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Optimisation of a Railway Sanding System for Optimal Grain Entrainment into the Wheel/Rail Contact

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Abstract

To combat adhesion loss, sand is fired into the wheel/rail contact via a hose using compressed air typically from a storage hopper mounted to the under frame of the train. Many passenger trains in the UK are fitted with stepped braking controllers which range from 1 to 3 with a 4th step being "emergency braking" [1]. According to GM/RT2461, [2], from brake step level 2 upwards, sand is fired automatically if wheel-slip is detected. Sand is automatically fired when the emergency brakes are applied irrespective of whether low adhesion/wheel slip has been detected [2]. For adhesion loss in traction, sand can be applied at the driver's discretion. Current railway standards [2] govern the maximum permissible sand flow rate to protect against impact wheel/rail isolation on track circuits, but do not address the hose position. This results in a range of hose set-ups across different train types, some of which may not be effective at delivering sand. The work here was carried out using a full-scale laboratory rail-wheel test machine to find the position for the hose and sand flow rates that give optimum sand entrainment to the contact. It was found that ideally the hose should be aimed at the rail or nip and be as close to that contact as safely possible. The use of a 20mm bore nozzle on the end of a 25mm bore hose increased sand passing through the contact by up to 70% relative to widely used 25mm bore hoses without a nozzle. Reduction in sand flow rate below the 2 kg/min threshold significantly reduced the amount of sand entering the contact. It was also shown that relatively small movements in the hose/nozzle from its ideal position and cross winds significantly reduced sand entrainment.

1.0 Introduction

The entrainment of sand into the wheel/rail contact is one of the most effective ways of improving friction levels between the wheel and rail under situations of low adhesion [3]. Work carried out by British Rail Research on causes of low adhesion in the 1970's showed that on parts of the UK rail network adhesion coefficient (the ratio of normal to friction force in the contact) varied between 0.04 – 0.55, averaging 0.3 in dry conditions [4]. The effect of adding water to the rail reduced this average to 0.2. It was also shown in [4] that leaves can have a dramatic effect on adhesion coefficient, reducing it to as low as 0.02. Other causes of low adhesion have been identified as: general moisture/dampness combined with contaminants such as rust, ice, coal dust, spilled diesel fuel/lubricating oils/flange lubricating grease/hydraulic fluid, airborne kerosene from nearby airports, or other chemicals from industrial sites [3]. Other sources of low adhesion have been found to be due to mud deposited on rails at road crossings by road vehicle tyres [5, 6] and small amounts of water on the rail [4, 5]. The issues caused by low adhesion have been highlighted as including signals passed at danger (SPADS) and platform overruns [3, 7, 6]. Low adhesion conditions can add over 1000 metres extra to the stopping distance of a train [3]. Low levels of adhesion can also cause railway vehicles to come within dangerous proximity to one another such as in the case at Esher (UK) [7] where the affected vehicle came within 200 metres of another vehicle travelling in the same direction which was crossing onto the same line. It is estimated [7] that the affected vehicle travelled approximately 3000 metres with little or no braking control. In a similar incident at Lewes (UK) the two vehicles involved came within 30 metres of each other [8]. Both of the trains involved in the above incidents failed to stop within the normally expected distances despite their braking and sanding systems working correctly within their design requirements [7, 8]. However, as the systems (particularly the sanding system) were tested with the train stationary after the accident, it cannot be determined whether the systems performed satisfactorily under dynamic conditions. For example, the hose position may have been affected by dynamic movements of the vehicle or aerodynamic forces; and the sand may not be delivered to the contact when there are different air flows (potentially turbulent) under the vehicle body. One full-scale sanding test which has been reported in the literature [9] was carried out on a test locomotive at a maximum speed of 21 km/h. However, the vehicle in this test accelerated from a standing start, therefore the average speed would have been much lower. A series of tests was also performed in the 1990's on a 2 car, class 165 DMU [10, 11, 12, 13, 14, 15]. The aim of these tests was to determine the effect of sanding equipment on the operation of track circuits. Although marked improvements in deceleration were seen in these tests; the vehicle speeds were only in the range of 16 – 80 km/h. In the incidents at Esher and Lewes the vehicles were reported to be traveling at speeds of 145 km/h and 112 km/h respectively when they experienced low adhesion with little or no retardation of the vehicle speed during braking and sand application [7, 8]. Tests reported in this paper show that even mild cross-winds can blow all of the sand exiting the end of the sander hose completely clear of the rail-wheel contact so that little or no sand passes through the wheel/rail interface.

It has been shown that when sand is entrained into the wheel/rail contact it can restore adhesion levels [16]. Adequate levels of adhesion for traction and braking are defined as 0.2 and 0.09 respectively [17]. However, the presence of sand in the contact also temporarily increases the wear rate of both wheels and rails and has the potential to cause isolation of track circuits [16, 18]. It has been shown that the size of the sand particles used can affect the rate of adhesion restoration when it is used to remove leaf layers [19]. These tests also showed evidence that increasing the number of axles receiving sand can also improve the rate of adhesion restoration, indicating that there may be an optimum number of sanding axles per train which would condition the railhead back to uncontaminated levels. In this way, following trains would be unaffected by the low adhesion.

Sand is usually fired into the wheel/rail contact from a storage hopper mounted to the underside of the train. Many of the passenger trains in the UK are fitted with stepped braking controllers which range from 1 to 3 with a 4th "emergency braking" step [1]. According to GM/RT2461, [2], from brake step level 2 upwards sand is fired automatically if significant levels of wheel slide, which are an indicator of low adhesion levels, are detected at the same time as the brakes are applied. Significant levels of wheel slide are defined in [2] as "wheelset rotational speed at 95% or less than the true train speed.". Sand is automatically fired when the emergency brakes are applied irrespective of whether low adhesion/wheel slip has been detected [2]. For situations where adhesion loss happens in traction sand can be applied at the driver's discretion. Ideally 100% of the sand which leaves the end of the hose should pass through the wheel/rail contact, avoiding wastage and contamination of other track infrastructure such as track ballast, switches and crossings. The current Railway Group Standard (RGS) GM/RT2461 [2], governing railway sanding, only covers aspects such as the maximum permissible sand flow rate, mass of sand laid down per metre, and sand grade. GM/RT2461 was derived from a series of tests, performed during the mid to late 1990's, with the aim of these tests to determine the effect of sanding equipment on the operation of track circuits [10, 11, 12, 13, 14, 15]. The tests were undertaken on a 2 car, class 165 DMU. GM/RT2461 states that "The sand deposition rate per rail during braking shall be such that the rear two axles of the multiple unit do not come to rest on sand laid at rate of 7.5 grams/metre or greater". This ensures that the rear of the train can always be detected by signalling circuits. GM/RT2461 also states that "A recognised method of achieving the above is a laying rate approaching, but not exceeding, 2kg/minute per rail when using a full service or emergency brake application". It was thus decided to use this recommended rate in these tests.. These standards are used to help manage the rail network and the potential isolation of track circuits and excessive wear of wheels and rails, however, there is no industry standard to govern hose positioning/dimensions or the proportion of sand delivered which actually reaches the contact.

Testing of adhesion improving fluids with potential to be used as an alternative to sand has been carried out [17]. However, while there may be benefits sometime after treatment this showed that most of these products actually reduced adhesion considerably immediately after application. Products such as friction modifiers are designed primarily to control high friction situations, rather than to combat low adhesion conditions, but there is evidence that adhesion can be restored by blasting the wheel and/or rail with hot air jets [5]. The primary measures taken to combat known areas of low adhesion on the UK rail network are high-pressure water jetting, Sandite® and/or traction gel application (Sandite® and other traction gels consist of sand particles suspended in a carrier gel). All three of these measures are trackside solutions and are performed by railway maintenance vehicles when the line is not in service. Unfortunately, the benefits of these adhesion improving measures can be quickly diminished by changes in atmospheric conditions or conditioning of the railhead by normal service traffic [7, 8]. Thus there is a need for an on-board solution, such as the currently used sand application method, so that low adhesion incidents can be treated as and when they occur with minimal disruption to rail services.

The work described in this paper was undertaken on behalf of The Rail Safety and Standards Board (RSSB) following an earlier study of sanding systems used on multiple units in Great Britain [1]. In the earlier study a survey was taken of the performance of different types of sander units at maintenance depots across the UK. The findings showed that there was considerable variability in performance of different sanding systems with many operating well below the 2.00 kg/min discharge rate recommended by GM/RT2461; the average discharge rate from 330 tests was 1.148 kg/min with a standard deviation of 0.602 kg/min. This large variation in discharge rates was thought to be due to a number of factors including, discharge hose length, hose bore diameter, nozzles fitted to end of discharge hoses, dampness of sand, design of sand storage hopper and many more factors. Some of the systems tested were found to discharge little or no sand at all while others discharged above the recommended 2.00 kg/min.

As of yet no work in the literature has been identified on sand entrainment into the wheel/rail contact. Tests reported have instead focused on secondary effects of railway sanding such as rail-wheel electrical isolation, damage to wheel and rail, and effects on adhesion. It is also noted that thus far the majority of the testing has only been performed on small scale test machines [9, 16, 18, 19].

In this paper the results are reported of tests using a full-scale laboratory rail-wheel test machine to investigate the effects of changing some of the factors identified in [1] on sand delivery to the rail-wheel contact. The effect of hose position relative to the wheel and rail on the amount of sand which passes through the contact was investigated, with imposed airflow to simulate the aerodynamic conditions in which sand may be applied. Sand pipe size and the effect of a nozzle was investigated, and a high speed camera was used to visualise the path that the sand made from the end of the hose toward the wheel/rail contact.

2.0 Apparatus

A schematic of the full-scale wheel/rail rig used in this study is shown in Figure 1. This was originally developed by British Rail Research and used for the investigation of wheel and rail wear [20]. It was later modified for the investigation of RCF [21] and was re-instrumented for this work. The wheel used in the tests (1) was 1016 mm in diameter, mounted on a rigid axle which rotates within two journal bearings located in a load frame (2). The load frame is pivoted at one end allowing the wheel to be raised and lowered. The wheel is free to rotate and sits on a 1010 mm length of rail (3) mounted to a linear slider bed (4) which slides on two grease lubricated PTFE strips (5). A horizontal actuator (6) moves the slider bed and rail a total distance of 600 mm. As the rail is moved the friction at the interface causes the wheel to rotate. A vertical actuator (7) is used to simulate an axle weight acting on the wheel, but is also used to lift the wheel from the rail as the rail is positioned back to the start of its cycle. Creepage of the wheel is controlled by a horizontal actuator (8) which acts at the rim of the wheel via a chain and pulley assembly (9). The wheel is also counterweighted so that the chain is always under tension even when the wheel is lifted from the rail. Under normal operation the action of the rig is for the rail to start fully toward the right hand side of the diagram in Figure 1. The wheel is then lowered onto the rail and the required half axle load applied. The rail then travels up to 600 mm (toward the left on Figure 1 side view) causing the wheel to rotate in a clockwise direction so that the effective travel direction of the wheel is from left to right. Once the rail moves to its maximum stroke the wheel is lifted clear and the rail is put back to its start position. The minimum cycle time achieved is 10 seconds. For this project only half a cycle was used. Once the rail had travelled to its furthest left position the rig was stopped so that sand could be collected from the rail.

