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WHEEL/RAIL CONTACT ISOLATION DUE TO TRACK CONTAMINATION

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Abstract

An experimental study has been carried out to investigate the effect of sanding on the electrical isolation of a wheel/rail contact. Sand is applied to the wheel/rail interface to increase adhesion in both braking and traction. Train detection, for signalling purposes, can be by means of track circuits. Signalling block occupancy is triggered by the wheelset of the train 'shorting out' the track circuit. Sand in the wheel/rail interface means that contact between the wheelsets and the track may be compromised, inhibiting train identification.

Static tests were performed using sections cut from wheels and rail and dynamic tests on a twin disc machine where rail and wheel steel discs are loaded together and driven under controlled conditions of rolling and slip. The electrical circuit used was a simplified simulation of the TI21 track circuit.

The application of sand was carried out under a range of mild and severe test conditions. The results indicated that a transition exists in the amount of sand applied, below which there is a measurable, but not severe, change in voltage, but above which the contact conductance decreases by an order of magnitude. A model of electrical isolation has been developed assuming either full disc separation by a sand layer or partial disc contact with some sand present.

Idealisations inherent in both test methods mean that they represent a severe case. Given these limitations, it is likely that the test methods, at their present stage of development, should be used as a means to qualitatively assess the relative effects on electrical isolation of different contaminants.

INTRODUCTION

Track circuits are devices designed to continuously detect the absence of a train from a particular section of track. Their designed failure mode is to indicate the presence of a train and therefore cannot be used to detect whether a train is present. A clear track circuit can be used to allow a train to safely progress.

A track section is electrically defined by insulated joints, as shown in *figure 1*. An electrical energy source (transmitter) is connected, via a series impedance, across one end of the track circuit. At the other end is a detector. If there is no train within the boundaries of a track circuit the detector picks-up the electrical energy from the transmitter. It in turn energises a repeater circuit, which tells the signalling system the section of track is clear.

If a train is present on the track section the rails will be short-circuited and the detector will no longer be able to sense the electrical energy from the transmitter. It therefore changes state and the signalling system is informed that the section of track is occupied.

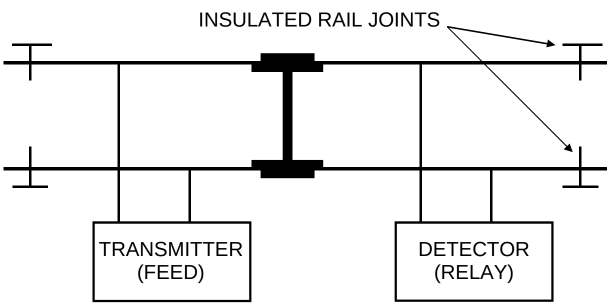


figure 1 Track circuit schematic

It can be seen that any short-circuit, caused by a train or otherwise, or a break in the circuit will fail the track circuit and inform the signalling system that the track is occupied, so a good degree of *fail-safe* is incorporated. The system, however, relies on good wheel/rail electrical contact to work.

There are a number of contaminants that could affect the wheel/rail electrical contact and compromise the operation of the track circuit. These include sand, ballast materials, leaf residue and rust. In order to design track circuits to cope with insulation of the wheel/rail contact due to these contaminants quantitative data is required on the affect they have on the resistance of the contact.

The aim of this work was to develop laboratory tests that could be used to assess the affect of contaminants on wheel/rail isolation to provide input data for electrical models of track circuits with a view to optimising their operation.

For the initial studies described in this paper, the emphasis was placed studying isolation due to track sanding. Sanding is used in train operation to improve adhesion in both braking and traction. In braking it is used to ensure that the train stops in as short a distance as possible. It usually occurs automatically when the train driver selects emergency braking. Sanding in traction, however, is a manual process. The train driver must determine when to apply the sand and how long the application should last.

The sand is supplied from a hopper mounted under the train. Compressed air is used to blow the sand out of a nozzle attached to the bogie and directed at the wheel/rail contact region. Clearly contamination of the wheel/rail contact in this manner could isolate the wheel from the track inhibiting the detection of a train. Most sanding equipment uses a fixed sand flow rate, so the worst case scenario is a train moving at slow speed or coming to a standstill, as under these conditions there will be a lot more sand present per unit length of track.

EXPERIMENTAL DETAILS

Test Apparatus

Two test methods were used; a static test employing actual wheel and rail sections to investigate the situation where a train has come to a standstill while sand is present on the track and a dynamic test based on a twin disc machine to study isolation as a train is moving.

The static test apparatus is shown in *figure 2a*. The wheel and rail sections are hydraulically loaded together. Contaminants can be placed in the contact area prior to loading.

A schematic of the twin disc test machine used to carry out the dynamic testing is shown in *figure 2b*. The original development of this machine and more recent work carried out to add a computer control system have been described previously [***1***, ***2***].

