results are converted into sand concentrations (kg/m^2) with the "rail at 10mph" value being obtained by dividing the sand density (7.5 g/m) by an estimate of rail head width (50mm), there results have been summarised in Table 2.

Table 2 – A comparison of critical sand concentrations calculated with different testing regimes.[11]

Experimental Method	Critical Sand Concentration (kg/m^2)
Static	0.3
Twin Disc at 2mph	0.75
Rail at 10mph	0.15

Work has been conducted concerning the effect the addition of both water and sand had on isolation; one might think the water's presence would decrease the likelihood of isolation but this was not the case. Both static tests by Lewis et al.[11] and dynamic tests by Lewis et al.[8] have shown that the presence of water reduces the amount of sand needed to cause isolation. In the static case, it was put forward that this was due to some form of the meniscus effect holding neighbouring particles together and preventing them from being pushed out of the contact under load; in the dynamic case, it was suggested that capillary action was entraining particles into the contact. These conclusions are affected by the contact conditions: the same static study found that under lesser contact loads the conductance between surfaces increased with the presence of moisture.

The previously mentioned static tests by Lewis & Masing[11] suggested that leaves and sand mixed together were more likely to cause isolation than either would just on their own. This conclusion is not surprising on a static test, where the powder created could not be carried away through the contact by the presence of shear forces such as in the experiments conducted by Arias-Cuevas et al.[12] which found that the presence of sand in a leaf layer removes said leaf layer thus reducing the risk of isolation.

3.2. Traction Enhancers

3.2.1. Twin-Disc Set-up

Very little work concerning traction enhancers' effect on isolation was sourced by the authors though there has been one such study from Lewis et al.[13] They found evidence that the presence of traction gel in a leaf contaminated contact was effective at decreasing impedance between the wheel and rail. The results, shown in Figure 4, also suggest that between 5-10s the impedance falls close to uncontaminated levels, which according to Lewis et al. occurred when the excess gel started to evaporate suggesting that the gel caused more impedance than the sand though this may also be due to more of the isolating leaf layer being removed.

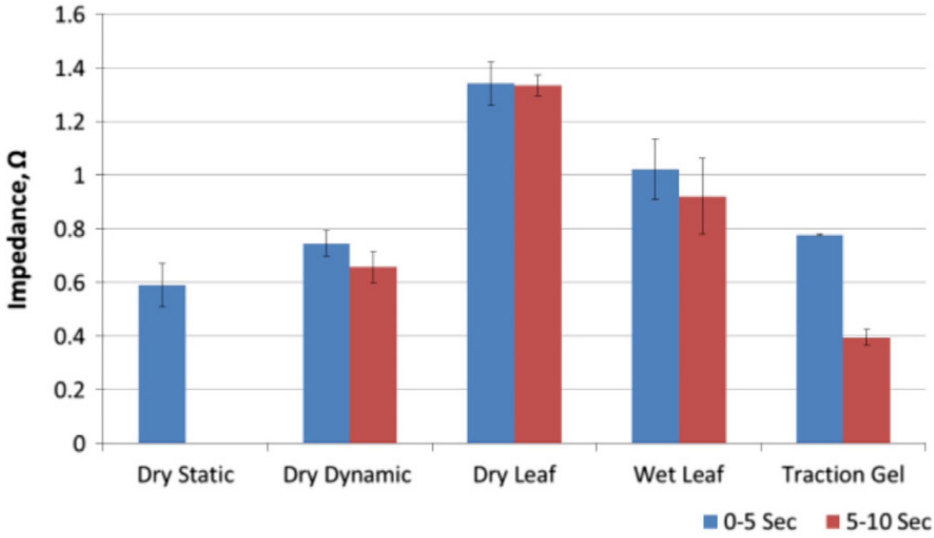

Figure 4 – Impedance between Wheel and Rail with Different Intermediary Layers.[13]

3.2.2. Field Tests

The only identified field work on isolation was by Zobel,[14] who studied the effects a traction gel called "slipmaster" had on isolation. Slipmaster is made up of sand suspended in an aqueous fluid which includes thickeners and corrosion inhibitors. Zobel found that as the train speed decreased the traction gel had a larger effect on isolation, however one layer alone was never enough to cause isolation. He also saw evidence that trains at lower speeds did not remove the gel suggesting that slipmaster applied at low speeds would build up, resulting in an isolation problem.

4. THE EFFECT OF PARTICLES ON DAMAGE

As the adhesive effect of the hard particles is dependent on them indenting and transferring traction from wheel to rail, inevitably there will be some damage to the surface. The amount of damage is important, but only as important as the damage mechanism that is occurring, for example abrasive wear could present a maintenance issue, but it's unlikely to cause a safety issue unlike a high amount of ratchetting fatigue.

4.1. Dry Particles

4.1.1. Twin-Disc Set-up

The exact amount of wear sand can cause is hard to quantify on twin-disc set-ups, due to almost all the sand being entrained and the much smaller geometry of the discs resulting in much more severe wear than would be expected in the field. Kumar et al.,[15] found that the application of sand into the wheel /rail contact increased the amount of wear by an order of magnitude of between 1 and 2, a very large increase and a possibly costly one.

Similarly, Lewis & Dwyer-Joyce[16] also found that sand particles being fired into the wheel/rail contact greatly increased wear compared to an unsanded contact. In Lewis & Dwyer-Joyce's tests three different scenarios were tested: dry with no sand, dry with sand, and wet with sand. In all scenarios, the wear at the wheel was always more than at the rail, this is unsurprising for the case with no sand as the wheel surface was softer (1.9 GPa) compared to the rail surface (2.9 GPa). In the sandless scenario the wear mechanism seemed to be ratchetting of the surface, with the wheel undergoing more delamination than the rail. The full results have been shown in Figure 5 were the amount of damage is analogous to the wear rate.

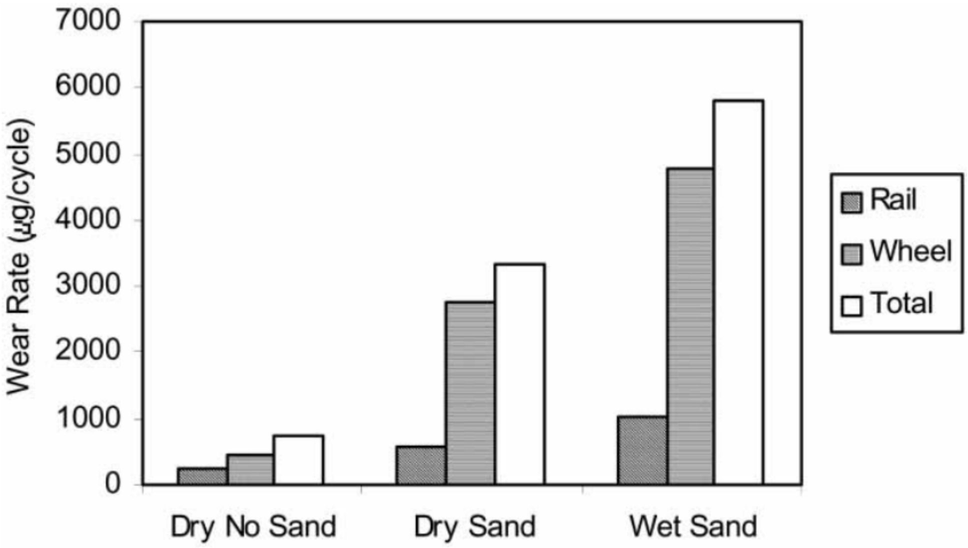

Figure 5 – Wear Rates Under Different Sanding Conditions.[16]

Furthermore, Lewis & Dwyer-Joyce found evidence of two body abrasion occurring in the contact as the sand indented the wheel and caused abrasion scars along the rail. It would be expected that this would result in higher wear rates in the rail (harder surface) than the wheel (softer surface) which was untrue in this case. Instead, Lewis & Dwyer-Joyce concluded that the sand indentation at the wheel surface was causing fatigue damage leading to spalling at the wheel surface. The wear features they identified are shown in Figure 6~~Figure 6~~. This observation has been backed up similar work done by Arias-Cuevas et al.[17] and Wang et al.[18]