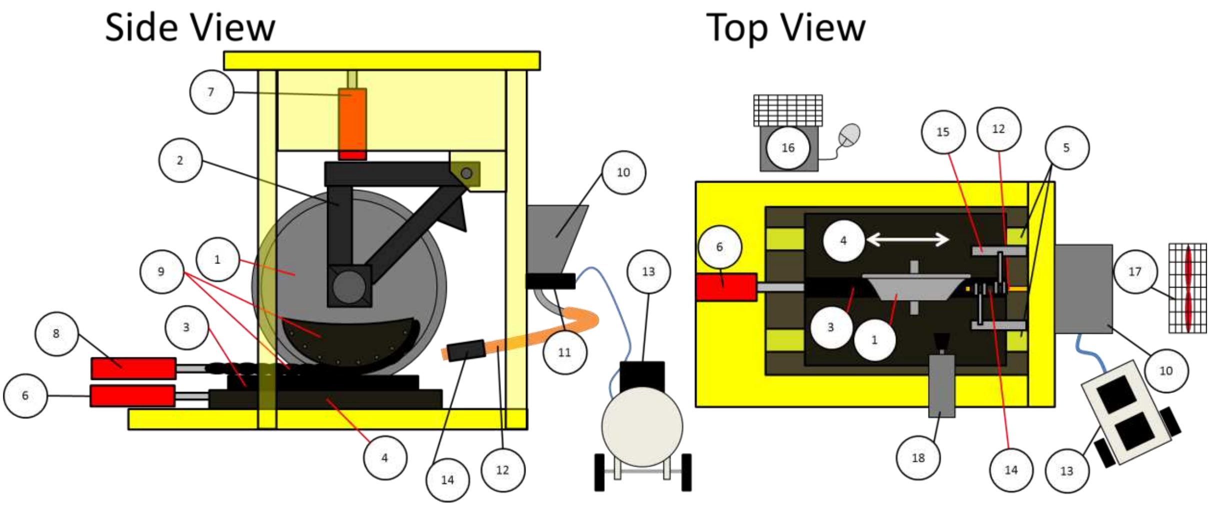

Fig. 1, Schematic of full-scale rig showing side and top views.

Railway grade sand (Garside 10/18) was stored in a hopper (10) mounted on the machine frame. A sand valve (11) attached to the bottom of the hopper fed sand via a hose (12) to the wheel/rail interface. The valve operates on a venturi principle which uses air from the air compressor (13) to agitate sand and subsequently draw it from the hopper into the hose. The air compressor used was a Bambi 150/500 unit with 50 litre reservoir capacity and stored 8.1 bar of pressure when fully charged. The compressor cut-in when the pressure dropped to 5.5 bar. The outlet/regulator pressure to the sand valve was then adjusted to give a desired sand flow rate, typically 2.00 kg/min. The position of the end of the hose was controlled by fitting an aluminium sheath (14) around the end of the hose. A frame (15), mounted to the rig, attached to the sheath at two points allowed control over parameters such as position of the end of the hose relative to the railhead and wheel, contact and angle of the hose, both longitudinally and transversely relative to the rail.

All actuators (6, 7 & 8) are connected to a hydraulic supply with servo-valves giving continuously variable control commanded by computer. Load cells are attached to actuators (7) and (8) and vertical actuator (7) is operated exclusively under load control. A linear position transducer connected between the slider bed and a fixed point on the frame of the machine allows horizontal actuator (6) to be operated under position control. Creep actuator (8) also has a linear position transducer attached so that it can also be operated under position control. The motion of the rig is digitally controlled from a computer (16) running National Instruments Labview. A centrifugal fan (17) was used to simulate wind speeds of up to 96 km/h (60 mph) representing a moving train since sustained ambient air speed of this level is rarely experienced. A high-speed camera (18) was used to observe the sand path from the end of the hose into the contact and a smaller digital camera mounted above the hose was also used to get a longitudinal view of the sand entering the contact.

Although the full-scale wheel/rail rig offers a closer representation of field conditions than alternative forms of testing such as twin-disc, there were some limitations. Firstly the wheel of 1016 mm nominal diameter available for the current tests was much larger than wheels used on modern DM/EMU's (typically 840mm diameter). This meant that it was not possible to get as close to the nip with the sand hose as it might be with smaller wheel diameters. Second, in these tests the maximum speed of the rail was 50 mm/s. This is much slower than speeds at which sanding systems work on service trains, and although the fan was able to raise airspeed over the rail-wheel contact to realistic values this slow speed means the speed of the track, wheel and air do not completely replicate the closing speed and air flow around the rail-wheel nip in service. Despite these limitations it was thought the controlled conditions of the full-scale test machine would offer the best environment for a detailed investigation of the sanding system.

3.0 Test Methodology

The investigation was split into two parts. The first series of tests focused on changing parameters such as: hose position, sand flow rate, hose bore etc. on the performance of the sanding system. For all of the tests in this investigation the chain and pulley system were removed from the rig so that a clear image of the contact could be taken with a high-speed camera as shown in Figure 2. This meant that no slip could be applied to the wheel and therefore no traction measurements made. However, as this initial part of the testing was primarily to observe the path of the sand particles entering the contact, traction measurements were not deemed necessary.

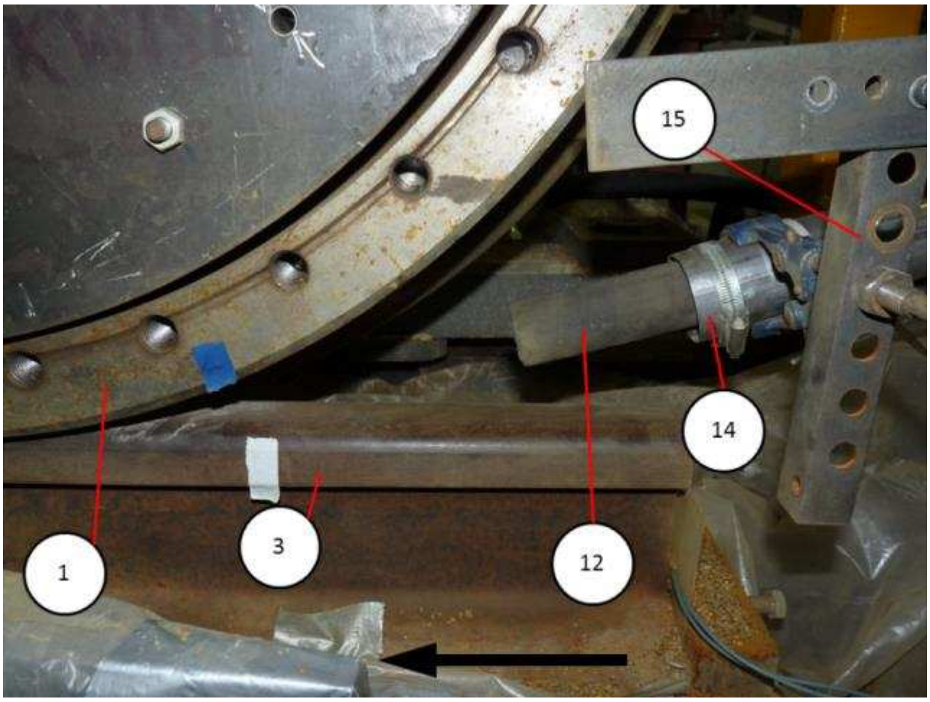

Fig. 2, Working section of full-scale rig. (Numbers refer to items shown in Figure 1). (Black arrow indicates direction of rail travel)

The position of the hose was adjusted according to the test plan (see Table 1 and Figure 3) by measuring: its horizontal position relative to the wheel rail contact (l), vertical position relative to the surface of the rail (h), its angle of attack relative to the rail surface (θ_a) and its angle of twist relative to the rail centreline (θ_t) as illustrated in Figure 3. Parameters l and h were measured with a ruler. Accuracies of 1mm could be achieved using this technique. The angle of attack was measured using a Digi-Pas™ DWL-200 digital spirit level accurate to 0.1° mounted on top of the aluminium sheath. The angle of twist was calculated by measuring the distance between the hose centreline and the rail centreline at the point where the hose mounting frame attached to the test machine. Knowing the length of hose from this point allowed θ_t to be calculated. A 2 dimensional CAD model was generated to give the position of the hose relative to both the centre of the wheel/rail contact point and the railhead. The steel ruler used to position the hose relative to the centre of the contact was located as far into the contact as possible. Because of the curvature of the wheel and the thickness of the ruler it was estimated that the end of the ruler was 20mm from the actual centre of the contact. Thus all l dimensions yielded by the CAD model had 20mm deducted so that they could be translated to the actual set-up of the rig.

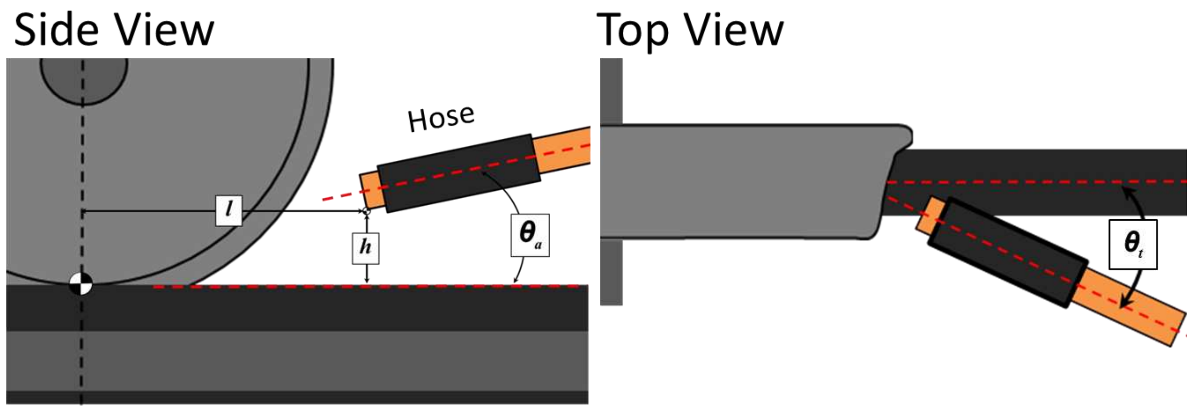

Fig. 3, Schematic of hose set-up variables.