The test discs are hydraulically loaded together and driven at controlled rotational speed by independent electric motors. Shaft encoders monitor the speeds continuously. A torque transducer is assembled on one of the drive shafts and a load cell is mounted beneath the hydraulic jack. The slip ratio required is achieved by adjustment of the rotational speeds. All data is acquired on a PC which is also used for load and speed control.

In order to apply sand to the wheel/rail disc contact in a manner similar to that used on an actual train, modifications have been made to the apparatus. An actual sand valve was used to mix compressed air and sand which was then directed into the rail/wheel contact via a pipe and nozzle. An environment chamber was fitted around the discs with inlets for the sand nozzle and a water feed pipe.

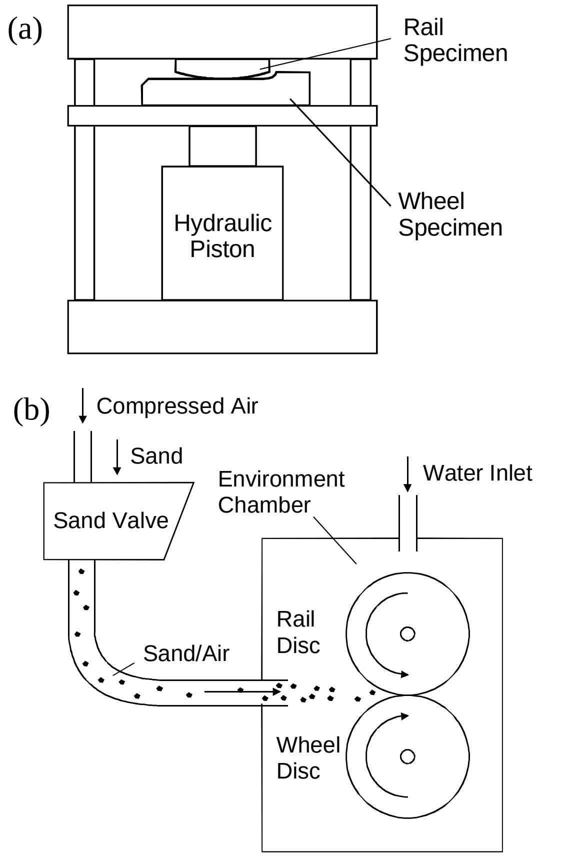


figure 2 Experimental set-ups for: (a) static tests and (b) twin disc tests

Electrical Circuit

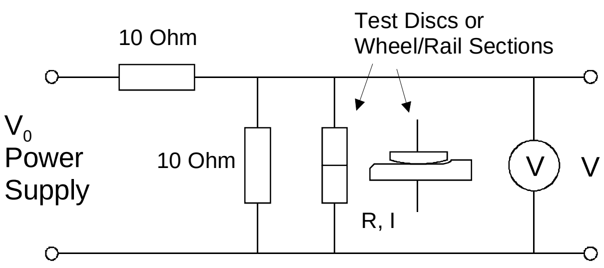
The electrical circuit used to measure voltages across the wheel/rail section and twin disc contact (see *figure 3*) was designed to provide a simplified simulation of the electrical conditions at a wheel/rail interface when using a TI21 track circuit.

The circuit consisted of a 2 kHz AC voltage source, V_0, connected in series with a 10 Ω resistor, in series with the disc contact. Another 10 Ω resistor was connected in parallel with the disc contact. The resistors were used to replicate the transmitter and receiver resistances found in the TI21 track circuit. RMS voltage, V, was logged using data capture apparatus with samples taken at 0.1s intervals.

In order to provide a means of assessing the likelihood of isolation occurring for all types of track circuit, it was necessary to characterise the resistance of a contact and relate it to sand flow rate. The resistance, R, across the discs can be calculated by:

$$R = \frac{10}{\left(\frac{V_0}{V}\right) - 2} \qquad \textbf{(1)}$$

As the voltage, V, approaches its open circuit value ($V_0/2$), however, the resistance across the discs becomes infinite. This makes assigning an average value for the contact resistance for a given amount of sand impossible. In order to overcome this, the conductance, G, was considered rather than resistance (where $G = 1/R$).



Expected Voltage and Current Values:

Open Circuit (no contact): $V = V_0/2$, $I = 0$

Closed Circuit (contact): $V = 0$, $I = V_0/10$

figure 3 Electrical circuit used for determining voltage across the wheel/rail section and twin disc contact

A voltage of 1.6V was chosen for all static and dynamic tests. This value represents the lower level expected at the transmitter end of a track circuit with short section and low power configurations or at the receiver end with long section and normal power. RMS voltage across the wheel/rail section or twin disc contact was logged during the tests.