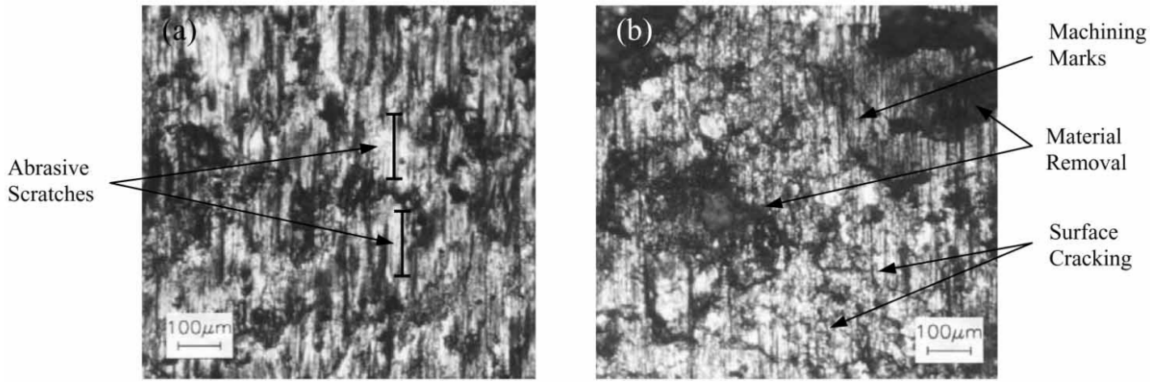

Figure 6 – Damage Features for *(a)* Rail Disc and *(b)* Wheel Disc.[16]

The Lewis & Dwyer-Joyce experiments[16] also assessed the effect the presence of moisture had on the damage. Results indicated that wet conditions seemed to almost double the wear rate at both wheel and rail compared to dry conditions, it was posited that this was due to sand particles sticking to the wheel and rail via meniscus effects and entrained via capillary action; a schematic of this effect has been included in Figure 7~~Figure 7~~.

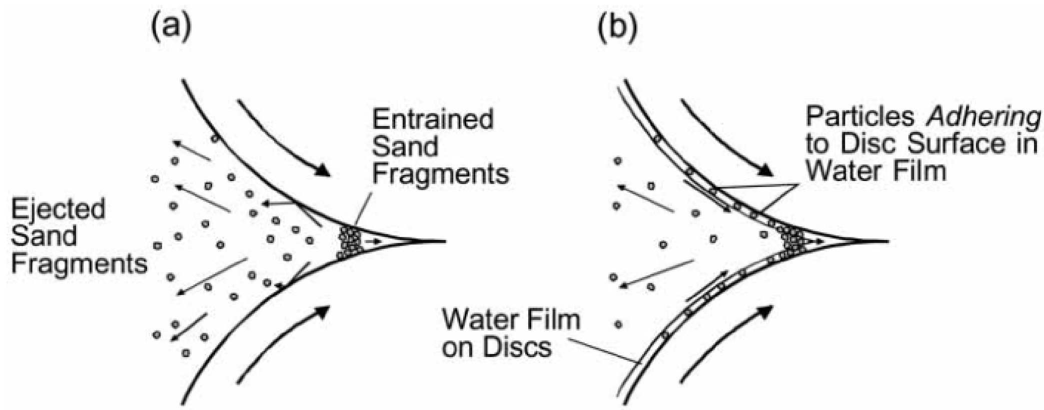

Figure 7 –Schematic of Particle Entrainment in *(a)* Dry Contacts & *(b)* Wet Contacts.[16]

Arias-Cuevas et al.[17] conducted a study to assess the effects particle size and slip in the contact had on the damage being caused to the wheel/rail surfaces. They found that smaller particles (<0.3mm) at lower slip rates (1%) produced a coating of crushed sand embedded into the disc surfaces, this may have been due to: the lower slips not abrading the surface as much therefore leaving the coatings intact or that less of the smaller particles are being entrained into the contact thus not being present in large enough numbers to be able to form the coating. At higher slips and larger particle sizes indentations in the surface were observed with no coating being present.

Furthermore, Arias-Cuevas' work seemed to show that when the sand separated the surfaces fully (when isolation was present) there was little plastic deformation compared to instances with metal to metal contact at similar adhesion levels. Arias-Cuevas posited that this may be due to the sand acting as a solid lubricant, protecting the surfaces whilst still being embedded into them, transferring traction and keeping adhesion high. Where large particles and slips were applied to the contact there was evidence of greater work hardening being present which correlated with a high adhesion coefficient, the images Arias-Cuevas et al. drew these conclusions from have been included in Figure 8 and Figure 9.

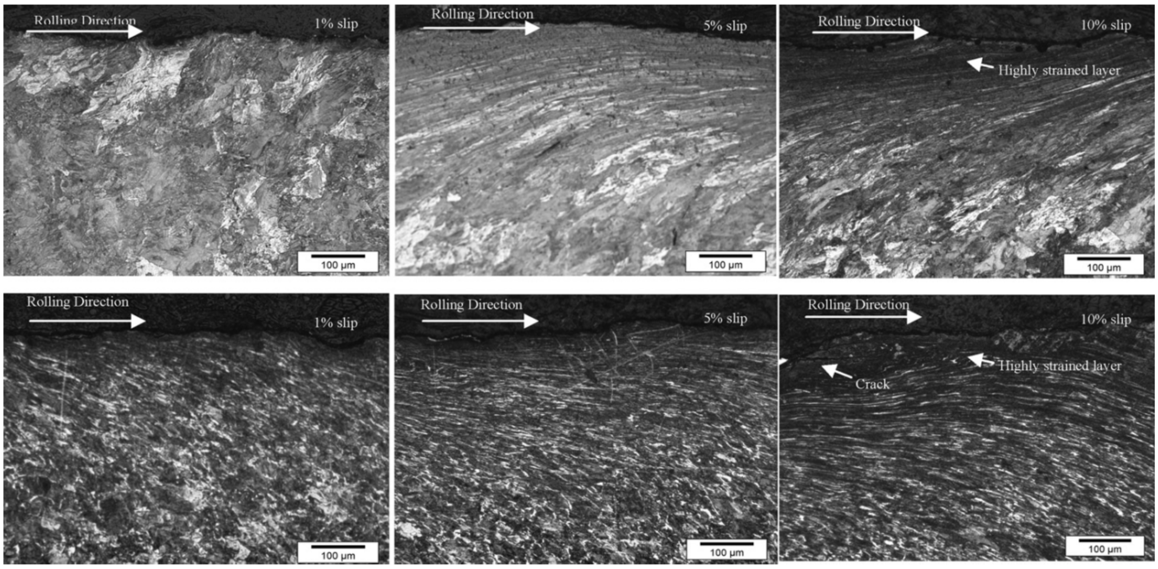

Figure 8 – Sections Parallel to Rolling Direction Using R Sand: *(Top)* Rail section, *(Bottom)* Wheel Section.[17]

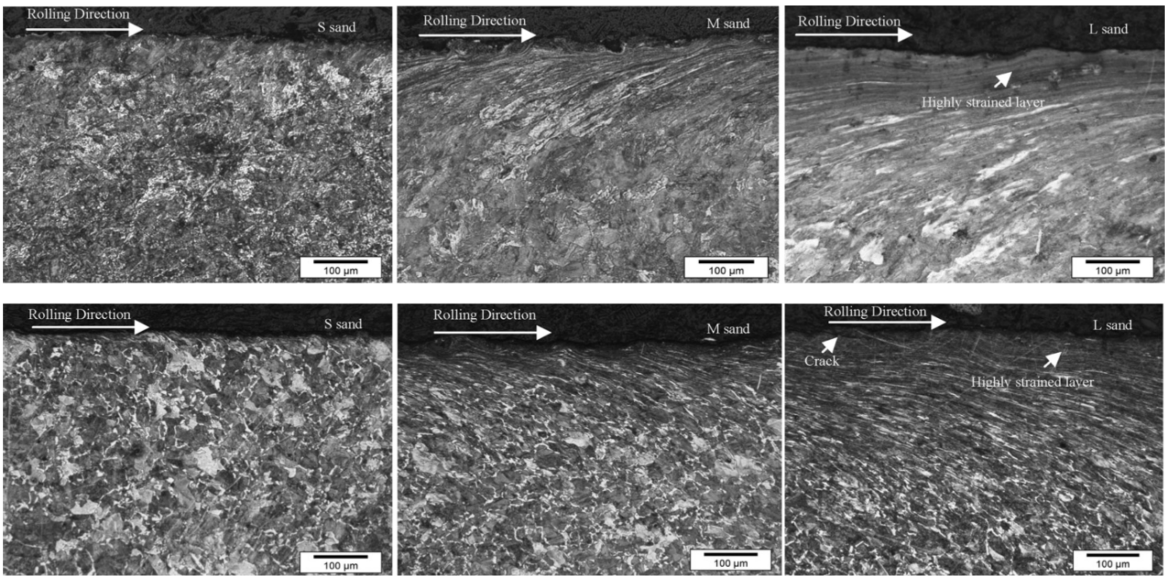

Figure 9 – Sections Parallel to Rolling Direction Using 5% Slip: *(Top)* Rail section, *(Bottom)* Wheel Section.[17]

Arias-Cuevas also took surface roughness measurements of all the discs and found that higher slips caused greater roughening, probably due to the lengthened abrasion scars caused by the sand in the contact. The same measurements also showed the medium sized particles (0.3-0.6mm) caused the most wear, possibly because they struck the balance between causing larger indentations than the small particles but being more easily entrained into the contact than large particles therefore causing greater damage due to sheer number of particles.