Once the hose was positioned, the sand flow rate was checked by placing a bag over the end of the hose and opening the regulator causing sand to flow for 30 seconds. The bag with sand was then weighed and the mass extrapolated to give a flow rate in kilogrammes per minute. The outlet pressure of the air compressor was adjusted to obtain the desired sand flow rate. A maximum permissible flow rate of 2 kg/min is applicable to train operating companies (TOCs) on the UK's rail network and unless otherwise stated this flow rate was used throughout the test work. A high-speed camera was then positioned so that a clear view of the wheel/rail nip and the end of the sand hose was visible. This camera was to observe the path of the sand particles from the end of the hose. A second standard video camera was placed above the hose looking into the wheel/rail nip in the direction of the rail. The second camera showed how the sand flared from the end of the hose, giving an indication of the proportion of sand which was not on trajectory toward the wheel/rail nip and was likely to fall to the side of the rail. The regulator was opened shortly before the rail and wheel started to move to allow the sand flow rate to reach a steady state. In order to prevent any sand being fired towards the contact while the wheel was stationary a deflector was placed over the end of the hose. Once the test was ready to start the deflector was withdrawn.

Both dry and wet tests were conducted, representing typical railway operating conditions. For the wet tests the rail was wetted using a water spray, and kept wet during the test with a gravity fed water supply. A centrifugal fan was used to subject the contact to simulated wind speeds of up to 96 km/h (60 mph). As the wind was applied a boundary layer was formed on the rail surface meaning that air speed varied along the length of the rail. To ensure consistency the wind speed was always measured at a fixed point on the rail just before the outlet of the sanding hose. Wind speed was measured using a Techno Line EA-3010 Hand Held Anemometer accurate to 0.1 km/h. The majority of sanders used on the UK's rail network consist of a hose with 19 mm bore with some of the newer systems having hoses with a 25 mm bore [1]. Any upgrades to existing 19 mm systems involve replacing the 19 mm hose with a 25 mm one. During preliminary apparatus trials a 1.5 metre long, 19 mm hose was used. However, the maximum sand flow rate achievable with this set-up was 1.2 kg/min, far below the 2.0 kg/min required for these tests. It was therefore decided to use a 1.5 metre length, 25 mm bore hose where the desired flow rate was easily achievable within the capacity of the air compressor. A 1.5m length of hose descended from the sand valve in a helix with its end aligned towards the rail-wheel contact. This arrangement allowed a gradual descent of roughly 450 mm in height from the sand valve to the open end of the hose just above the rail, aiming to replicate the hose and hopper positioning within the underframe of a train.

3.1 Phase 1 Tests: Sanding System Optimisation

The Phase 1 tests were designed to find the sanding hose position which would deliver the maximum amount of sand through the contact for a given flow rate of sand. Data was collected from these tests using high-speed footage from the side-view of the contact, standard video facing into the contact and by measuring the mass of sand which had passed through the contact. In these tests no additional vertical load was applied to the wheel so that just the weight of the wheel and frame assembly was acting on the contact. The rail travelled at a speed 50 mm/s or 0.18 km/h.

Strips of tape were used to mark the starting (extreme left) and end (extreme right) contact points on both the wheel and the rail in order to visualise the working section of the rail as in Figure 4. A contact position in between the start and end position was also marked to allow consistency in gathering sand which had passed through the contact. When a test had finished only the sand between the start and mid points was brushed from the railhead into a section of ducting which as then carefully emptied into sample bags. The bags with sand were then weighed and labelled. The average weight of an empty bag was then deducted from the combined weight to give a measure of the weight of sand which had passed through the contact. For wet tests the sand was left in an open bag for a period of days for the sand to dry out. This meant that a fair comparison could then be made between dry and wet tests. This method of measuring the effectiveness of each test is shown to be accurate by the error bars in the following charts. The accuracy of the balance used to measure the sand was + or – 0.000005 grams.

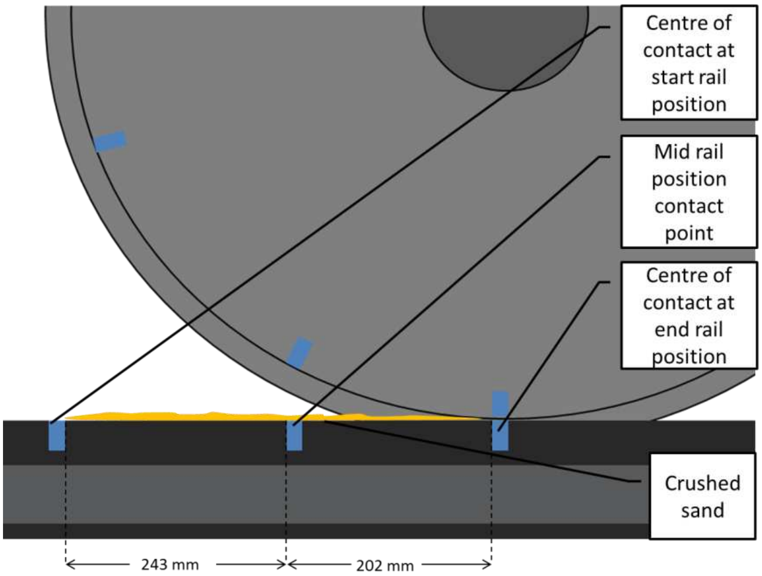

Fig. 4, Working section of full scale wheel-rail rig

3.2 Phase 2 Tests: Effects of Variations of Optimised Hose Position

Effects of changes in the hose position were investigated, aiming to replicate inevitable differences between nominally identical hose positioning, and changes over time from accidental knocks or vibration during service which may not be rectified until scheduled maintenance of the vehicle. These tests were carried out to the same procedure used in Phase 1 testing.

4.0 Results

4.1 Phase 1 Tests: Sanding System Optimisation

The Phase 1 tests were broken down into further sub-stages to isolate system parameters including hose position, sand flow rate, dry/wet conditions, and wind speed.

4.1.1 Sub-Stage 1: General Hose Aim

The previous research mentioned above found that there was great variability between different vehicles and TOCs in hose outlet position relative to the wheel and rail, with no standard set for hose position [1]. Tests in sub-stage 1 were designed to look at the effects of changing the general hose aim towards (a) the rail, (b) the wheel/rail nip, or (c) the wheel as summarised in Figure 5. A sand flow rate of 2 kg/min was used for all test in sub-stage 1. Each test was repeated twice. No wind was used in these tests and the wheel and rail were both dry. Table 1 shows the parameters used for each test. A hose with 25 mm bore was used for sub-stage 1 tests.

Aim of Test	Aim at point of rail (f) mm from centre of contact	Distance of Hose from contact patch (x) mm	Height above rail (y) mm	Angle to rail (θ) deg
RAIL	200	350	20	15
	200	348	33	20
	200	344	45	25
	200	340	58	30
NIP	100	330	20	10
	100	327	40	15
	100	323	60	20
WHEEL	300	451	104	10
	300	448	131	20
	300	440	156	5

Table 1. Sub-stage 1: General hose aim hose set-up parameters

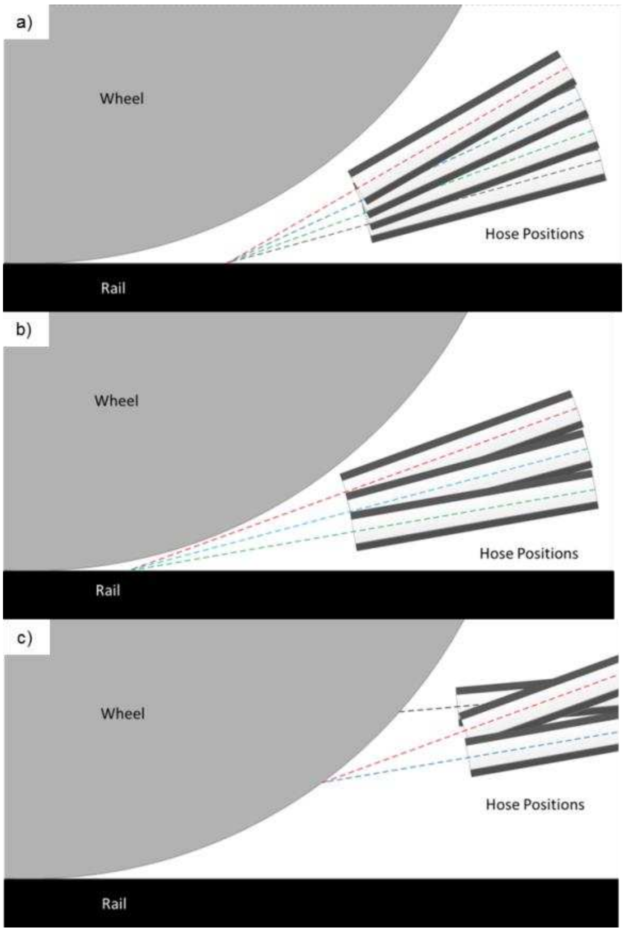

Fig. 5, Schematics showing hose position relative to wheel and rail: a) hose aimed at rail; b) hose aimed at wheel/rail nip; c) hose aimed at wheel

Figure 6 shows the average mass of sand which was collected from the railhead once the machine had completed 1 pass quantified using the method described in Figure 4.

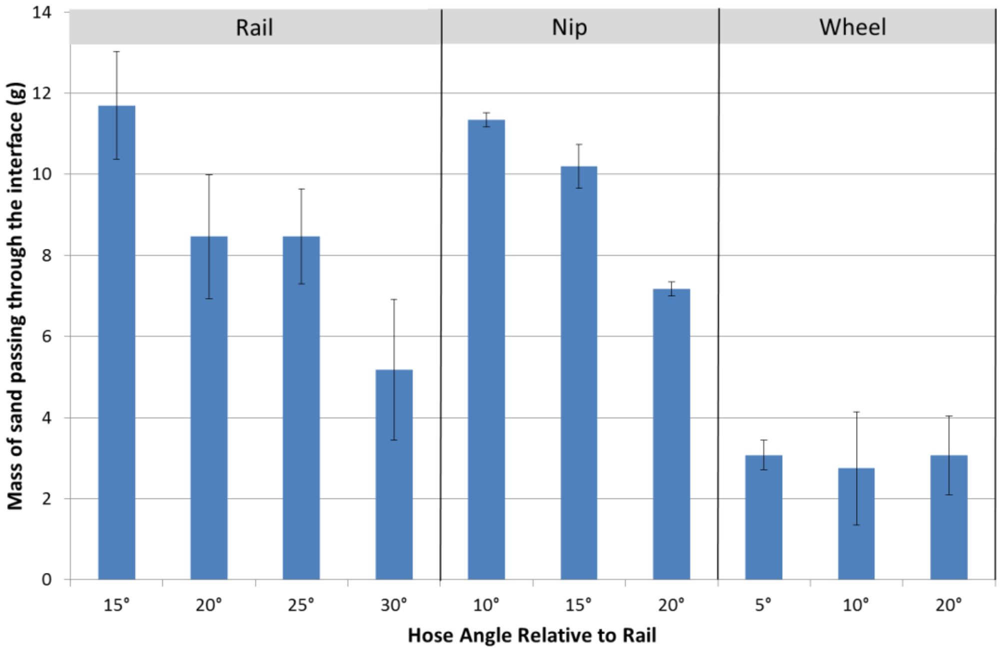

Fig. 6, Mass of sand collected from rail at three different positions, average of three readings: a) hose aimed at rail; b) hose aimed at wheel/rail nip; c) hose aimed at wheel. Error bars show maximum and minimum readings.