Specimens and Contamination

Wheel and rail sections used in the static tests (see *figure 4a*) and the discs used in the dynamic tests (see *figure 4b and 4c*) were cut from R7 wheel rims and BS11 rail sections. The discs were machined to a diameter of 47mm with a contact width of 10mm. Standard commercial sand complying to the guidelines issued by Railway Safety for fitting of sanding equipment to multiple units [***3***] was used in the tests (see *figure 5*).

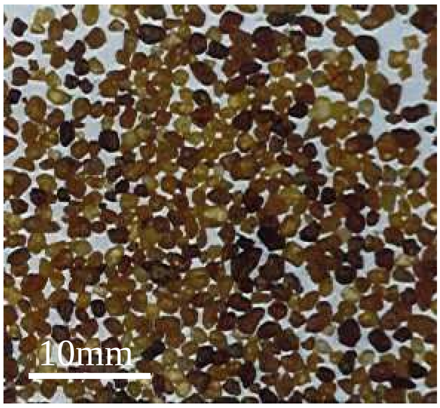


figure 5 Sand grains

Experimental Procedure

In the static tests dry pre-crushed sand was placed in the contact region and loads of up to 60kN were then applied. After the tests, sand that had actually been in the contact was collected and weighed. Using crushed sand gave greater control over the amount of sand in the contact. When whole grains of sand were loaded in the rig most of the sand was ejected as they were crushed.

During the dynamic tests, discs were loaded and rotated to achieve surface speeds of 2 mph and 0.5 mph with a mean contact pressure of 1500MPa and a slip of 20% (typical for a driving wheel experiencing loss of adhesion).

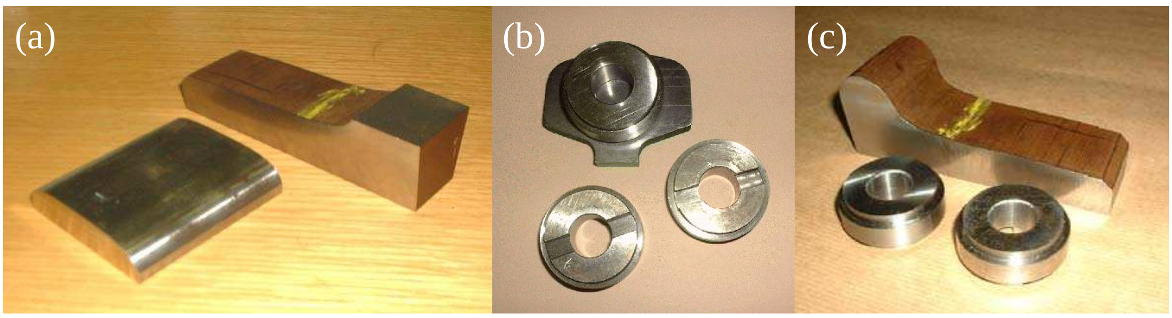


figure 4 Test specimens: (a) wheel and rail sections for static testing; (b) rail disc specimens for dynamic testing; (c) wheel disc specimens for dynamic testing;

Tests were carried out applying sand to both a dry disc interface and a wet disc interface (water has been shown to be one of the more frequent causes of adhesion loss [***4***]). When running discs with water and sand, water was dripped onto the top of the rail disc (as shown in *figure 2b*) at a rate of one drip every 2 seconds; this was found to cause just sufficient water flow such that the discs were always wetted.

During the tests the discs were run out of contact and then under load (either wet or dry) with no sand application for a short period to allow traction at the interface to stabilise and enable voltage readings to be recorded before sand entered the contact. A fixed quantity of sand (0.25 kg) was then fed into the contact, for a pre-determined time (achieved by setting the mixing air pressure). The feeding time was recorded in order to calculate an accurate mass flow rate of sand.

A variety of different sand flow rates were used, between 0.1 and 0.75kg/min. These sand flow rates represent the amount of sand leaving the valve. Not all of this sand will actually enter into the contact. A significant proportion will be dispersed before entry into the contact and when a particle is entrained into the entry region, when it fractures, the fragments may also be partially dispersed. The amount of dispersion will clearly vary according to the geometry of the contact and the sanding apparatus set-up. Typical sand flow rates are 1 or 2 kg/min for sanders fitted to multiple units.

Low surface speeds were used as these represent the worst case. At lower speeds the sand is spread over a shorter distance and therefore more is likely to enter the wheel/rail interface.