Lastly Arias-Cuevas saw that at high slips larger particles created more wear (measured through mass loss), in large part due to plastic deformation and spalling due to ratchetting at these higher slips being aggravated by the larger particles. This trend did not exist at low slips however, as the only wear mechanism was abrasion and as less large particles entered the contact compared to medium and small particles less abrasion occurred. These results are shown in Figure 10 where the size categories are the described in Table 3.

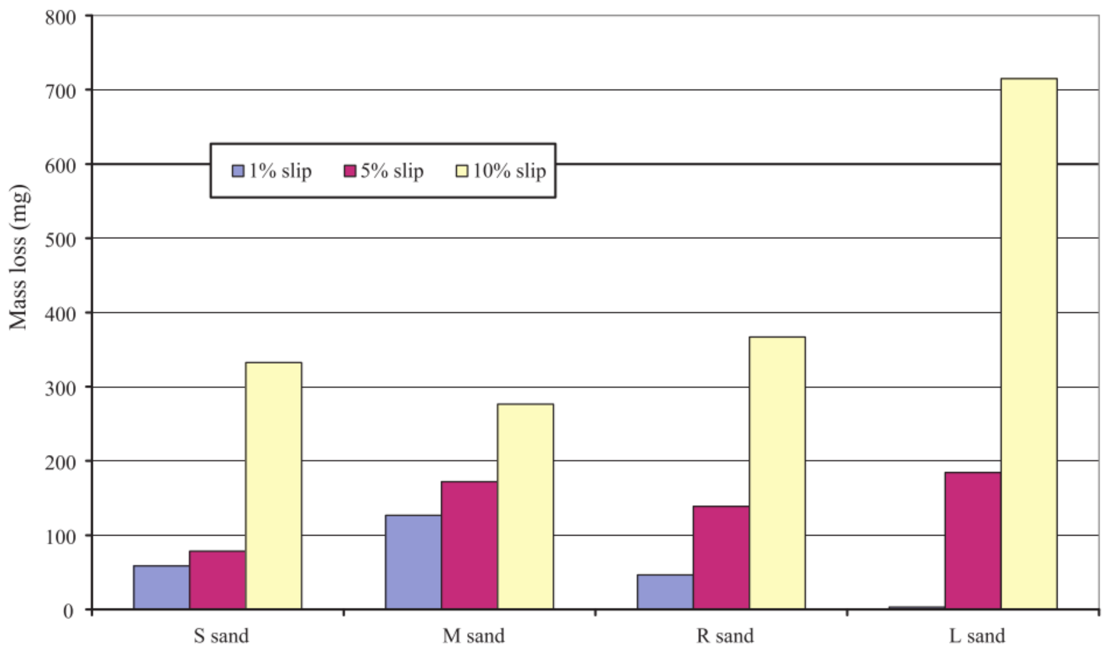

Figure 10 – Mass Loss due to Wear at a range of particle sizes and slip rates.[17]

Table 3 – Particle Size Categories as used by Arias-Cuevas et al.

	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

More particles than just sand have been assessed. A study by Wang et al.,[18] investigated the effect alumina particles had on wheel/rail damage when applied to the contact, these results are shown in Figure 11. Though it should be noted that the alumina particles were five times smaller than the sand particles, the alumina caused 3 times less wear whilst still being a more effective adhesion enhancer than the sand particles in some situations. These results are promising and may bear greater scrutiny going forward.

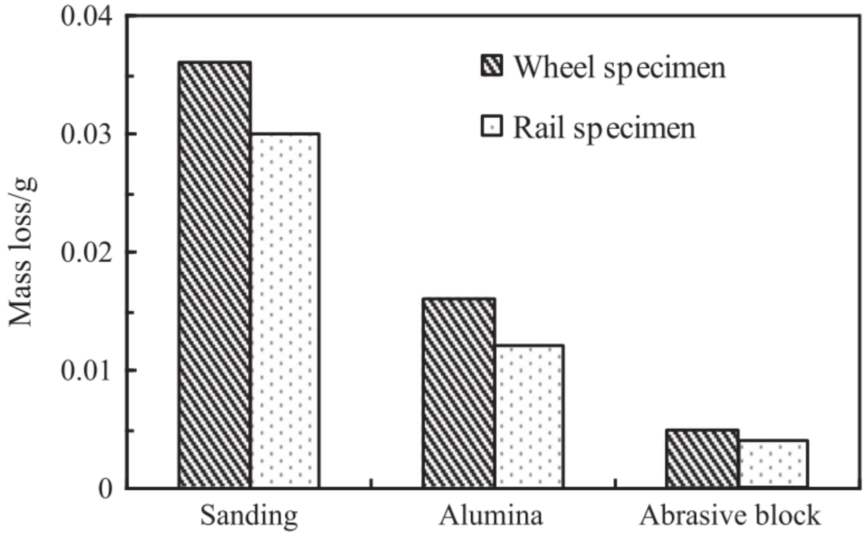

Figure 11 – Mass Loss for Different Particle Systems.[18]

4.2. Traction Enhancers

4.2.1. Twin-Disc Set-up

The consensus on damage caused by traction enhancers is that they reduce the amount of wear in the contact compared to a dry rail. This was the case in a study carried out by Lewis et al.,[13] though this may have been due to the traction gel particles abrading the leaf layer as opposed to the rail itself whereas traction enhancer on a dry contact may cause more damage. The results have been included in Figure 12.

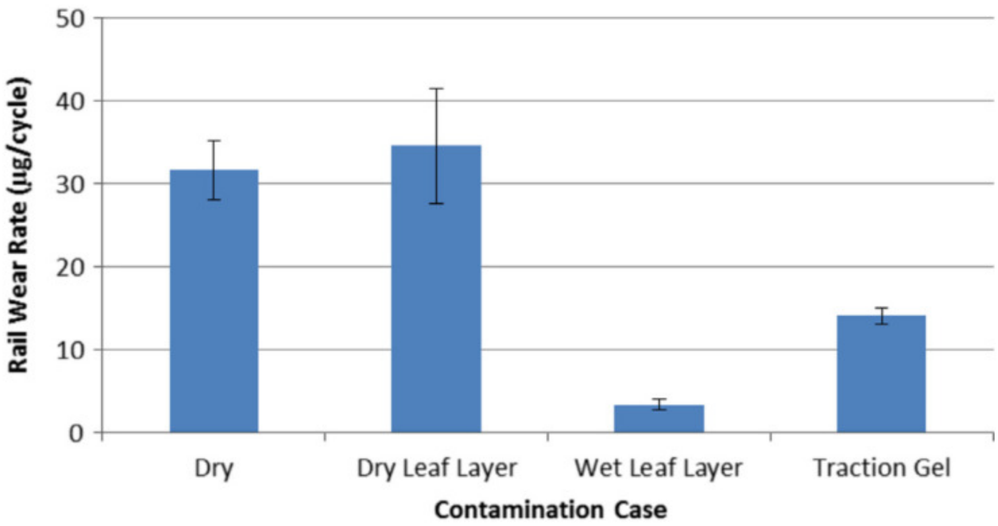

Figure 12 – Wear Rates with Different Intermediary Layers.[13]

Further damage research was conducted by Li et al.[3] who found correlation between size of particles used in the traction enhancer and the amount of damage to the surface. The conclusion was that larger, harder particles seemed to cause more wear, which is an unexpected result and in line with what was found for dry particles and may be due to the gel aiding entrainment of these larger particles.