Figure 6 shows that the least effective position in terms of delivering sand to the contact was when the hose was aimed at the wheel, with change in hose angle having little effect. Aiming at either the rail or the nip resulted in much more sand passing through the contact with the least variation in quantity seen in the nip position. Hose angle had a significant effect on sand delivery, with less sand passing through the contact as the angle was increased for both the rail and nip positions. These results make sense as pointing the hose directly at the place where the sand needs to be delivered would be expected to result in more sand entering the contact. The result for the hose aimed at the rail at a shallow (15°) angle is surprising as this position would not be expected to be as effective as aiming the hose directly at the nip, and the tests at the higher angles confirm this. However, the test at 15° yielded a slightly higher average result than for 10° aiming at the nip albeit with increased variability in the results. It can therefore be deemed that a hose position aiming at the rail at 15° is at least as effective as a hose position aiming at the nip at 10°. Stills from the high-speed footage of the side-view of the wheel are shown in Figure 7.

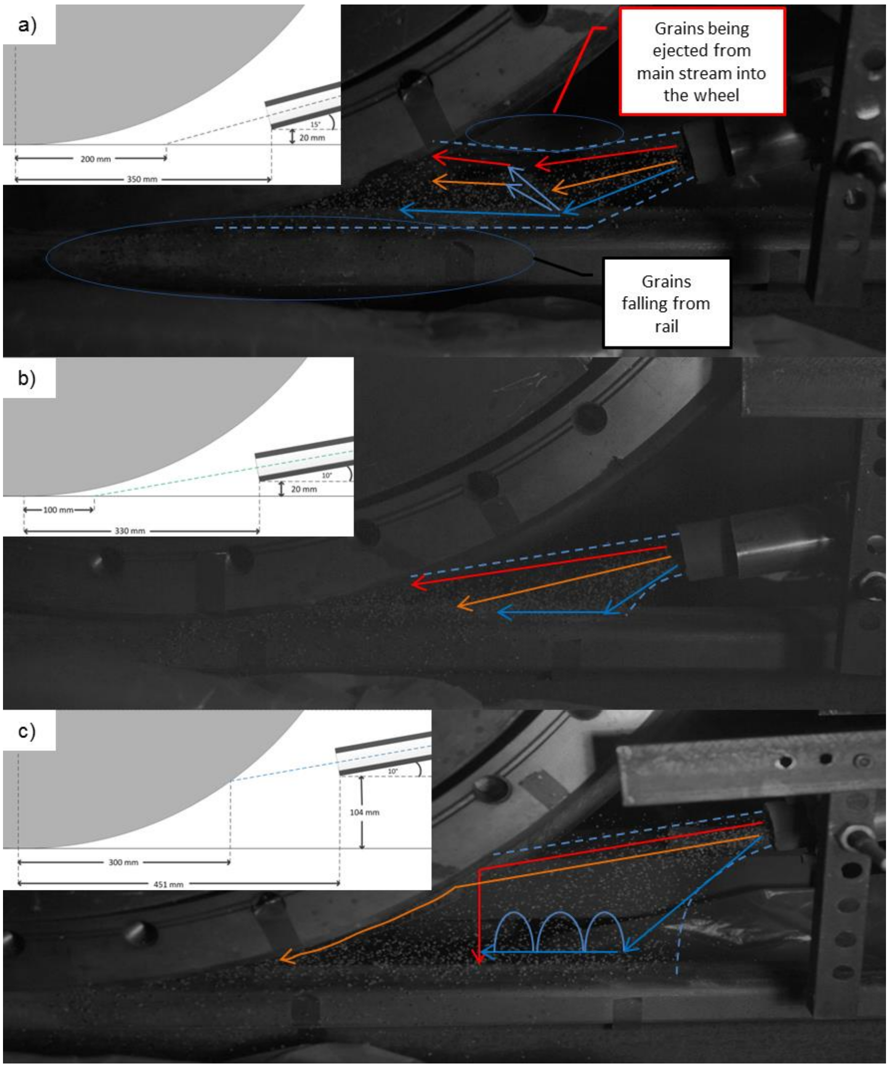

Fig. 7, High-speed stills taken during testing at three different positions: a) hose aimed at rail with 15° angle; b) hose aimed at wheel/rail nip with 10° angle; c) hose aimed at wheel with 10° angle

What is immediately obvious from the stills in Figure 7 is that the sand flares from the end of the hose and spreads either side of the theoretical aim point. So, for example, in Figure 7b) even though the hose is aimed at the nip, some sand hits the rail and some hits the wheel. The arrows have been added to illustrate the dynamic path of the sand with the red (upper) arrow indicating the upper, orange indicating the mid and blue (lower) indicating the lower-stream. Figure 7a) shows the hose aimed at the rail. Most of the particles from the lower and mid-stream hit the rail at high velocity (judged from the high-speed video footage). Some of these particles then roll/bounce along the rail with most of them entering the nip, but a small proportion falling from the rail before they reach this point. Some of these particles which hit the rail hit with enough energy that they are bounced up into the mid and upper streams whereby they are carried along with the main stream toward the nip. What is not clear from Figure 7a), but is apparent in the video, is that a small number of particles exiting the hose in the mid and upper streams collide with each other causing some of the particles to be ejected up towards the wheel. They then either fall straight back down onto the rail or are carried along toward the nip by the main stream.

4.1.2 Sub-Stage 2: Effects of Wind and Wet Rail

To limit the number of tests carried out in studying the effects of wind and wet rail, a fixed hose position was used. The position chosen was with the 25 mm hose pointing at the nip at a 10° angle as it yielded less variability in results than for a hose aimed at the rail. The sand flow rate was kept constant at 2.00 kg/min and wind speeds of 32, 48, 64, 80 and 97 km/h were simulated for both dry and wet conditions. Figure 8 shows the mass of sand that was collected from the rail after each test. For the wet tests the wheel and rail were wetted prior to the test with a water mist. However, it was noted that the wind would act to dry out the rail during the test. Therefore a gravity fed water feeder was placed just below the sand hose to keep the rail damp.

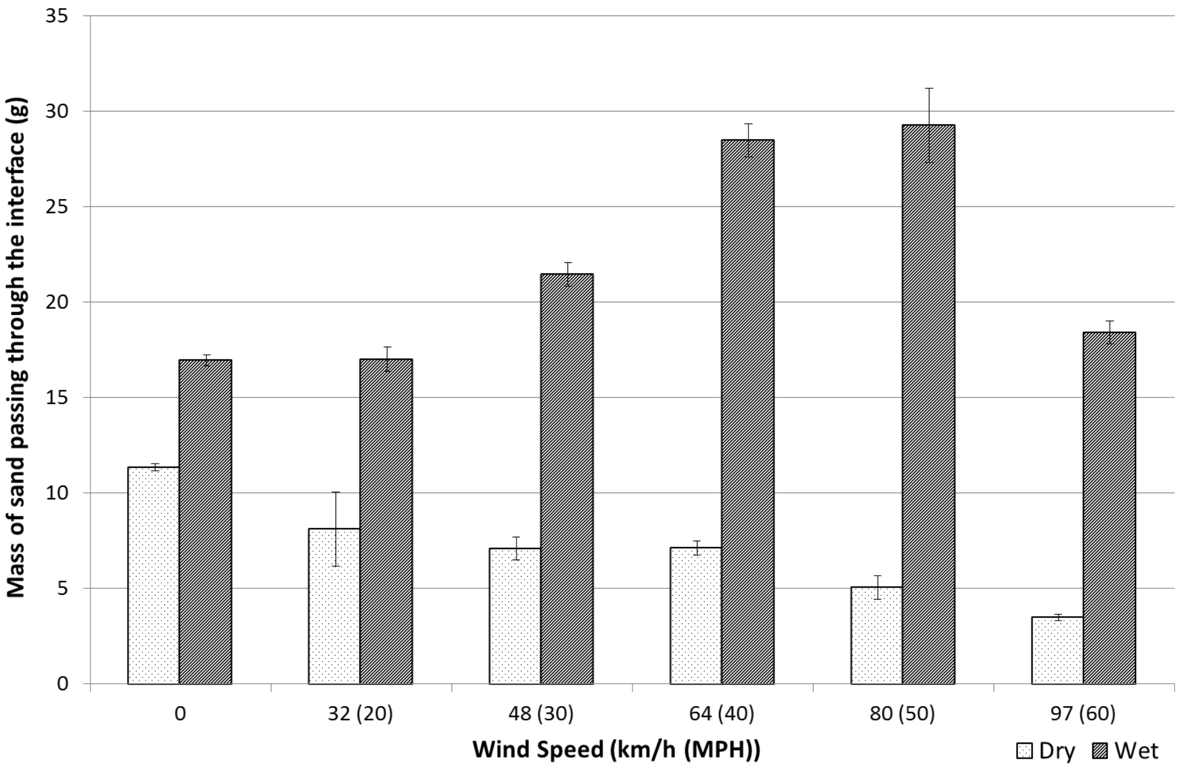

Fig. 8, Mass of sand collected from rail (average of three readings) after experiments at different wind speeds under both dry and wet conditions. Error bars show maximum and minimum readings.

The first thing to notice from Figure 8 is that water is significantly influential on the amount of sand left on the rail after the test. From the high speed video it was seen that the wetted sand adhered to the rail and also the wheel meaning less of the sand that lands on either surface falls clear of the rail. This effect was also seen in twin-disc testing with sand [16]. The other effect to be highlighted by Figure 8 is the different effect that wind speed has on sand passing through the interface depending on dry or wet conditions. In dry conditions, there is a trend to reduced sand retention with increasing wind speed. For wet conditions this trend is reversed except at the highest speed considered.