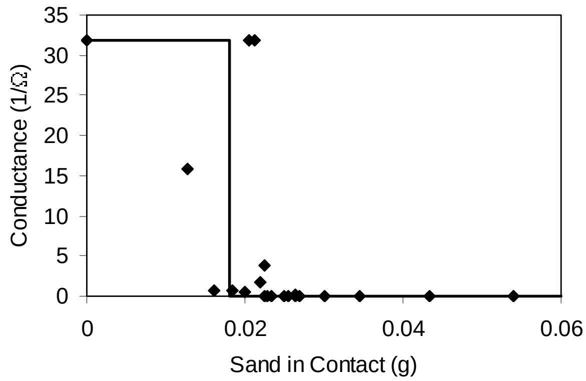


figure 6 *Conductance against amount of sand in the contact for static tests*

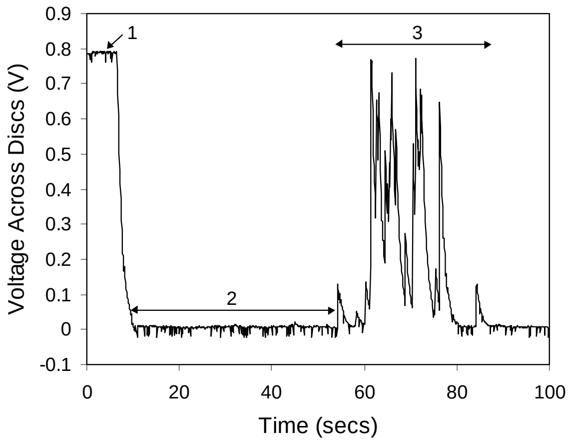


figure 7 *RMS voltage for a test run dry with dry sand (0.5 mph, 1500MPa, 20% slip, input voltage of 1.6V and a sand flow rate of 0.52kg/min)*

RESULTS

Static Tests

Figure 6 shows how conductance varies with amount of crushed sand in the contact for static tests. It is clear that a transition occurs at a sand content of 0.02g below which conductance occurs, but above which the wheel and rail sections are likely to be isolated.

Dynamic Test Results

Figure 7 shows RMS voltage plots for a twin disc contact run with dry sand (0.5 mph, 1500MPa, 20% slip, 1.6V and a sand flow rate of 0.52kg/min). The three stages indicated correspond to: (1) discs out of contact, no sand; (2) discs in contact and under load, no sand; (3) discs in contact and under load with sand application.

Figure 8 shows data for dry tests run with three different sand flow rates. Also shown is the expected “open circuit” voltage (0.8V, discs out of contact). For disc operation without sand the signal is stable (with some small amounts of noise). For sand flow rates of 0.5 kg/min and above the voltage is almost continuously above the closed circuit value. Whilst for sand flow rates below 0.5 kg/min the voltage changes intermittently, but tends towards its closed circuit value.

The intermittent voltage signal is probably caused by a non-uniform flow of sand particles into the contact. Whilst the sand is fed into the contact inlet region directly at a uniform rate, it appears that sand enters the contact itself fairly unevenly.

Similar results were seen for wet tests although the voltage was above the closed circuit value for longer and greater complete disc isolation was seen than with dry tests at the same sand flow rate. This may be because the water makes the sand clump together and also adhere to the rail surface better. *Figure 9* illustrates how crushed sand particles may be ejected from a dry contact, but pulled into a wet contact after adhering to the water film on the disc surfaces.

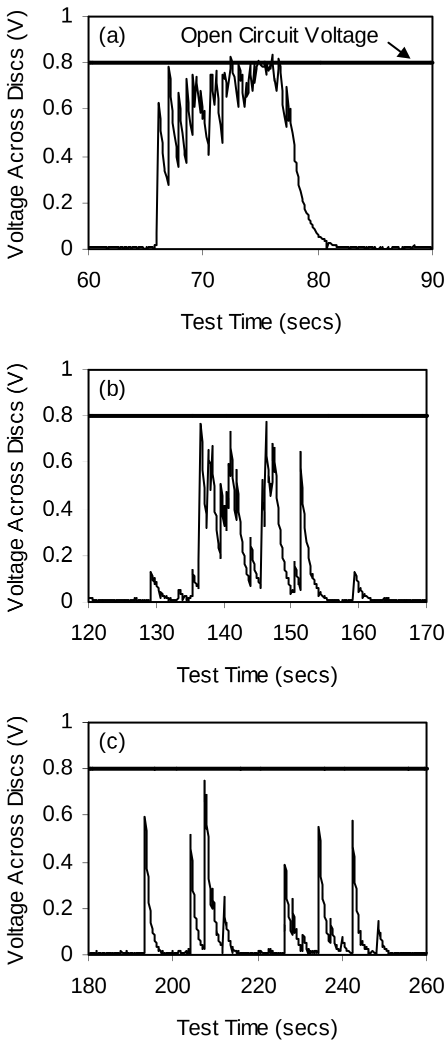


figure 8 *RMS voltage plots for tests run with dry sand at (0.5 mph, 1500MPa, 20% slip, input voltage of 1.6V and sand flow rates of: (a) 0.75 kg/min; (b) 0.52 kg/min; (c) 0.25 kg/min*

Figure 10 shows how the average conductance (calculated from voltage reading using equation 1) varies with sand flow rate for wet and dry tests. It is clear that, as seen with the voltage plots, a transition occurs at a sand flow rate of 0.40 kg/min for tests run at 2 mph. Sand flow rates below 0.40 kg/min giving much better conductance at the contact than those above. For dry tests better conductance occurred at a surface speed of 0.5 mph than at 2 mph. This suggests that sand entrainment was greater at the higher speed. For the wet tests surface speed had no effect on conductance. With wet discs it is possible that the sand particles were pulled into the contact in the water film on the discs. This effect is probably overriding any speed effects.