Arias-Cuevas et al.[19] have also conducted work into the effect traction gels have on damage in both a wet and a dry contact. In dry contacts he found evidence that the traction gels reduced the amount of wear, on both wheel and rail, by effectively lubricating the contact whilst keeping adhesion at an acceptable value; this reduction in damage was especially prevalent in the traction gel with particles <100µm, corroborating Li's results. The results from Arias-Cuevas et al. have been summarised in Table 4 where FMA and FMB are two types of commercially available traction enhancers.

Table 4 – Mass Loss Comparison Between Different Traction Gels.[19]

	Dry		**FMA**		**FMB**	
	Wheel	**Rail**	**Wheel**	**Rail**	**Wheel**	**Rail**
Mass Loss (mg)	114.9	90.1	30.3	28.4	109.6	70.5

5. APPLICATION OF PARTICLES INTO THE WHEEL/RAIL CONTACT

The following sections involve research conducted into the mechanical application of particles into the wheel/rail contact. The reviewed papers mainly focus on the efficacy of application systems and what measures can be implemented to maximise the number of particles being entrained into the wheel/rail contact, therefore reducing the amount of sand not entering the contact and being wasted.

5.1. Dry Particles

5.1.1. Location and Frequency of Application

Usually the frequency with which the sanding procedure is used is dependent on the levels of adhesion being measured in the interface, i.e. when significant sliding occurs between the wheel and rail (significant sliding is defined as the wheelset rotational speed being ≤95% of the true train speed[2]). In addition, the sand application will normally engage whenever the locomotive is undergoing emergency braking.

5.1.2. Mechanical Aspect

The application of sand into the wheel/rail contact will depend heavily on the amount of sand being discharged from the hose; the T796 RSSB report undertaken in 2009 found huge variance in discharge rates with an average discharge rate of 1.148kg/min[5] (it should be noted that industry believes this situation has improved since this report). The report also investigated different sanding system parameters to try and diagnose the cause of low discharge rate.

The effect of hose lengths on discharge rate are dependent on the system being used. The work in T796 found that shortening or removing hoses on Venturi plate systems generally increased discharge rate, whilst for pressurised air systems there was no discernible difference, overall it was recommended that short hose lengths should be used. The report also studied the hose configuration, i.e. straight, bent, sag, no sag: the existence of sag in the hose reduced the discharge rate whereas tight bends seemed to have no effect.

The same study[5] analysed the effect the diameter of the sand exit point on discharge rates. The study concluded that onsite testing produced some weak evidence to suggest the discharge rates increase with exit diameter. This was partly backed up by a controlled test of a sand hose that measured discharge rates with a 19mm nozzle and 25mm nozzle; the discharge rate more than doubled for the larger nozzle. Whilst a smaller diameter nozzle does reduce the discharge rate this can be compensated for by using a higher regulator pressure.

If a smaller diameter nozzle is utilised, tests carried out on a full-scale rig by Lewis et al.[20] have shown a marked increase in the amount of sand going through the contact with a nozzle attached to the end of the hose, these results are shown in Figure 13. This was due to the nozzle focusing the sand stream more precisely at the contact. The optimum hose configuration derived from these results was a 25mm bore diameter hose with a nozzle attached.

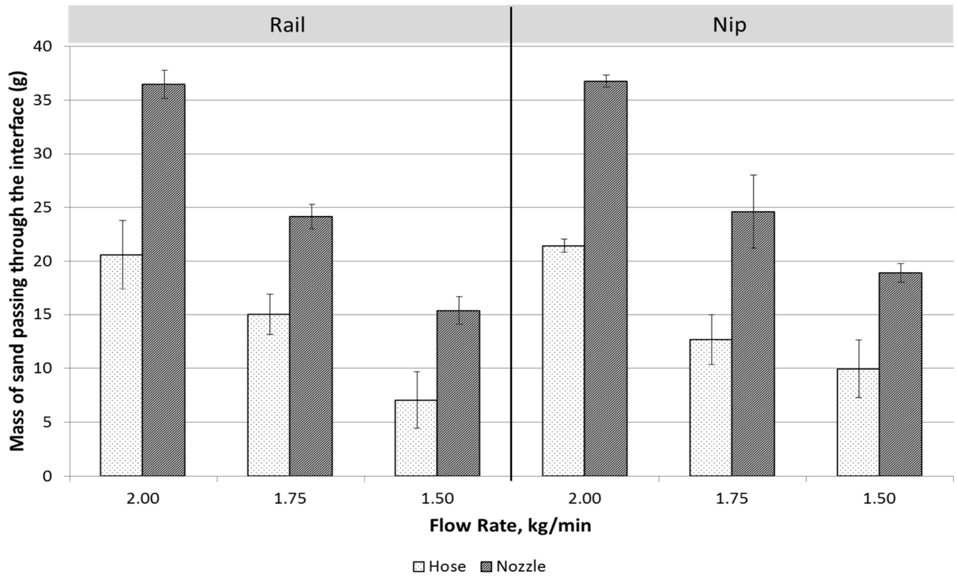

Figure 13 – Effect of the Nozzle on Sand Entrainment.[20]

A common sand application system uses an orifice plate to discharge sand from the sandbox. The orifice plate has two holes in it: one hole directs the air into the sand reservoir to agitate it; the other hole uses the Venturi effect to draw the agitated sand into the hose. A typical orifice plate is shown in Figure 14.

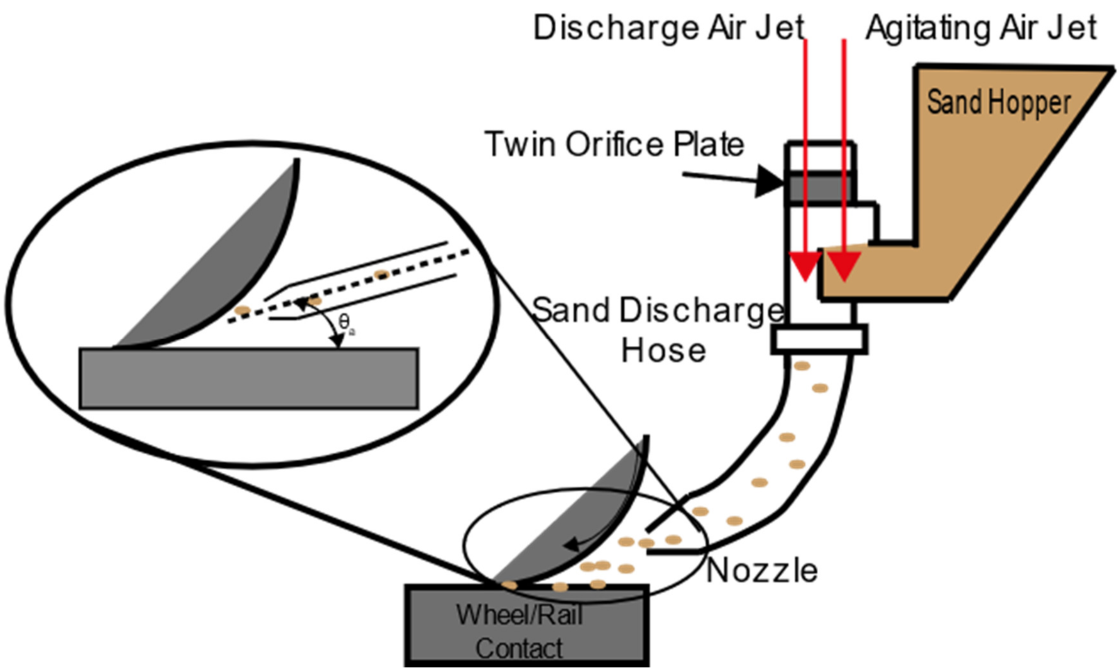

Figure 14 – Orifice Plate Sanding Valve with Angle of Attack (θ_a).

All sandbox designs that use the Venturi effect to draw sand into the hose require a breather to prevent the formation of a vacuum.[5] The breather design has a large effect on the discharge rate as it must shield the sand from contaminants whilst allowing enough air to prevent vacuum. It is vital to ensure that the moisture content in the sander is kept very low as Zobel found that as little as 2-3% moisture content could prevent the sand being ejected from the sand box.[21]

The sanding system's ability to aid adhesion will be very dependent on the amount of sand it can deliver into the wheel/rail interface. Any sand not going into the interface is increasing cost and reducing effectiveness. Much of the work cited here was undertaken by Lewis et al.,[20,22] who studied the entrainment of sand into the wheel rail contact on a full-scale rig; in all these tests the wheel travelled over 600mm at a maximum speed of 50 mm/s.