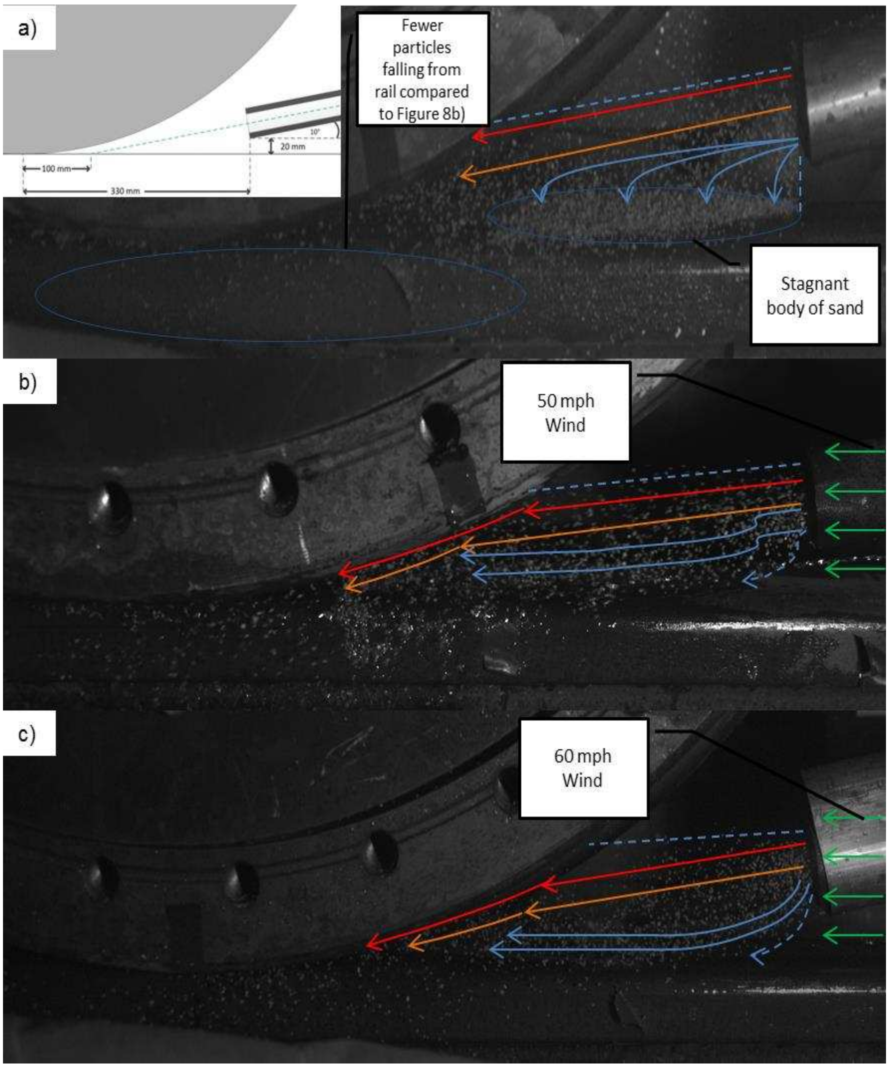

Fig. 9, High-speed stills taken during testing for sub-stage 2 tests with hose aimed at nip at 10°: a) no wind, wet conditions; b) 80 km/h wind, wet conditions; c) 97 km/h wind, wet conditions

Figure 9 shows high-speed stills taken from the Sub-stage 2 tests. Firstly to isolate the effects of dry and wet conditions Figures 7b and 9a are compared. In both figures it can be seen that the lower-stream of sand falls directly onto the rail. However, when the rail is wetted as in Figure 9a, the sand does not bounce along the rail as is the case for a dry rail. Instead the sand adheres directly to the spot where it falls. This quickly builds up a stagnant mass of sand on the railhead which is conveyed toward the nip by the movement of the rail. In the dry case the video showed this mass of sand which built up was very dynamic and constantly changed in particle number and shape as it was bombarded by further falling particles. In the wet case these falling particles added to the stagnant mass until it effectively became a dry surface for further falling particles to bounce off of toward the nip. Not as many particles fell from the railhead in the wet case as in the dry case.

When wind is introduced, as in Figures 9b and c, the lower side of the stream which would normally fall straight onto the rail is carried by the wind toward the nip and lands on the rail further toward the nip. The stagnant mass, seen in Figure 9a, is eliminated by the wind as it blows the particles further toward the nip. When there is a wind blowing much more sand is seen to fall from the rail than in the case of a wet rail with no wind. This is because in the experiments with wind a proportion of the sand which is blown toward the nip is blown clear of the rail. The reason for the difference in the amount of sand which falls from the rail in the 80 and 97 km/h cases is not clear from the video.

4.1.3 Sub-Stage 3: Effects of Flow Rate and Adding a Nozzle to the Hose

In Sub-stage 3 the effect of changing the flow rate and adding a nozzle to the end of the hose was investigated. These tests were carried out under wet conditions with a 48 km/h wind using the 25 mm bore hose. Hose positions aiming at both the nip (10°) and rail (15°) were tested. The lowest repeatably achievable flow rate using the 25 mm hose was 1.50 kg/min, so three flow rates 1.50, 1.75 and 2.00 kg/min were tested. For each flow rate and aim position the hose was either used as standard (i.e. straight 25 mm bore hose with no restriction) or fitted with a nozzle, while keeping the outlet position identical. The nozzle was constructed of a 150 mm long 25.5 mm diameter steel bar with a 20 mm internal bore. For the tests marked

“Nozzle” in Figure 10, the nozzle was inserted into the end of the hose so that it protruded 100 mm from the end of the hose. The nozzle effectively reduced the internal bore diameter of the hose from 25 to 20 mm, but without the choking effect of using a full length of 20 mm hose. For example, the regulator pressure on the compressor required for a sand flow rate of 2.00 kg/min was 3.5 bar and adding a nozzle to the hose increased this pressure to 4.2 bar. When tests were carried out with an identical length (1.5 metres) of 19 mm bore hose the maximum flow rate obtained was 1.2 kg/min at a regulator pressure of 8 bar which was the limit of the air compressor.

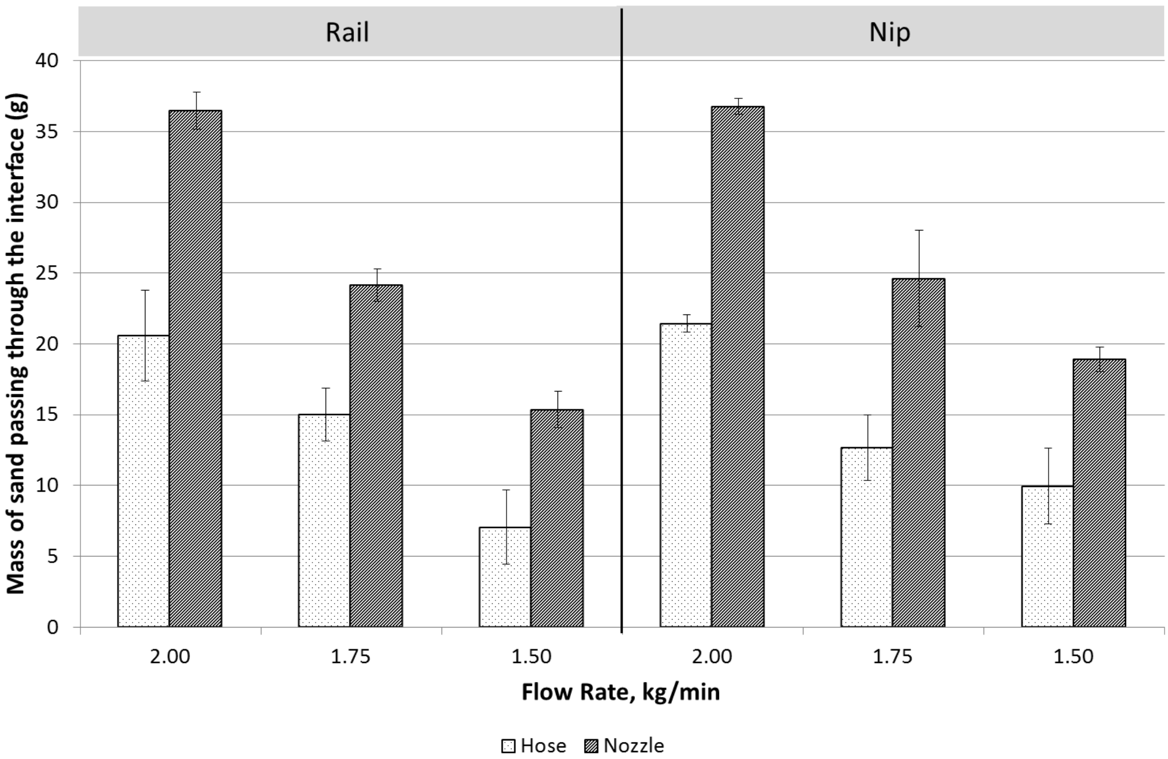

Fig. 10, Mass of sand collected from rail (average of three readings) after experiments with different sand flow rates with a plain hose and hose fitted with a nozzle, all test performed under wet conditions with 48 km/h longitudinal wind. Error bars show maximum and minimum readings.

The increase in the amount of sand which passes through the contact when a nozzle is attached to the hose is immediately clear from Figure 10. The percentage increase in the average amount of sand collected from the rail by using a nozzle at a flow rate of 2.00 kg/min is 77% for the pipe aligned with the rail, and 71% for pipe aligned with the nip. At a flow rate of 1.75 kg/min it is 61% and 94% for alignment with the rail and nip respectively, corresponding figures being 118% and 90% at a flow rate of 1.50 kg/min. The average increase for a pipe aligned with the rail was 85% and for the nip 55%. The effect of reducing the flow rate for a standard hose can also be seen. For a pipe aligned with the rail a 12.5% reduction in the flow rate from 2.00 to 1.75 kg/min results in a 32% reduction in the amount of sand passing through the contact, and a 25% reduction in the flow rate results in a 68% reduction in the amount of sand passing through the contact. Similar results are seen for the hose aligned in the nip position. It can therefore be concluded that small changes in flow rate can lead to significant reductions in the amount of sand delivered to the wheel/rail contact. Figure 10 also shows that a nozzle or a restriction in the diameter of hose exit can help compensate for a reduction in the flow rate of the sanding system. A nozzle has the benefit of demanding only a small increase in the regulator pressure to maintain sand flow rate, relative to using a smaller diameter pipe. Data shown in Figure 10 confirms the findings in Sub-stage 1 that at the highest flow rate examined there is little difference in sand mass reaching the rail-wheel interface between the hose pointing at the rail or the nip.