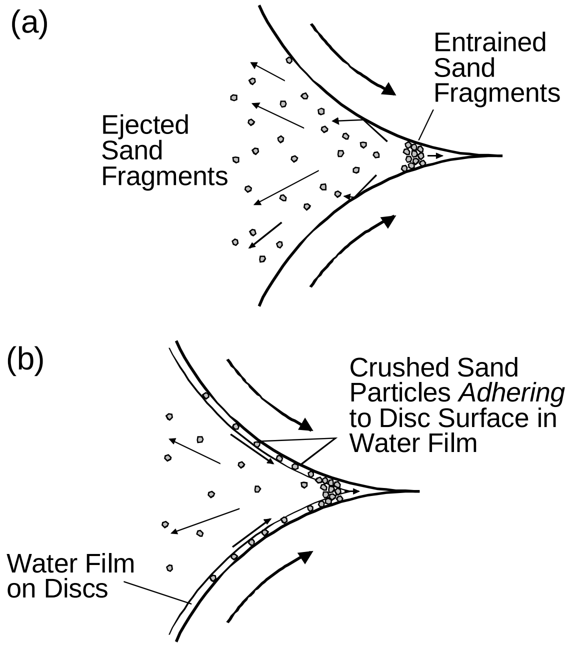


figure 9 *Sand grain crushing and entrainment into: (a) dry disc contact; (b) wet disc contact*

MODELLING CONTACT RESISTANCE

The disc interface is modelled using two approaches. The first approach assumes full disc separation by a sand layer. The second is based on a calculation of the amount of metal to metal contact likely with partial disc separation by sand particles.

Wheel/Rail Surfaces Separated by Sand

For the situation when the two discs are separated by a thin layer of sand (with a thickness, l, equal to the size of one fractured sand fragment) (as shown in *figure 11*), the contact resistance can be given by:

$$R = \frac{\rho l}{A} \quad \textbf{(2)}$$

where ρ is resistivity (of the sand layer).

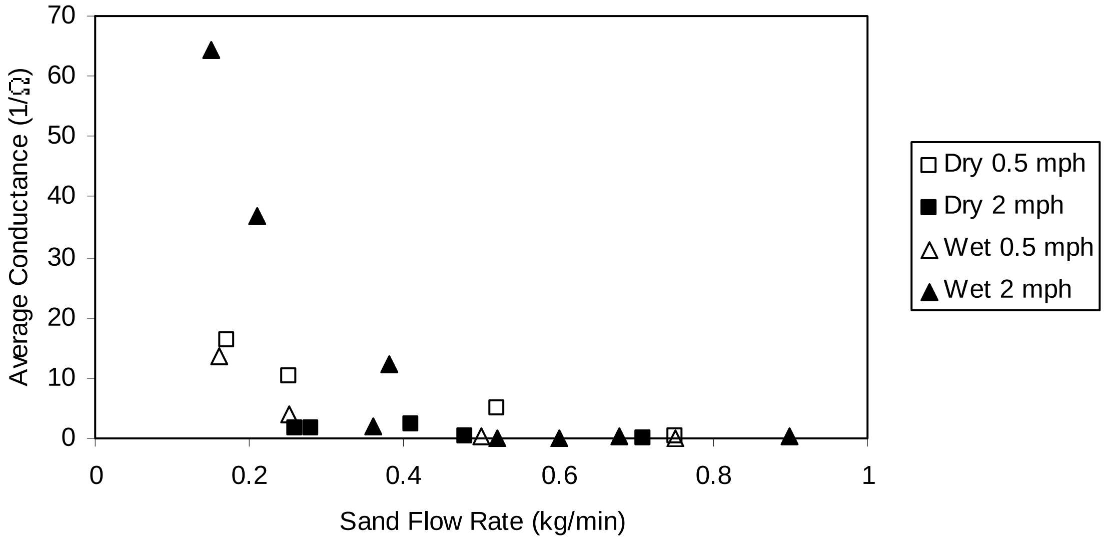


figure 10 Average conductance against sand flow rate for wet and dry dynamict tests