5.1.2.1. Angle of Attack

The angle of attack can be defined as the angle between the rail and the direction of discharge, a schematic has been included as part of Figure 14.

The angle of attack between the hose and rail does not affect the discharge rate,[5] but it does affect the entrainment of sand into the contact. Lewis et al.,[20] found that shallower angles of attack resulted in an increased amount of sand entering the contact. These results are summarised in Figure 15 where the angles of attack were varied with target area: the rail, the nip (where the wheel and rail meet), and the wheel. Each measurement of sand passing through the interface was conducted after one wheel pass. A shallow angle of attack of 15° aimed at either the rail or nip seems to entrain more particles with the latter doing so more consistently.

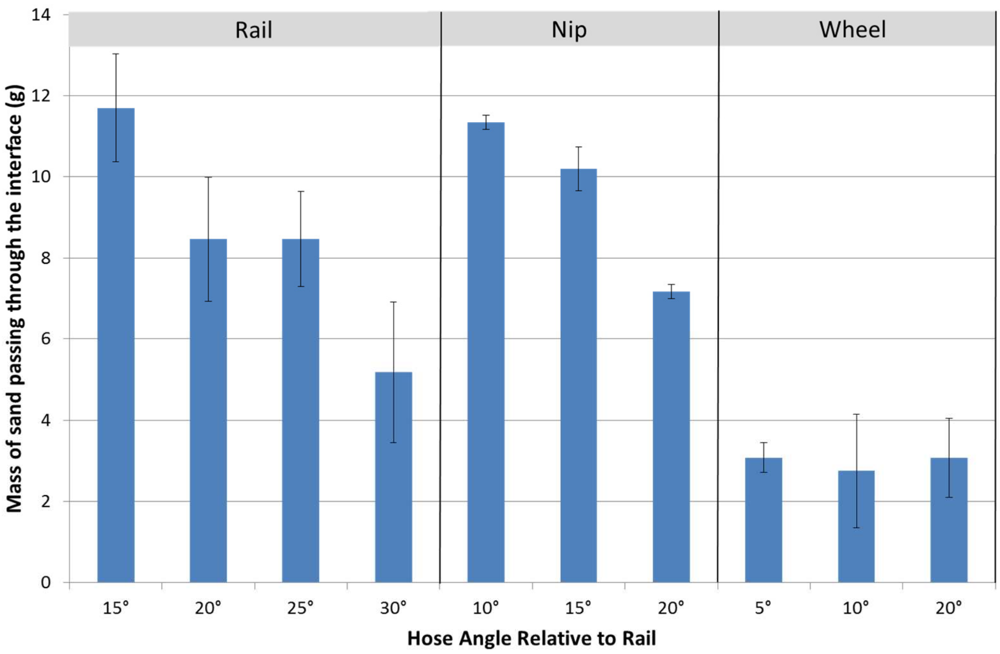

Figure 15 – Effect of Angle of Attack and Application Direction on Entrainment over one Wheel Pass.[20]

High speed stills taken from the Lewis et al. work[20] have been included in Figure 16. With higher angles of attack the particles bounce away from the contact and when aimed at the wheel the particles seem to bounce straight off and away. These stills corroborate the findings from Figure 15, particles bouncing on the rail may go anywhere and will do so unpredictably whereas those particles hitting the wheel will just bounce away.

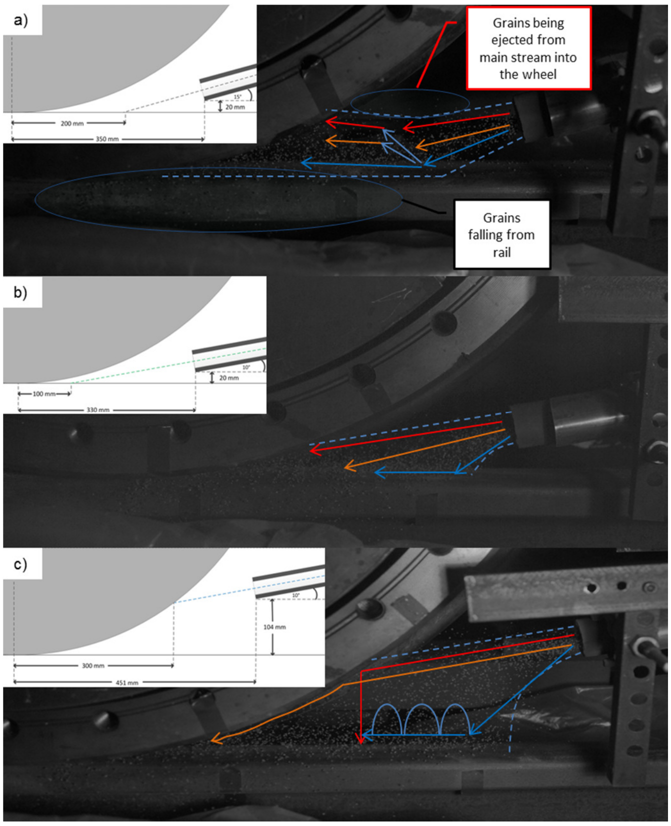

Figure 16 – High Speed Stills; *(a)* hose aimed at rail with 15° angle; *(b)* hose aimed at wheel/rail nip with 10° angle; *(c)* hose aimed at wheel with 10° angle.[20]

5.1.2.2. Nozzle Alignment

Lewis et al.[20] investigated the effect the hose alignment and position had on the amount of sand being entrained into the wheel/rail contact. Unsurprisingly, the amount of sand entering the contact increased the closer the hose exit was placed to the contact, meaning more sand was directed at the contact as the discharge pattern would be more closely grouped from shorter distances away.

The hose alignment was shown to have a large effect on entrainment, the optimum condition found by Lewis et al. was a hose pointed directly at the wheel/rail centreline with the hose running parallel to the rail. Any slight misalignment was shown to have a detrimental effect on entrainment. The effect of the hose's lateral position from the centre line is shown in Figure 17 (Top) and effect of the nozzle alignment angle is shown in Figure 17 (Bottom).

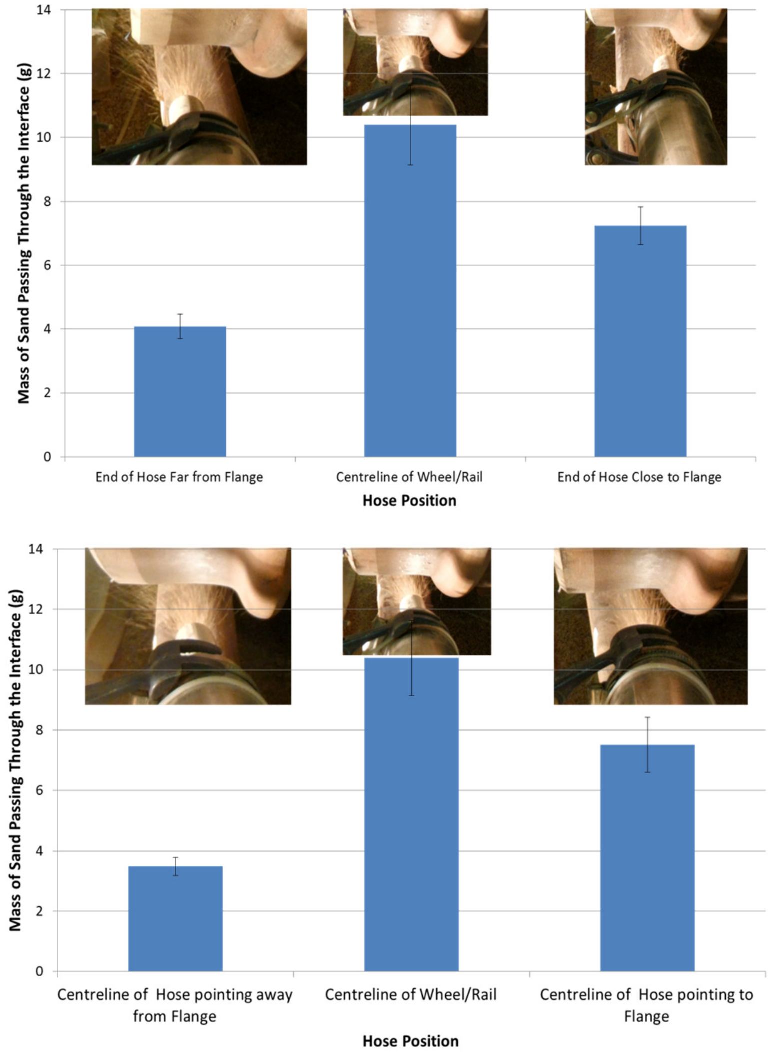

Figure 17 – Effects of Changing: *(Top)* Lateral Alignment, *(Bottom)* Nozzle Alignment Angle with Respect to the Rail Direction over one Wheel Pass.[20]

5.1.2.3. Discharge Pattern

The discharge pattern from the nozzle to the rail head is an important parameter for optimum sand entrainment into the wheel/rail interface. In static tests conducted indoors, nozzles focused the sand stream more precisely onto the rail head,[5] though it should be noted that the lack of real world complications from crosswind etc. were not accounted for. The comparison between a wide and narrow discharge pattern and the subsequent amount of sand being entrained can be seen in Figure 18 where more sand is clearly entering the contact when the discharge pattern is narrow.