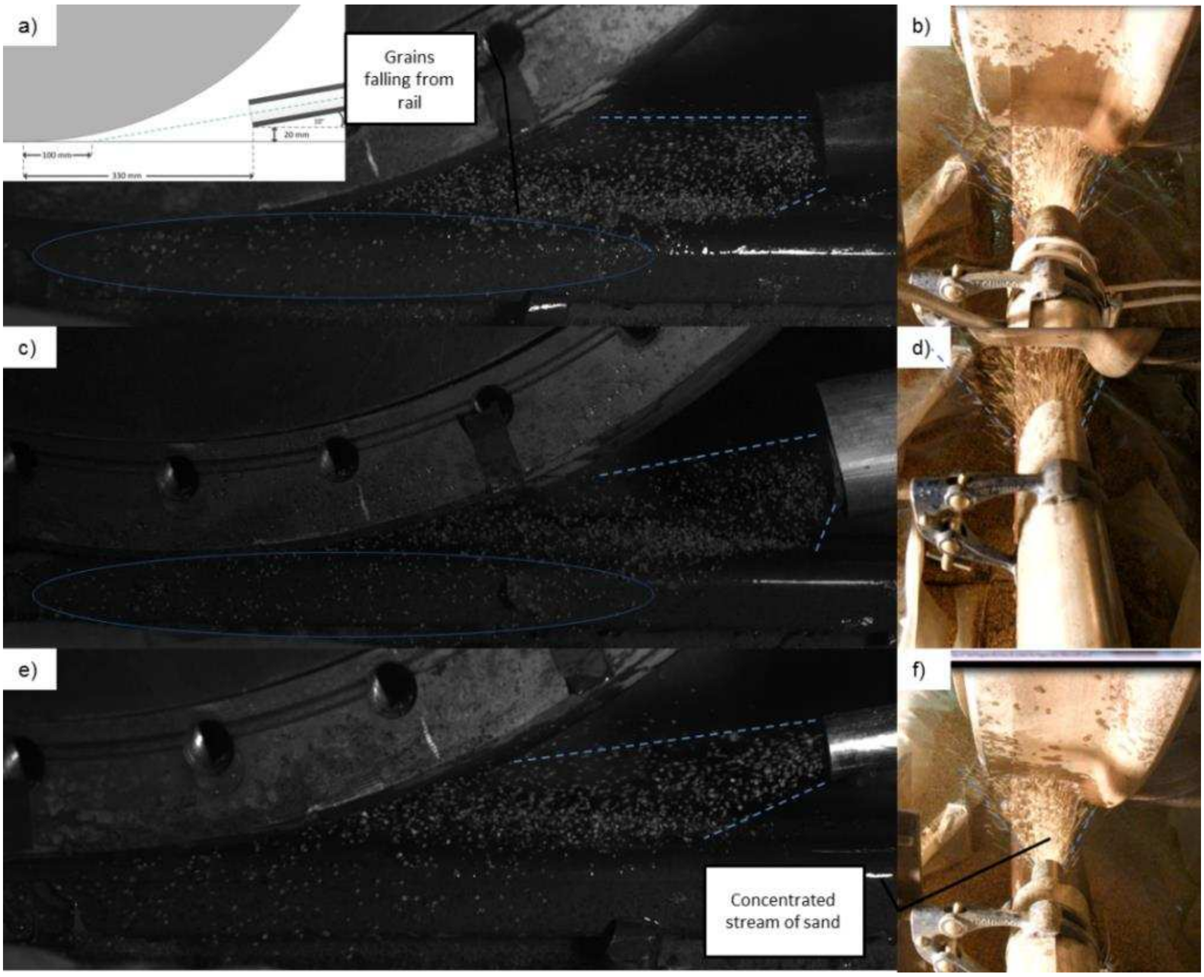

Fig. 11, High-speed stills taken during testing for sub-stage 3 tests with hose aimed at nip at 10°: a) side view, flow rate of 2.00 kg/min; b) front view, flow rate of 2.00 kg/min; c) side view, flow rate of 1.50 kg/min; d) front view, flow rate of 1.50 kg/min; e) side view, flow rate of 2.00 kg/min, hose with nozzle; f) front view, flow rate of 2.00 kg/min, hose with nozzle. All tests performed under wet conditions with 48 km/h longitudinal wind

Figures 11a and b show camera stills from a test performed with a plain 25mm hose at a flow rate of 2.00 kg/min. Figures 11c and d show stills from an experiment performed at 1.50 kg/min. It can be seen Figure 11c that the sand exiting the hose is less densely packed than the sand flowing at a rate of 2.00 kg/min (Figure 11a). This can also be seen in the front views shown in Figures 11b and d. Figures 11e and f show tests done with a flow rate of 1.50 kg/min, but with a nozzle fitted to the end of the hose. It can be seen in Figure 11e that there is a much more focused flow of sand coming from the end of the nozzle compared with the case without a nozzle. The front view of the test in Figure 11f shows that when a nozzle is used there is still some flare of the sand flow to either side of the rail as in the cases without a nozzle attached to the hose. However, in the case of a nozzle there is a central concentrated flow of sand which would be expected to have a better chance of entering the contact and is less likely to fall from the rail before entering the rail-wheel nip.

4.1.4 Effect of a Side-wind

To examine the effect on sanding of a side-wind (perpendicular to train motion) combined with the headwind due to train motion, a test was performed with the fan blowing at 45° relative to the rail. The wind speed of this test was 64 km/h in a direction toward the flange root and gauge corner, i.e. not onto the outside of the flange, but across the rail head and into the flange root. A hose fitted with a nozzle (see Section 4.1.3) was used with a sand flow rate of 2.00 kg/min. After this test there was no sand left on the rail to be collected. Video capture of this trial was taken and it can be seen from the front facing camera that the sand particles are blown toward the flange of the wheel as they leave the end of the nozzle. The side facing high-speed video also shows that as the particles hit the rail they lose enough forward momentum that they are blown clear of the rail by the wind, with no particles entering the nip. This is a significant result could potentially indicate that moderate side winds may be enough to render sanding systems completely ineffective in the field.

In addition to head and side winds, it is also conceivable that when a train is travelling at speeds in excess of 80 km/h airflows on the underside of the vehicle may turn turbulent which may lead to sand not reaching the contact as in this trial test. This would particularly be the case on sanders which were located behind the leading axle, as is current practice in the UK. This is done to avoid potential isolation/signalling issues at the extremities of the vehicle. However, the further back from the leading axle sanding hose is, the more structures and components upstream of the hose which will cause disturbance to the airflow. This might also explain why the vehicle speeds were not affected when drivers applied the emergency brakes and on-board indicators showed the sanding systems to be active at both incidents at Esher and Lewes [7, 8]. Both of the vehicles were traveling at over 90 km/h at the time and it was also subsequently found that the sanding systems were functioning adequately in post-incident static tests on the vehicles involved. The results here suggest that at higher speeds in the presence of a side-wind sanders can be dispensing sand, but little or none of it will enter the rail-wheel nip. Supporting this finding, the high speed videos taken in this sub-stage show that the particles leave the hose with too little forward momentum to overcome the aerodynamic forces of a laterally blowing wind.

4.1.5 Check of Repeatability

Some of the tests from Phase 1 were repeated in order to check the consistency of the tests. Figure 12 shows results from tests done in Sub-stage 3 marked Day 1 along with two other identical tests performed on different days. The figure shows the individual test and the two associated repeat tests performed straight after with no alteration to the hose position or regulator pressure (three repeats were carried out on Day 3). There is some variation seen in tests done in a single day, however, larger variations are seen between tests done on different days. For example the difference between the highest and lowest test on the Day 1 is 2.54g, but the difference in average results between Day 1 and Day 2 is 8.43g. No correlation was seen between changes in atmospheric conditions and the amount of sand left on the rail at the end of each test, with differences instead attributed to small changes in hose set-up, wind-speed and sand flow rate between days. Once the hose had been set-up for each specific test and the flow rate calibrated the hose was not touched between tests and repeats. The relatively smaller variations in result between initial test and repeats on each day is probably down to the chaotic nature of the sand's journey from the hopper to the nip as each particle will follow a different path from the valve down to the end of the hose. The maximum variability between the Day 1 and Day 2 averages of 8.43g is lower than the difference between 2.00 and 1.75 kg/min flow rates shown in Figure 10 (12.35g) indicating that the effect of flow rate change would dominate regardless of the variability between nominally identical tests. To keep consistency in the results the other sub-sections of work reported here consider only tests performed on the same day, with no interference with the system between test and repeats.

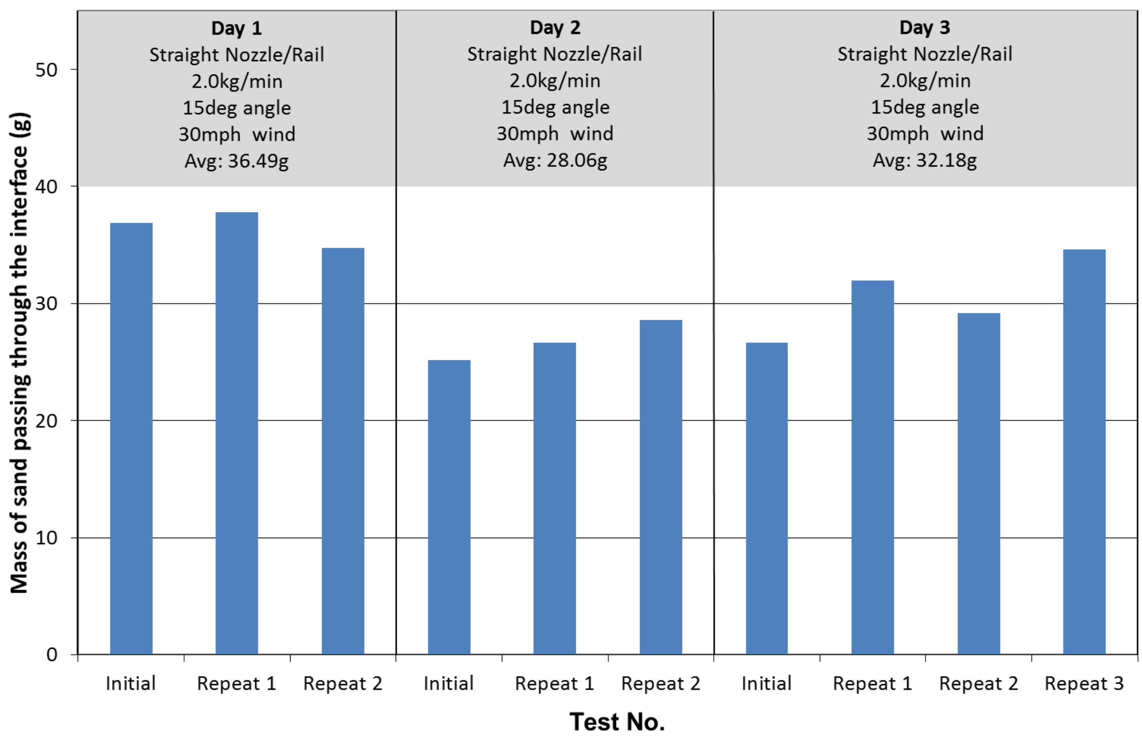

Fig. 12, Check of repeatability. Mass of sand collected from rail after experiments with hose fitted with a nozzle, all test performed under wet conditions with 48 km/h longitudinal wind. Tests performed under nominally identical conditions on separate days.

4.1.6 Sub-Stage 4: Effect of Narrower Hose

In the sanding system performance study carried out on behalf of RSSB [1] evidence was seen that sanders fitted with a wider bored hose (25 mm) would generally have a higher sand discharge rate compared to the more commonly used 19 mm bore hose. As mentioned above it was found that the desired flow rate of 2.00 kg/min was not achieved in the lab when a 1.5 m length of the narrow bore hose was used due to the restrictive effect of the smaller bore. It was found, however, that 2.0 kg/min was achievable when the hose length was shortened to 0.5 m. This meant that the two hose types could be compared because the flow rate was the same between them even though their lengths differed. Figure 13 shows results of tests with a 19 mm, 25 mm and 25 mm nozzled hoses. All tests presented in this section are performed at both the rail (15°) and nip (10°) at a flow rate of 2.00 kg/min under wet conditions and with a longitudinal wind of 48 km/h.