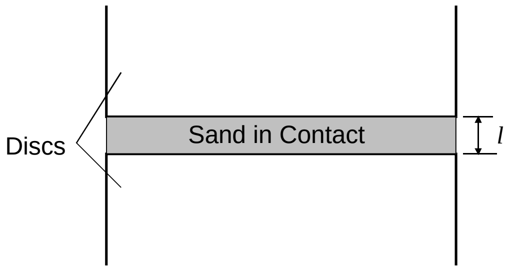


figure 11 Wheel/rail discs separated by sand

The size of a crushed sand fragment will be dictated by the fracture toughness and the size of any flaws in the material [*5*]. An estimate of the minimum fragment size after crushing in the disc contact can be obtained from the stress surrounding the particle, σ, and the size of the largest flaw, a, in the material of fracture toughness K_{IC}.

$$K_{IC} = Y\sigma\sqrt{\pi a} \qquad \textbf{(3)}$$

where Y is a constant depending on the crack geometry (e.g. Y = 1.12 for an edge crack or 0.6 for a semi-circular flaw). When a sand particle is in the disc contact it can be assumed that it will be subjected to a maximum stress equal to the hardness of the disc material (2.9GPa for the rail). Using a fracture toughness value of 1.5MPa√m for the sand gives a maximum flaw which will not propagate to fracture. Thus a crude estimate for the smallest possible surviving fragment can be obtained as 0.1 - 0.2μm.

Figure 12 shows how conductance at the twin disc interface changes with resistivity of the separating layer between the discs for varying layer thickness. Resistivity values for a number of materials are plotted to indicate how conductance varies with different separating layers and to determine how water alone affects conductance. The maximum conductance calculated for the tests carried out is also shown (65 Ω^{-1}).

As can be seen, resistivity for particular materials can vary across orders of magnitude so only approximate conductance values can be determined. It is clear though that if the disc surfaces are fully separated by a layer of sand of only one grain thickness (~0.1μm), there is negligible conductance. However, when the surfaces are separated by a layer of dry sand of similar thickness mixed with sufficient water it would seem possible that the conductance is much greater and could reach the highest levels recorded during testing (up to 65Ω^{-1}). Indeed, during testing it was seen that at low sand flow rates higher conductances were seen with wet tests than with those run dry (see *figure 10*).

Wheel/Rail Surfaces in Partial Contact

Bowden and Tabor [*6*] showed that the electrical resistance of the interface between two contacting metal bodies could provide a measure of the real area of contact at the interface. The assumption was made that if two surfaces are supported on n equal *bridges* of radius b (see *figure 13*), the contact resistance when the *bridges* are relatively far apart is given by:

$$R = \frac{\rho}{2bn} \qquad \textbf{(4)}$$

where ρ is the resistivity of the contacting metal bodies (Ωm).