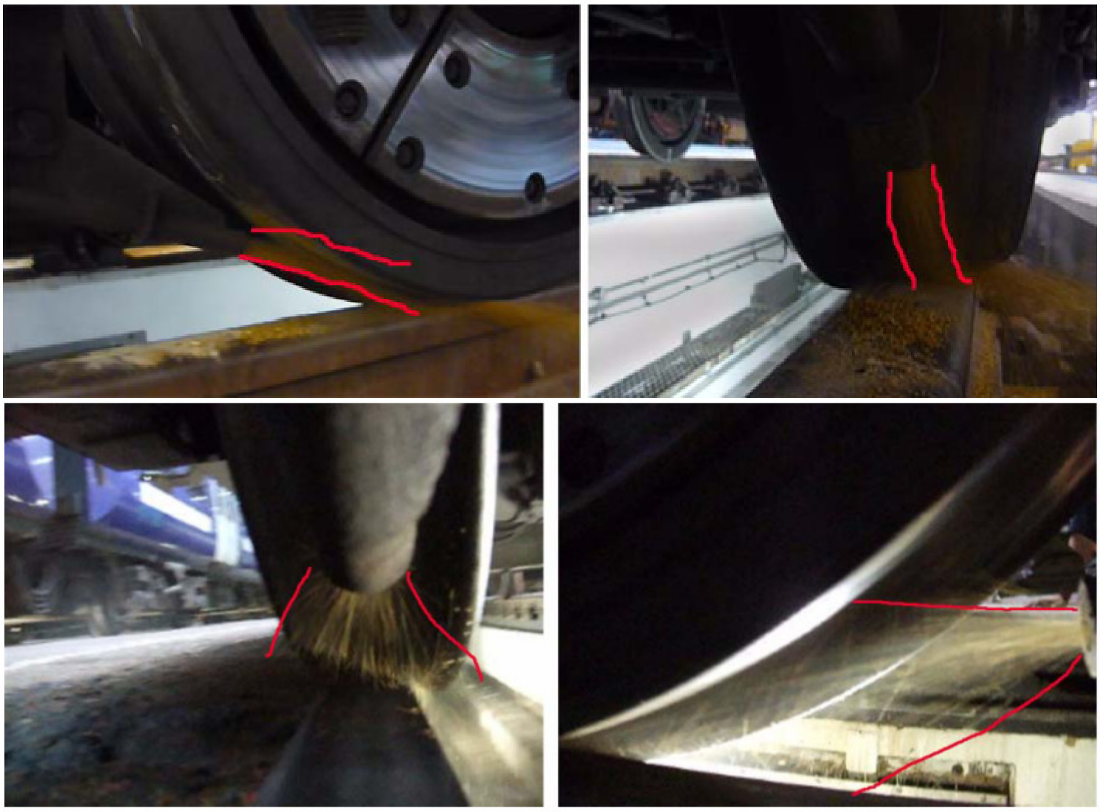

Figure 18 – *(Top)* Narrow Discharge Pattern vs *(Bottom)* Wide Discharge Pattern.[5]

5.1.3. Wind

The research conducted by Lewis et al.,[20] looked at the effect wind had on the application of sand into the contact. The work suggests that increasing the velocity of the air flowing parallel to the train's direction of travel gradually decreased the amount of sand entering the contact when dry conditions were present. This trend was reversed in wet conditions were higher air velocities increased the quantity of sand being entrained. Generally, wet rail seems to increase the quantity of sand being entrained. All these observations were obtained from the results shown in Figure 19.

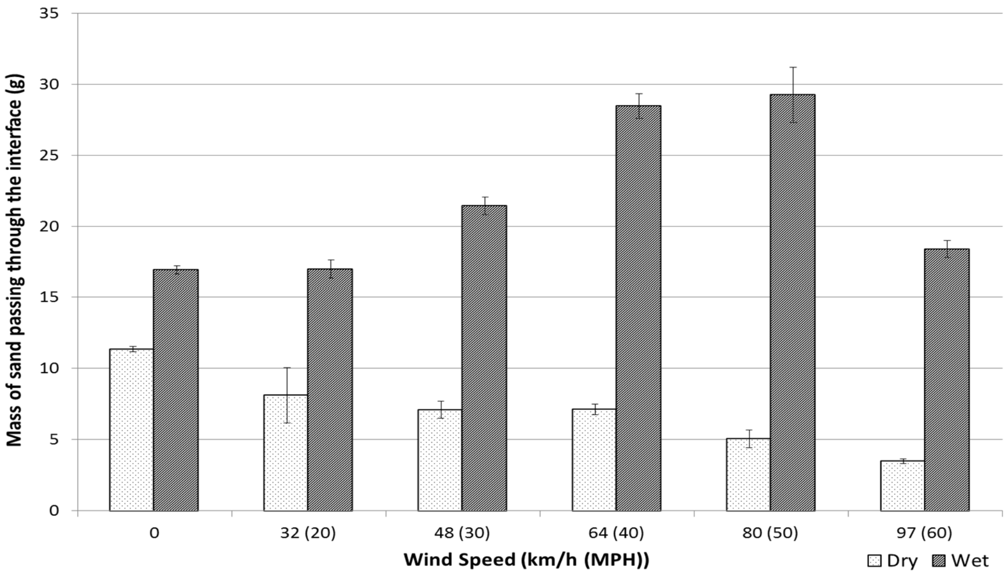

Figure 19 – The effect of Head Wind on Sand Entrainment over one Wheel Pass.[20]

The same study also investigated the effect of cross-wind on the amount of sand applied to the rail. The findings were that even a moderate amount of cross-wind may remove all the sand from the rail, making the sanding system effectively useless. Lewis et al. also suggested that these findings may have significant consequences for sanding systems being used at high train speeds; the speed of the train may cause the air flow to become turbulent, blowing all the sand away from the rail; evidence of this was found at head winds of 60mph as seen in Figure 19.

The speed at which the particles are discharged at seems to have a positive effect on the entrainment of particles into the contact,[23,24] probably due to lessening the effects of crosswind.

5.1.4. Effect of Sand Quantity on Adhesion Recovery

Whilst the previous sections have covered how to maximise the amount being entrained into the contact, this does not mean that maximising the amount of sand is the best tactic. Maximising entrainment is beneficial as it lessens the amount of wasted sand but the optimal quantity of sand in the contact is not clear. Lewis et al.[22] found evidence to suggest that quantities below 7.5 g/m/rail were ineffective at restoring adhesion whilst 106 g/m/rail was found to restore adhesion it resulted in a lower peak adhesion than lower quantities. The optimal sand quantity for restoring traction in the contact is between 7.5-106 g/m/rail judging from these results, however higher quantities will increase damage and the likelihood of isolation so these must be taken into account when finding the optimal sand quantity.

5.2. Traction Enhancers

An early examples of traction gel systems included mixing in sand into a water jetting system which was applied to the track by a specially modified train.[25–28]

A common traction enhancer used by the UK rail industry is a liquid-sand mixture known as sandite (sand and aluminium particles suspended in a silicate clay called Laponite which becomes a gel when water is added).[29,30] Sandite can be applied using modified trains or by trackside applicators, the former method can also utilise water jetting to first blast off contamination and initially improve adhesion before applying sandite to maintain this higher adhesion level.[30]

In work conducted by Garner[31] the application of traction enhancers was studied, specifically application using TGA's. TGA's use a peristaltic pump to send traction enhancer up a hose and onto the rail head; Garner found that pumping losses increased with hose length and pumping time. She also found that the traction enhancer with a higher viscosity did not flow as well through the pipe, also leading to a decrease in output. However, the higher viscosity traction enhancer stayed on the rails more leading to less wasted material and contamination of the ballast.