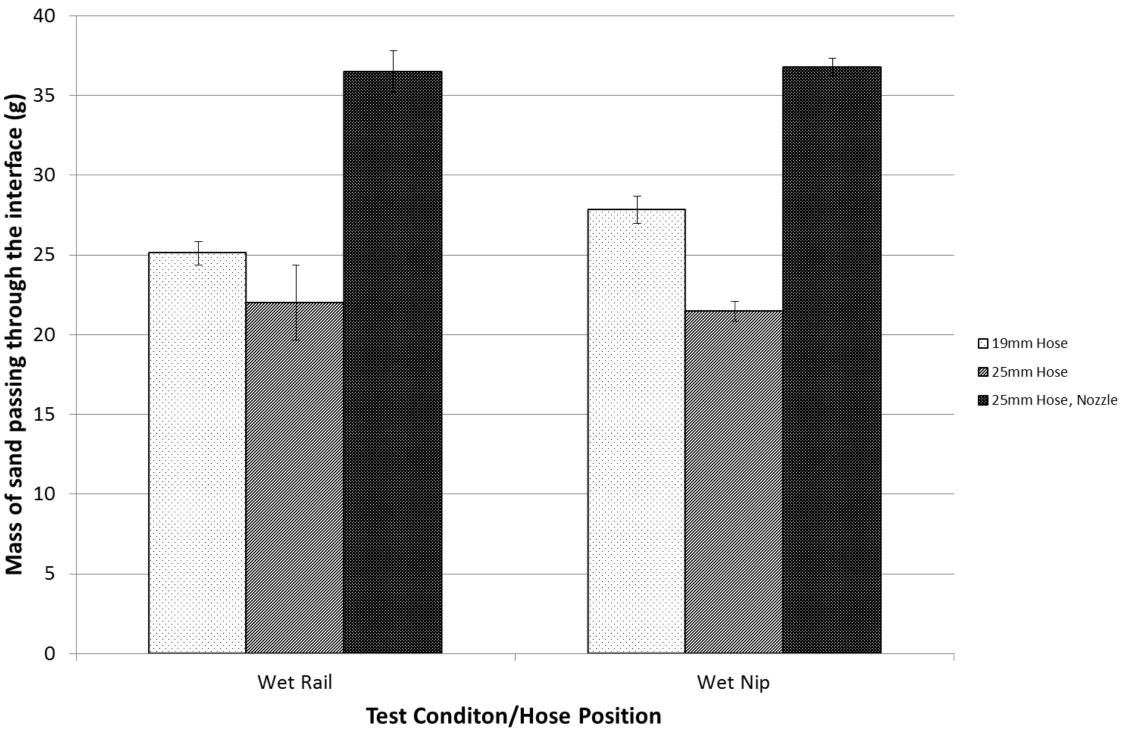

Fig. 13, Mass of sand collected from rail (average of three readings) after experiments with 19 and 25 mm hoses and 25 mm hose fitted with a nozzle. Tests done with hose at rail (15°) and nip (10°) with all test performed under wet conditions with 48 km/h longitudinal wind. Error bars show maximum and minimum readings.

Figure 13 shows that a 19 mm hose is more effective in delivering sand to the contact than a 25 mm hose and is most effective when used in the nip position. Included in Figure 13 are results of testing with 25 mm hoses and nozzles performed under identical conditions. This shows that the use of a 25 mm hose with a nozzle is the most effective method for delivering the sand to the contact, with a performance exceeding the other cases..

4.2 Phase 2 Tests: Effects of Variations of Optimised Hose Position

The optimal solution found in the Phase 1 tests was using a flow rate of 2.00 kg/min with a nozzle arrangement. There was little difference in sand mass reading between the hose aimed at the nip or the rail. For tests in Phase 2 the hose was aligned with the rail only, at a fixed angle of 15° to the horizontal.

4.2.1 Sub-Stage 5: Changes in Distance from Contact and Height above Rail

Testing began with the nozzle as close to the nip as was physically possible without it coming into contact with the wheel or rail. In this position the nozzle was aimed at the nip. The nozzle was then moved in a matrix of horizontal and vertical positions to build the map of nozzle position and sand quantities passing through the contact that is shown in Figure 14.

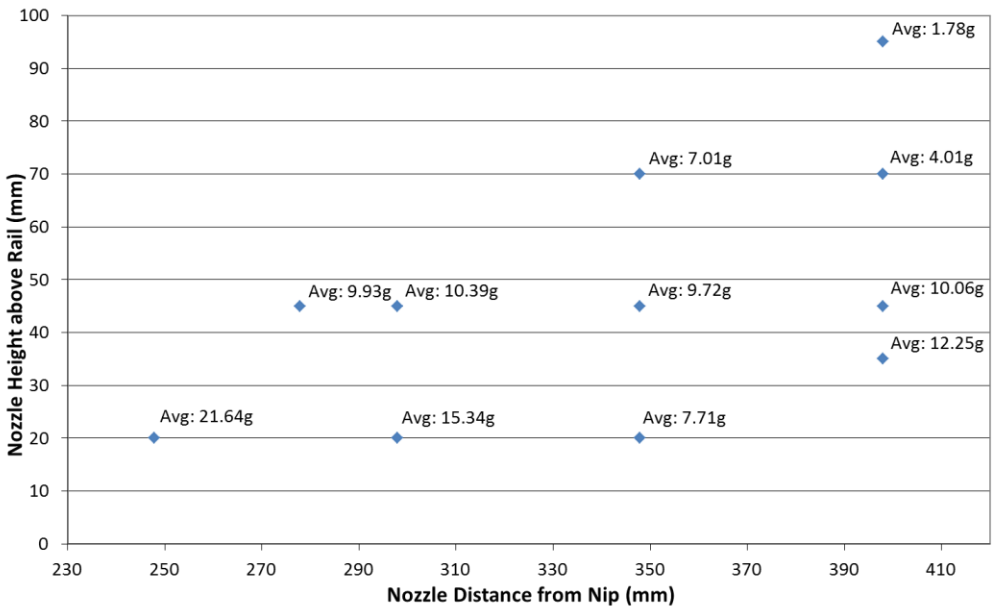

Fig. 14, Average mass of sand collected from rail (average of three readings) after experiments with 25 mm hose fitted with a nozzle with nozzle at various positions relative to nip and rail. Tests done with hose at a 15° angle to the rail all test performed under dry conditions with 48 km/h longitudinal wind

As might be expected, the position closest to the contact delivers the most sand through the interface. As the nozzle is moved away from the contact the amount of sand collected from the rail at the end of the test reduces. There are some exceptions such as in the tests at x:y co-ordinates 398:35 and 398:45, although these variations are within the uncertainty already known to exist in the readings (Section 4.1.5). Figure 14 shows the high sensitivity of effective sand delivery to nozzle position with, for example, a movement of only 33.5 mm from x:y position 248:20 to 278:45 reducing the mass of sand delivered to the rail-wheel contact by more than 55%. This indicates the critical nature of installation and maintenance of the hose and nozzle position in efficient operation of the sanding system.

4.2.2 Sub-Stage 6: Changes in Lateral Alignment of Nozzle

In Sub-stage 6 the lateral alignment of the nozzle was changed relative to the centreline of the rail. The nozzle was moved to x:y co-ordinate 298:45 so that there was enough clearance between the wheel and the nozzle for the nozzle to be moved laterally. As above the angle was held at 15° and the tests were performed dry with a 48 km/h wind. Figure 16 shows the effects of moving the hose laterally. The hose was moved 20 mm either side of the rail centreline.

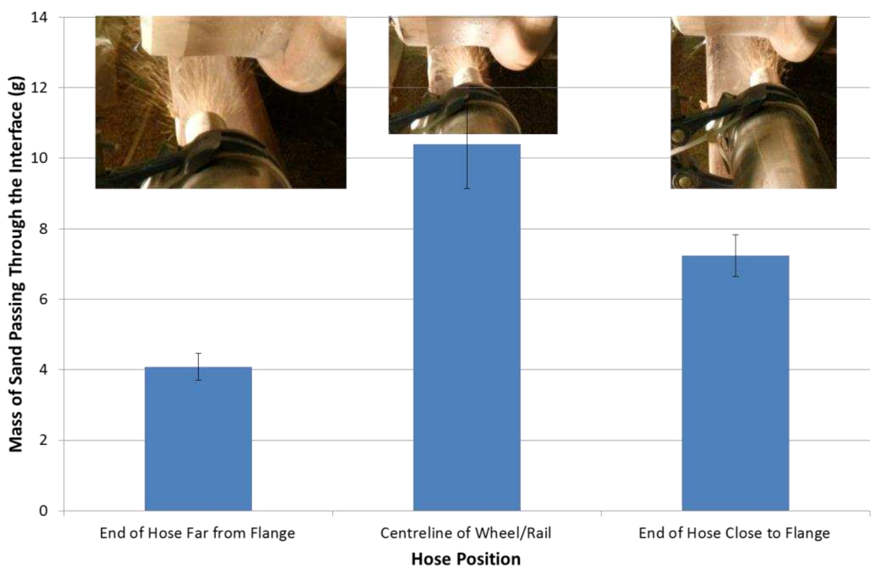

Fig. 15, Average mass of sand collected from rail after experiments with 25 mm hose fitted with a nozzle when lateral alignment of nozzle is changed. Tests done with hose at a 15° angle to the rail all test performed under dry conditions with 48 km/h longitudinal wind

Figure 15 shows that the most effective position is with the hose on or very close to the rail centreline. A movement either side of the centreline will reduce the amount of sand delivered to the interface with less reduction seen when the nozzle is moved closer to the wheel flange. This was thought to be because some of the particles which are on a trajectory to clear the rail will bounce off of the flange and back in towards the nip. When the nozzle is aligned to the far side of the wheel from the flange a large proportion of the sand is never on trajectory towards the nip and flies clear of the rail. Also, because the sand fans from the end of the hose, the proportion of sand toward the right-hand side of the fan will most likely enter the nip.

4.2.3 Sub-Stage 7: Changes in Nozzle's Angle of Twist

As in Sub-stage 6 the x:y co-ordinate of 298:45 was used for investigation of the effect of nozzle angle of twist on sand delivery. A positive (nozzle aimed toward wheel flange) or negative (nozzle aimed away from wheel flange) angle of twist of 5° was applied to the hose by measuring the length of the hose/nozzle arrangement from a fixed point and then deflecting the hose at this point by a certain distance so that the resultant was a 5° angle. The open end of the nozzle was located such that it sat above the centreline of the rail but aimed either toward the flange or away from the flange. Figure 16 shows the results of the angle of twist investigation.