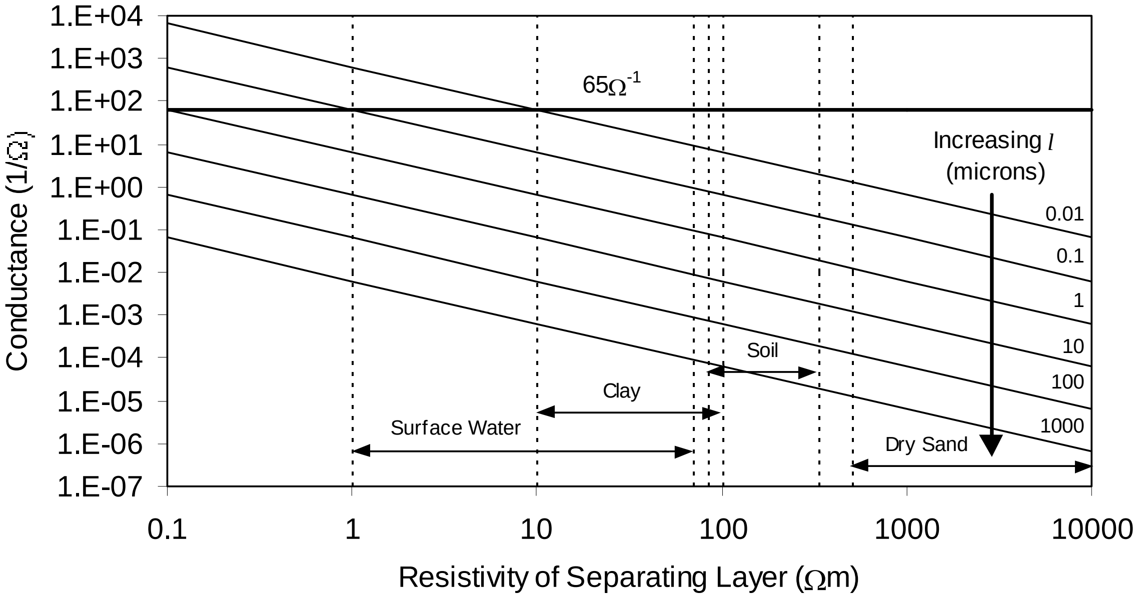


figure 12 Conductance against resistivity for varying layer thickness

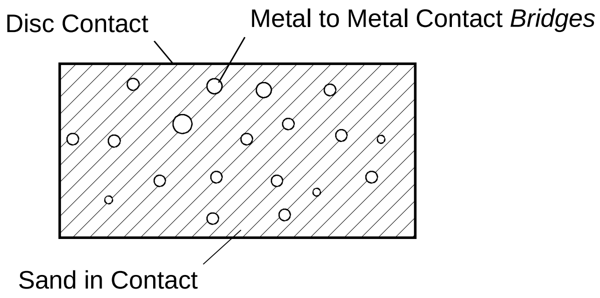


figure 13 Schematic of disc contact showing metal to metal contact bridges

It is possible to calculate, for the disc contact, how many *bridges* there are when sand is present from the resistance or conductance data presented in *figure 10*, using equation 4.

Figure 14 shows the relationship between the number of *bridges* and the conductance at the disc interface (calculated using $\rho = 5\times10^{-7}$ Ωm (typical value for steel)). The maximum conductance calculated for the tests carried out is also shown (65 Ω^{-1}).

Assuming that a contact will not be smaller than a crushed sand fragment (0.1 to 0.2μm), gives the lowest *bridge* radii to be expected as 0.05 to 0.1μm. This means that the the largest number of contacts will be approximately 300 (looking at values below the 65Ω^{-1} line). With larger contact *bridges* ($b \geq 0.1$μm) far less contacts would be expected.

These numbers seem reasonable, however, they represent only a very small proportion of the total contact area. It is clear that for conductance to occur, only a very small amount of metal to metal contact is necessary. In other words, practically, isolation will only occur when the surfaces are completely separated by sand.

DISCUSSION

It is clear that the quantity of sand fed into the contact is an important parameter. Both static and dynamic testing indicated that a transition exists in the amount of sand/sand flow rate, below which there was a measurable, but not severe, change in voltage, but above which the contact conductance decreased by an order of magnitude and the voltage tended towards its open circuit value.

Field tests conducted within the railway industry to determine the maximum acceptable level of sand application to maintain track circuit actuation have led to the definition of a critical sand density in dry conditions of 7.5g per metre of track at 10 mph [***3***].

The 0.40 kg/min transition noted in the results for wet and dry dynamic tests at 2 mph equates to approximately 7.5g per metre of disc circumference. Looking at the data for the tests run at 0.5 mph in Figure 10 it is much harder to see a clear transition. However, it appears that much higher critical sand densities are observed. This implies that less sand enters the contact at lower surface speeds, contrary to the expectation that sand build-up would be worse at lower speeds. This could be due to the differences between the test geometry and an actual wheel/rail contact where one body has a flat surface.

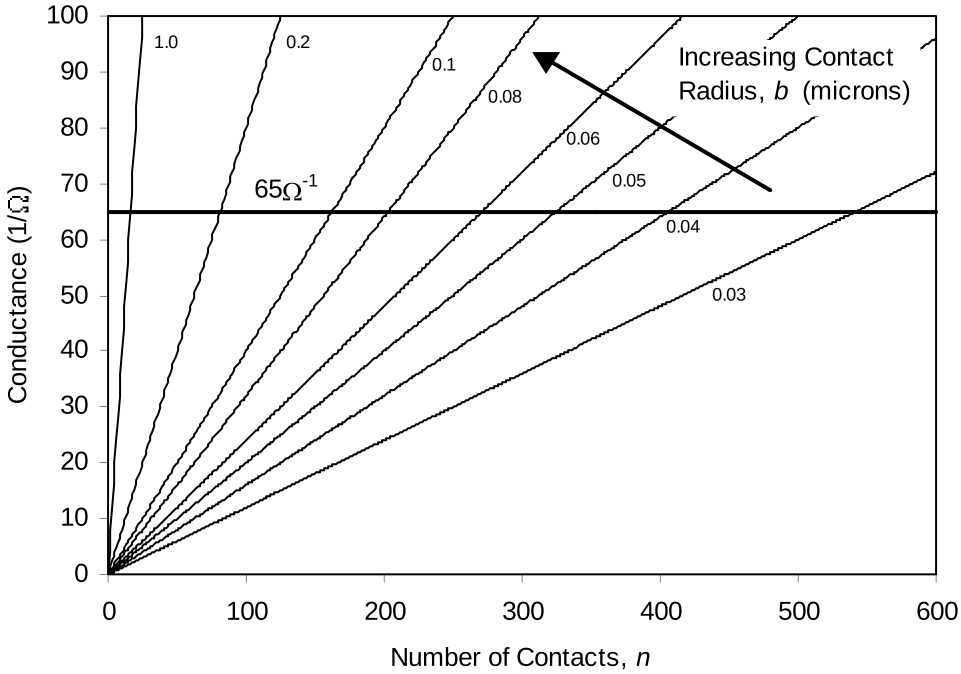


figure 14 Number of contacts (bridges) against conductance for varying contact radius

Critical sand flow rate clearly depends on the disc speed as sand entrainment varies with speed. Given that sand entrainment at 2 mph is greater than that at 0.5 mph, at higher disc speeds still it could further increase giving a much lower critical sand density.