A Network Rail project conducted by Marshall[32] looked at certain aspects of traction enhancer application using TGA's. He found that a new type of cylinder applicator bar is more effective at delivering traction enhancer as it can apply across the rail with a length equal to the circumference of a typical wheel meaning more gel can be carried down by the wheel leading it to be effective for a larger length of rail section. He also found that there was no link between the flow rate of the traction enhancer and the amount of traction enhancer in the hopper, he did however find a weak correlation between rising climatic temperatures and increasing flow rate.

There are some yet untested traction foams, these are based on US 6,297,295 B1 patent,[33] the idea being that the sand particles are suspended in the foam allowing more control of the dispersion onto the rails.

5.3. Future Application Techniques

Some new technologies for potentially aiding particles into the wheel/rail contact have been discussed in a report written by Barnard and Cooke;[34] to the authors' best knowledge, none of these techniques are currently under consideration in the railway industry. Some of these measures include:

- *Electrostatic particles.* This would use a similar technique to traditional electrostatic coating, the particles are charged using a high DC voltage. These charged particles repel each other, aiding uniformity, and are attracted to the nearest ground, the wheel. The particles could be picked up by an electrode of opposite charge on the other side of the wheel.

- *Magnetically responsive particles.* Radial electromagnets would be present in selected wheels; iron particles would then be fired at the wheel and stick through the contact. The particles could be picked up by an electromagnet of opposite charge on the other side of the wheel.
- *"Smart Sand".* A mixture of iron particles and ceramic particles attracted to the wheel electromagnetically, the presence of ceramic may give greater adhesion.
- *Particle wedge.* This wedge of particles in front of the contact would be created by a build-up of magnetically responsive powder, thus absorbing the rotational energy.
- *Magneto-Rheological Fluid.* Small ferrous particles suspended in a carrier fluid, when subjected to a magnetic field the viscosity of the fluid will increase to the point that it acts as a viscoelastic solid. This solution would have the benefit of providing relatively precise adhesion control in the contact.

6. GAP ANALYSIS

6.1. Paper Grading

The gap analysis technique used by this review comes from a review paper by Harmon and Lewis.[35] The technique grades each paper according to seven criteria, these have been included in Table 5~~Table 5~~. If a paper achieves 5 or more of the criteria it is graded as an "A" paper, 4 criteria and it is a "B" paper, whilst 3 or less criteria being met means a "C" grade. "A" grade papers are papers which have validated their conclusions over multiple testing scales and/or with theoretical models. The conclusions from lower grade papers are not to be ignored but should be interpreted with the caveat that more research is needed to validate their findings.

Table 5 – Paper Grading Criteria.

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

The first two criteria were chosen to assess if the conclusions in these papers stood up to scrutiny and the rest of the criteria assessed how well these conclusions were supported by work at multiple scales or from a validating model.

In addition, each paper was categorised to better assess where the research has been conducted. The primary categories included wheel/rail isolation, damage, and application; the secondary categories were dry particles and traction enhancers.

6.2. Outcomes

The gap analysis has been included as a schematic, in Figure 20, to better visualise where the knowledge gaps are located; each number in the schematic relates to its reference number. Most of the research was of “B” grade due to only testing at one scale and with no modelling to back results up. There were a couple of papers achieving “A” grades due to their inclusion of modelling work. All the “C” grade papers were from industry due to their lack of peer review, meaning the papers have not stood up to any academic scrutiny. There also seems to be very little research conducted in all the categories, highlighting the need for further work.

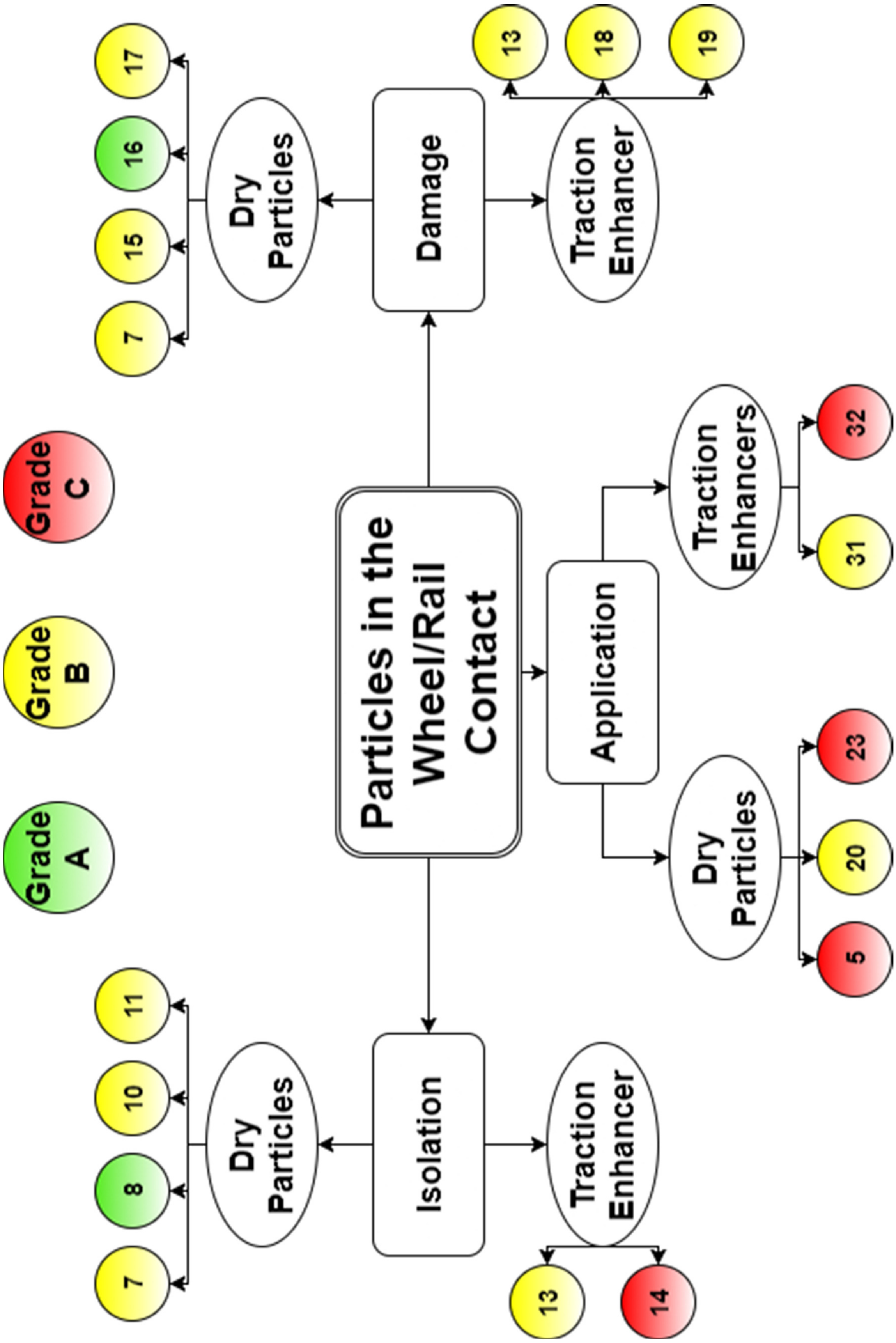

Figure 20 – Gap Analysis Schematic.

7. CONCLUSIONS

The obvious conclusion to take from the gap analysis is that there are a lack of papers surrounding the negative effects of sanding and sanding application especially in comparison to the amount of research conducted into the adhesion restoring effects, as seen in the gap analysis from a review of sanding tribology.[1] This lack of research is especially prominent for application, with only two grade "B" papers existing, one for each category of dry particles and traction enhancers.

The lack of linkage between academic and industry research, and the lack of a consistent methodology when conducting twin-disc sanding tests were two more conclusions drawn after analysing the papers in this review. The former is evidenced by none of the papers reviewed consisting of either: academic work being taken forward by industry, or industry work being studied in more depth in academia. This has led to a lack of real world verification of academic findings and little understanding of the physical mechanisms behind industry results.

The lack of consistent twin-disc methodology is due to: different sand application methods being used, non-continuous vs continuous sand application, and different methods being used to simulate contaminants in the contact. All this means it is difficult to compare the quantitative effects of sanding across different papers, a more consistent methodology would alleviate this issue.