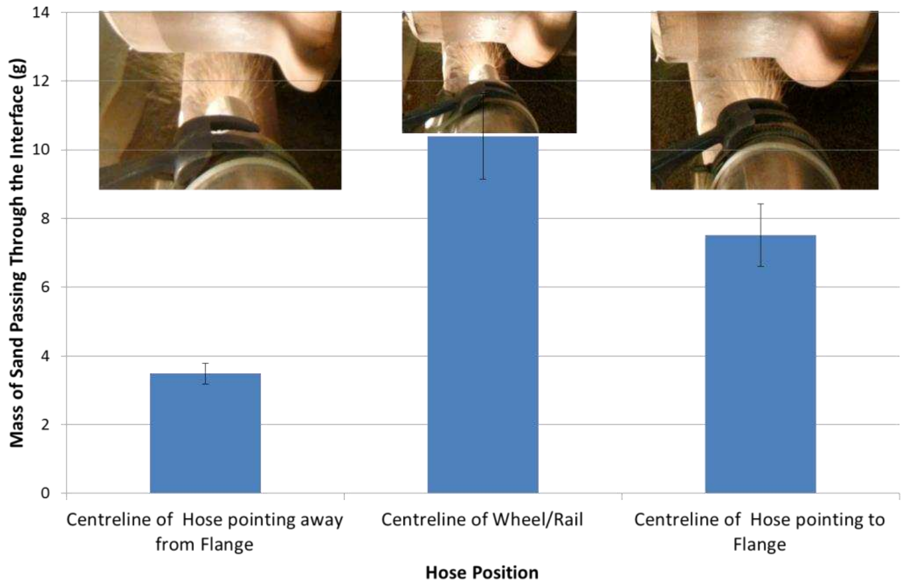

Fig. 16, Mass of sand collected from rail (average of three readings) after experiments with 25 mm hose fitted with a nozzle when angle of twist of nozzle is changed. Tests done with hose at a 15° angle to the rail all test performed under dry conditions with 48 km/h longitudinal wind

Figure 16 shows a similar pattern to the lateral alignment tests with a reduction in sand passing through the interface with a deviation of the direction of the hose from the centreline of the rail and the greatest reduction when the nozzle aims away from the flange. An unexpected result from these tests is that any sand at all passed through the interface when the nozzle is pointed away from the flange. It seems in this case that the wind blows some of the particle back on trajectory toward the nip.

5.0 General observations

During testing the following general observations were made which it is hoped will be of value in further investigation and use of sanding systems.

- Evidence from testing suggests that a more evenly distributed particle speed within the upper, mid and lower-stream improves the chances of sand being entrained in the contact. The addition of a nozzle to the 25mm bored hose increases particle speeds in the lower-stream from 0.6 m/s to 1.4 m/s. This corresponds with an increase of 15.3g of sand passing through the contact. This evidence also suggests that increasing particle speed will increase the amount of sand which enters the contact. This could be achieved by increasing the sand flow rate beyond 2.00 kg/min. In [1] it was found that the 2.00 kg/min limit was set into standard GM/RT2461 [2] because it was found that this discharge rate provided an improvement in adhesion in low adhesion conditions based on tests and a safety case submission used to support the installation of sanding equipment to a particular class of train in the UK in 1996 [1]. No reasoning was found as to why 2.00 kg/min was set as a maximum limit in traction. It is clear that a requirement needs to be placed on the sand discharge rate in order to avoid isolation of track signalling circuits. Thus there is a need for further testing of to investigate: a) the effects of higher flow rates on adhesion and efficiency of sand delivery to the wheel/rail interface and b) the effects of higher flow rates upon electrical isolation between the wheel and the rail and to find a scientifically justified upper limit.

- The current method of delivering sand to a wheel/rail interface using compressed air and a hose may not be the most efficient method. Even the best solutions found in the current test series leave most of the sand which is delivered to the end of the hose on the side of the rail rather than delivering it to the rail-wheel interface. For example at a flow rate of 2.0 kg/min and with each test lasting approximately 9 seconds 300g of sand will leave then end of the hose per test. The highest amount of sand left on the rail after a test for a plain 25 mm hose was 21g and for a 25mm hose fitted with a nozzle was 36g, both in wet conditions. This equates to only a 7% efficiency for the plain hose and a 12% efficiency for a hose fitted with a nozzle. Even in the best case scenario this means that multiple units potentially have to carry around 88% more sand than they need too. This not only means increased weight of the trains, hence greater energy demand, but also a waste of sand and increased fouling of track ballast and other railway infrastructure

6.0 Conclusions

Tests have been performed to find the optimum set-up of current train borne sanding systems, using a full-scale wheel/rail machine in the controlled environment of the laboratory. The main findings of this investigation are:

6.1 Hose Type and Position

- The most effective position for the hose to aim is either toward the nip or toward the rail at 10 and 15° angles of attack respectively
- A damp rail allows more of the particles which fall from the hose to adhere to the rail meaning fewer particles fall from the rail and are more likely to be rolled over by the wheel compared to dry conditions
- A hose with a 19mm bore offers a slightly better solution in delivering sand to the contact than a 25mm bored hose. However, this size of hose demands a much higher regulator pressure to achieve a sand flow rate of 2.00 kg/min compared to a 25mm bored hose. For a lower pressure a 25mm hose can offer almost the same level of sand delivery to the rail-wheel contact
- Fitting a nozzle to the hose increases the amount of sand which passes through the wheel/rail interface by a factor of 65 – 70% over a standard 25mm hose alone. Fitting a nozzle to current sanding systems should not require a significant modification as there is only a moderate increase in regulator pressure needed in order to maintain the sand flow rate at close to or near 2.00 kg/min
- It has been found that a reduction of only 25% in the flow rate can potentially lead to a 54 – 68% drop in the amount of sand passing through the interface. The percentage reduction is similar even when a nozzle is fitted to the hose but the absolute amount of sand passing through the contact will increase with the addition of a nozzle despite a reduction in flow rate
- The end of the hose /nozzle needs to be placed as close to the wheel/rail nip as practically and safely possible to ensure that the maximum proportion of the sand which is dispensed from the hose is rolled over by the wheel
- Tests have shown that sand delivery to the rail-wheel interface is very sensitive to slight movements in the hose position i.e. vertically, longitudinally, laterally and angular relative to the rail. This indicates the critical nature of choosing the installation position of the hose and nozzle, and maintaining this position over the life of the system to achieve good sand delivery

6.2 Effects of Wind

- Air flow past the rail-wheel contact was shown to have a significant effect on the delivery of sand to the rail-wheel contact. Longitudinal winds increase the amount of sand which enters the contact as the wind speed increases up to 80 km/h in wet conditions. The opposite is true in dry conditions, however, sand is most likely to be applied in wet conditions.
- The experiments showed that even moderate cross winds can render sanders entirely ineffective, with all of the sand blown completely clear the rail-wheel nip when only a 64 km/h wind (i.e. a combined train speed headwind and a lateral ambient flow) blows at a 45° angle relative to the rail. This is equivalent of lateral and longitudinal winds of only 45 km/h. Positioning of sanders relative to under floor equipment may subject the sand flow to additional turbulence and further influence sand delivery, and this remains to be fully investigated in future work. An increase in sand particle speed to increase its forward momentum and overcome aerodynamic forces may offer opportunities for improved sand delivery.

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References

[1] 2009. Understanding the Current Use of Sanders on Multiple Units, Rail Safety and Standards Board, Research Program Report; http://www.rssb.co.uk/pdf...esearch/T796_rpt_final.pdf

[2] RSSB:GM/RT2461 issue 1, Sanding Equipment Fitted to Multiple Units and On-Track Machines; http://www.rgsonline.co.uk/Railway_Group_Standards/Rolling%20Stock/Railway%20Group%20Standards/GMRT2461%20Iss%201.pdf

[3] 2007. Autumn Adhesion Investigation Part 3: Review of adhesion-related incidents autumn 2005. Rail Accident Investigation Branch: Rail Accident Report, Report 25 (Part 3)/2006; http://www.raib.gov.uk/publications/investigation_reports/reports_2007/report252006.cfm

[4] Broster, M., Pritchard, C., Smith, D A., 1973. A Basic Study of Wheel/Rail Adhesion 6 – Adhesion and Contamination on BR Track, BR Research; http://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=10337

[5] Jenks, C W., 1997, Improved Methods for Increasing Wheel/Rail Adhesion in the Presence of Natural Contaminants. Transit Cooperative Research Program: Research Results Digest, 17

[6] Nagase, N., 1989. A Study of Adhesion between the Rails and Running Wheels on Main Lines: Results of Investigations by Slipping Adhesion Test Bogie. Proc. IMechE Part F: Journal of Rail and Rapid Transit, Vol. 203, pp 33-43 [3]

[7] 2007. Autumn Adhesion Investigation Part 1: Signals WK338 and WK336 Passed at Danger at Esher 25 November 2005. Rail Accident Investigation Branch: Rail Accident Report, Report 25 (Part 1)/2006; http://www.raib.gov.uk/publications/investigation_reports/reports_2007/report252006.cfm

[8] 2007. Autumn Adhesion Investigation Part 2: Signal LW9 Passed at Danger at Lewes 30 November 2005. Rail Accident Investigation Branch: Rail Accident Report, Report 25 (Part 2)/2006; http://www.raib.gov.uk/publications/investigation_reports/reports_2007/report252006.cfm

[9] Arias-Cuevas, O., Li, Z., 2011, Field investigations into the adhesion recovery in leaf-contaminated wheel-rail contacts with locomotive sanders. Proc. IMechE Part F: J. Rail and Rapid Transit, Vol. 225, pp 443-456

[10] STG-D-REF-RP-1: Class 165 Automatic Sander Track Circuit performance, Issue 1, 20/2/1996

[11] STG-D-SND-RP-8: Class 165 Automatic Sander Track Circuit performance, Issue 1, 20/3/1996

[12] RR-TRS-96-016: Braking and Track Circuit Tests for a 2-Car Train, Issue 1, 1/8/1996

[13] RR-TRS-96-044 Safety Submission for Class 165 Automatic Sander Part 1: Overview & Evaluation of Braking Performance, Issue 1, 28/8/1996

[14] STG-D-SND-RP-10 Safety Submission for Class 165 Automatic Sander Part 2: Evaluation of Track Circuit Performance, Issue 1, 29/8/1996

[15] RR-TRS-96-047 Safety Submission for Automatic Sanders fitted to Class 165/166 3-Car Stock, Issue 1, 28/8/1996

[16] Lewis, R., Dwyer-Joyce, R S., 2006, Wear at the Wheel/Rail Interface When Sanding is used to Increase Adhesion. Proc. IMechE Part F: J. Rail and Rapid Transit, Vol. 220, pp 29-41

[17] Fulford, C R., 2004. Review of Low Adhesion Research, Rail Safety and Standards Board, Research Program Report

[18] Lewis, R., Dwyer-Joyce, R S., Lewis, J., 2003. Disc Machine Study of Contact Isolation During Railway Track Sanding. Proc. IMechE Part F: J. Rail and Rapid Transit, Vol. 217, pp 11-24

[19] Arias-Cuevas, O., Li, Z., Lewis, R., Gallardo-Hernandez, E A., 2010, Laboratory investigation of some sanding parameters to improve the adhesion in leaf-contaminated wheel–rail contacts. Proc. IMechE Part F: J. Rail and Rapid Transit, Vol. 224, pp 139-157

[20] McEwan, I J., Harvey, R F., 1985, Full Scale Wheel on Rail Testing: Comparisons with Service Wear and Developing a Theoretical Predictive Model. Lubrication Engineering, Vol. 41 (2), pp 80-88

[21] Burstow, M., 2006. Whole Life Rail Model Application and Development for RSSB (T115) – Rolling Contact Fatigue Testing, Rail Safety and Standards Board, Research Program Report, AEATR-ES-2004-907 Issue 1

[22] 2013. Performance and installation criteria for sanding systems - Summary report, Rail Safety and Standards Board, Research Program Report; http://www.rssb.co.uk/research-development-and-innovation/research-and-development/research-project-catalogue/t797