It is the quantity of sand per unit area covering a surface, which will determine the conductivity. So it is preferable to use mass/area as a means to compare the critical flow rates rather than mass/distance or the amount of sand fed per unit time.

Calculating the critical mass/area of sand for the 2 mph disc test gives 0.75 kg/m^2 (for a *track* width of 10mm). The critical mass/area of sand spread on actual rail at 10 mph (assuming a track width of 50mm and using 7.5 g/m) is 0.15 kg/m^2 (critical sand concentrations for test and rail conditions are summarised in *table 1*).

Test	Critical Sand Concentration (kg/m^2)
Static	0.3
Dynamic (2 mph)	0.75
Rail (10 mph)	0.15

table 1 Critical sand concentrations for test and rail conditions

These calculations ignore dispersion of the sand, so actual sand rates entering the contact will be much lower. In the dynamic test more sand enters the contact than would in actual contact. This is mainly because the disc geometry is smaller than a wheel/rail contact and both are in rotational motion and the sand nozzle was placed closer to the interface.

The critical amount of sand in the static test leading to isolation equates to 0.3 kg/m^2. This figure as well as that calculated for the twin disc contact are above that used in practice, which suggests that above 10 mph train identification should be unhindered.

The sand particles are easily entrained into both wet and dry contacts. The entrained particles are crushed to a fine sub-micron sized powder. This process leads to considerable contact noise as the particles are comminuted. The particle entrainment process is, however, intermittent. This causes the recorded voltage traces to be intermittent. This is partly because controlling the sand flow rate accurately is difficult. The mixing valve was not designed for fine control of air or sand.

Modelling of the disc interface with sand present, using the approach proposed by Bowden and Tabor [***6***] relating number of contact *bridges* to resistance/conductance, showed that there could be up to several hundred for the range of tests carried out. This, however, represents only a very small fraction of the actual contact area. This indicates for very low conductance the discs are completely isolated and high conductance is apparent if only a very tiny amount of metal to metal contact occurs. It would follow that conductance is therefore only likely to be very low or very high.

Modelling the contact resistance assuming that the discs are fully separated by a sand layer indicated that for a dry contact that the conductance would be low. It was evident, however, that with water present the conductance could reach the levels recorded during testing which were higher at low sand rates for the wet tests.

If conductance is indeed only very high or very low this could raise the possibility that the voltage plots recorded, with intermediate values, are a consequence of the measuring technique used and that actually all peaks should go to the open circuit value (one particle entrainment may happen too fast to be picked up when sampling data at 0.1 second intervals). This would suggest that averaging of the voltage values to obtain the conductance values shown in *figure 10* is not the right approach. However, the inductance in a track circuit is higher than that in the rig and the sampling time is much slower (1-1.5 seconds between samples). The track circuit is therefore unlikely to pick-up any of the small fluctuations in contact isolation seen in the testing and even though some voltage peaks may have been missed in measurements taken during testing this still represents a more severe scenario than would be seen in reality.

There are a number of idealisations inherent in the test methods, particularly the dynamic technique. Results are therefore only to be taken as a guide to what happens in the full size wheel/rail interface. However, as mentioned previously, it is suggested that the test method used here represents a severe case. Both the geometry and feed method will tend to entrain more sand particles into the contact and the electrical circuitry with its high sampling rate and relatively low inductance will be more sensitive to transient contact resistance fluctuations.

Given these limitations, it is likely that, at their present stage of development, they are best used as a means to qualitatively assess the relative effects on electrical isolation of different contaminants.

CONCLUSIONS

Static and dynamic tests have been used to study electrical isolation by the presence of sand particles at the interface. The static test-rig uses actual wheel and rail sections whilst the twin disc test machine used for dynamic tests reproduces wheel/rail loads, traction and slip, but on a greatly reduced geometrical scale. It can thus only be used as a guide to what will happen in the full size wheel/rail contact.

The application of sand was carried out under a range of mild and severe test conditions. The results indicated that a transition exists in the amount of sand in the contact below which there was a measurable, but not severe, change in voltage, but above which the contact conductance decreased by an order of magnitude and the voltage tended towards its open circuit value.

The disc machine test is severe. It is thought that sand is more easily entrained into the contact than it would be in an actual wheel/rail contact as the nozzle is positioned much closer to the contact inlet and because there are no surrounding air currents. Whilst the static and disc machine results are similar to those for track testing, at this stage it is difficult to relate the critical sanding levels to those in the full size application.

At their present stage of development the test methods are best used as a means to qualitatively assess relative effects on electrical isolation of different contaminants.

Acknowledgments

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