The two grade "A" papers identified by the gap analysis received their grade due to the creation of a model to predict both isolation and damage respectively; the use of accurate models demonstrates that the hypotheses for the particle mechanisms has validity and can be taken forward as an accurate way of assessing the impact of abrasive particles on isolation and damage. The grade "A" rating can also be seen as a vote of confidence as to the veracity of any conclusions.

The conclusion gathered from the grade "A" paper studying isolation (Lewis et al.[8]) was that when sanding was used the likelihood of isolation occurring increased by an order of magnitude above a certain application rate. Finding this critical application rate for an actual wheel/rail contact may be a way of setting an upper limit on amount of sand being applied to the contact before isolation occurs.

The grade "A" paper studying wheel/rail damage (Lewis & Dwyer-Joyce[16]) provided a number of conclusions, such as:

- The presence of sand in the wheel/rail contact increased damage by an order of magnitude compared to an unsanded contact, a finding backed up by Kumar et al.[15]

- Damage increased in the presence of moisture, due to the moisture aiding entrainment.
- The sand particles indented into the softer wheel material and abraded the rail surface. The wheel surface underwent low cycle fatigue resulting in spalling.

As both these papers used a twin disc set-up, isolation and damage results will be more severe than what would be found within a real wheel/rail geometry. Therefore the conclusions can only give a trend and no quantitative results.

In future work more research needs to be conducted on the negative effects of traction enhancers as well as the negative effects of abrasive particles under different scales of testing i.e. more field tests of isolation and damage, thereby exploring if conclusions from laboratory tests can be validated with field tests. More work needs to be conducted into application of particles, especially modelling and field tests; future application techniques suggested by Barnard and Cooke[34] could also be assessed as they do not seem to have been considered further by industry.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Steve Lewis for his help in identifying relevant papers included in this review. The authors would also like to thank the RSSB and ESPRC for funding this work.

FUNDING STATEMENT

Funding for this work was provided by the Rail Safety and Standards Board (RRSB) and the Engineering and Physical Sciences Research Council (EPSRC).

REFRENCES

1. Skipper WA, Chalisey A, Lewis R. A Review of Railway Sanding System Research: Adhesion Restoration and Leaf Layer Removal. *Awaiting Publ.*
2. Rail Safety and Standards Board. GMRT2461 Sanding Equipment (Issue 2)https://www.rssb.co.uk/rgs/standards/GMRT2461 Iss 2.pdf (2016).
3. Li Z, Arias-Cuevas O, Lewis R, et al. Rolling–Sliding Laboratory Tests of Friction Modifiers in Leaf Contaminated Wheel–Rail Contacts. *Tribol Lett* 2009; 33: 97–109.
4. Hutchings I. Wear by Hard Particles. In: *Tribology - Friction and Wear of Engineering Materials*. Butterworth-Heinemann, 1992, pp. 135–141.
5. Rail Safety and Standards Board. Understanding the current use of sanders on multiple units (T796)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=629 (2009).
6. Rail Safety and Standards Board. Research brief: Review of the risks and opportunities from the application of sand during braking (T1046)https://www.rssb.co.uk/library/research-development-and-innovation/research-brief-T1046.pdf (2015, accessed 12 May 2017).
7. Arias-Cuevas O, Li Z, Lewis R. Investigating the lubricity and electrical insulation caused by sanding in dry wheel-rail contacts. *Tribol Lett* 2010; 37: 623–635.
8. Lewis R, Dwyer-Joyce RS, Lewis J. Disc machine study of contact isolation during railway track sanding. *J Rail Rapid Transit* 2003; 217: 11–24.
9. Bowden FP, Tabor D. The Friction and Lubrication of Solids. *Am J Phys* 1951; 19: 428.
10. Descartes S, Renouf M, Fillot N, et al. A New Mechanical-Electrical Approach to the Wheel-Rail Contact. *Wear* 2008; 265: 1408–1416.
11. Lewis R, Masing J. Static wheel / rail contact isolation due to track contamination. *J Rail Rapid Transit* 2006; 220: 43–53.
12. Arias-Cuevas O, Li Z, Lewis R, et al. Laboratory investigation of some sanding parameters to improve the adhesion in leaf-contaminated wheel–rail contacts. *J Rail Rapid Transit* 2010; 224: 139–157.
13. Lewis SR, Lewis R, Cotter J, et al. A new method for the assessment of traction enhancers and the generation of organic layers in a twin-disc machine. *Wear* 2016; 366–367: 258–267.
14. Zobel FGR. Effect of 'slipmaster' on track circuit operation. Tests using the 'silica gun' and high speed tribometer train (IM-ADH-004) (British Rail Report)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=12925 (1972).
15. Kumar S, Krishnamoorthy PK, Prasanna Rao DL. Wheel-Rail Wear and Adhesion With and Without Sand for a North American Locomotive. *J Eng Ind*

1986; 108: 141–147.

16. Lewis R, Dwyer-Joyce RS. Wear at the wheel/rail interface when sanding is used to increase adhesion. *J Rail Rapid Transit* 2006; 220: 29–41.

17. Arias-Cuevas O, Li Z, Lewis R. A laboratory investigation on the influence of the particle size and slip during sanding on the adhesion and wear in the wheel-rail contact. *Wear* 2010; 271: 14–24.

18. Wang W, Liu T, Wang H, et al. Influence of friction modifiers on improving adhesion and surface damage of wheel/rail under low adhesion conditions. *Tribiology Int* 2014; 75: 16–23.

19. Arias-Cuevas O, Li Z, Lewis R, et al. Rolling–sliding laboratory tests of friction modifiers in dry and wet wheel–rail contacts. *Wear* 2009; 268: 543–551.

20. Lewis SR, Riley S, Fletcher DI, et al. Optimisation of a Railway Sanding System for Optimal Grain Entrainment into the Wheel/Rail Contact. *J Rail Rapid Transit*. Epub ahead of print 2016. DOI: 10.1177/0954409716656220.

21. Zobel FGR. Development of Remedies for Poor Adhesion (IM-ADH-019) (British Rail Research)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=9038 (1974).

22. Lewis SR, Riley S, Fletcher DI, et al. Optimisation of a Railway Sanding System , Part 2 : Adhesion Tests. In: *Conference: 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM 2015), August 30th – September 3rd, Colorado Springs, Colorado, USA, 2015.* 2015.

23. Pollicott ID. Advantages of a high speed sanding device in overcoming the adverse effects of air-flow near wheels (IM-TRIB-017) (British Rail Report)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=9054 (1974).

24. Pollicott ID. Review of service trails with the high velocity sander (IM-TRIB-029) (British Rail Report)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=8138 (1977).

25. McEwen IJ, Taylor RK. Adhesion and Leaves: Wet Abrasive Blasting Tests on Southern Region 1974 (TM-TRIB-7) (British Rail Report)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=5127 (1975).

26. Pollicott ID, Taylor RK. Assessment of the Southern Region Water Cannon on Leaf Affected Track in 1976 (TM-TRIB-19) (British Rail Report)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=5120 (1977).

27. Taylor R, Pollicott ID. Assessment of the cleaning of leaf affected track on Southern region - 1977 (TM-TRIB-29) (British Rail Report)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=16453 (1978).

28. Taylor RK, Pollicott ID. Assessment of the Cleaning of Leaf Affected Track on

Southern Region - 1978 (TM-TRIB-35) (British Rail Report)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=16456 (1979).

29. McEwen IJ. Service Experience with Sandite - South Devon Banks, Autumn 1976 (TM-TRIB-020) (British Rail Report)https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=8314 (1977).

30. Tunley J. A succesful approach to rail operations in low adhesion conditions. In: *World Congress for Railway Research*. Tokyohttps://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=11289 (1999).

31. Garner L. *Investigation into the Benefits Afforded by Traction Gel Applicators and the Traction Enhancers Alleviate® and U5®*. Liverpool John Moores University, 2011.

32. Marshall T. *Six Sigma project: WSP5.4 LNE Static Sandite Units*. 2006.

33. Gay F., Constantiner D, Champa JT, et al. *Transport of solid particulates*. 2001.

34. Barnard S, Cooke J. Summary Report : Low Adhesion project – Technologies and Solutions for more reliable and predictable braking (RSSB Report). Epub ahead of print 2014. DOI: IN000503.

35. Harmon M, Lewis R. Top of Rail Friction Modifier Review Paper. *Tribol - Mater Surfaces Interfaces* 2016; 10: 150–162.