Article:

Ishizaka, K., Lewis, S.R. orcid.org/0000-0003-2597-9625 and Lewis, R. (2017) The low adhesion problem due to leaf contamination in the wheel/rail contact: bonding and low adhesion mechanisms. Wear, 378-379. pp. 183-197. ISSN 0043-1648

https://doi.org/10.1016/j.wear.2017.02.044

The Low Adhesion Problem due to Leaf Contamination in the Wheel/Rail Contact: Bonding and Low Adhesion Mechanisms

Kei Ishizaka [a, b], Stephen R Lewis [a] and Roger Lewis [a]

[a] Department of Mechanical Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

[b] East Japan Railway Company, 2-2-2 Yoyogi, Shibuya-ku, Tokyo 151-0053, Japan

Corresponding author: Roger Lewis

Email: roger.lewis@sheffield.ac.uk

Address: Department of Mechanical Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

Tel: +44 (0) 114 222 7838

Abstract

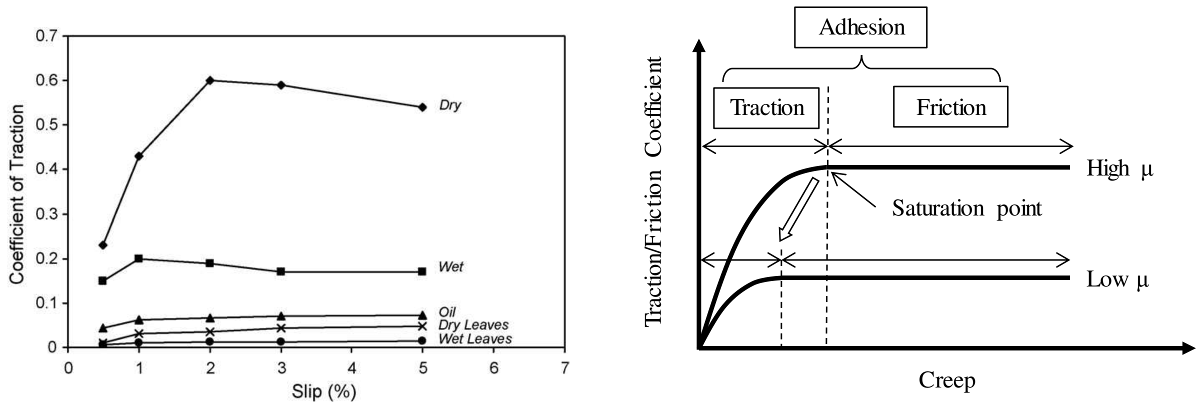
Autumn leaves often cause low adhesion problems for train operations, leading to station overruns and signals passed at danger (SPADS). The aim of this paper was to review operational data and research methods to assess the current understanding of the problem and formulate hypotheses for the causes. Incident analysis showed the relatively high possibility of incidents between the hours of 05:00 – 10:00 and 20:00 – 24:00, suggesting the dew effect was important. This result corresponds to the knowledge that wet leaves in the contact area produce very low friction coefficients, below 0.1. Current mitigation methods, such as sanding, seem inadequate to remove the leaf films completely. To explain the bonding mechanism between the leaf film and the rail, a laboratory-based model and a field-based model were developed based on previous studies. Moreover, key parameters for a strong bond formation were identified, which are iron oxide, temperature, pressure and leaf material. The research gaps were identified by a paper grading method, and several hypotheses for bonding mechanisms and low adhesion mechanisms were proposed, such as sub- or super critical water and pectin gel.

Keywords: Low adhesion, Leaves, Pectin, Cellulose, Lignin, Railway, Wheel/Rail Contact

1. Introduction

Recently, railways have been re-evaluated as an eco-friendly method of transportation, which could achieve long-term sustainability due to their relatively low energy consumption and low carbon dioxide emissions [1, 2]. These characteristics are brought about by low rolling resistance due to the high stiffness of the wheel and rail. This leads to a relatively small contact area between the wheel and rail, resulting in a low dissipation of the driving energy by a friction force.

The tribological conditions between the wheel and rail are commonly expressed using three words, namely, friction, traction and adhesion. Friction is the tangential force transmitted between two objects which slide against one another. On the other hand, traction is the force transmitted between a driven cylinder rolling along a flat plane, further explanation can be found in [3]. The underlying friction level between two bodies of known materials will dictate the relationship between creep (the difference in relative surface speeds of the rolling/sliding body and the plane) and the traction force as shown in Figure 1 [4]. Friction and traction are different properties of a contact. The term used depends on the measurement technique. For example, if a sliding device such as the pendulum [5] is used, then any result will be a measurement of friction. However, if a rolling/sliding device is used such as the hand pushed tribometer [6], then any result will be a measurement of traction. It must be noted, however, that any friction/traction coefficient measured by such devices will be the coefficient between the rail and that device. Measuring the actual traction coefficient between the wheel and rail is very difficult/impractical. Thus, devices such as the pendulum and tribometer can give reliable estimations of what the traction coefficient between the wheel and rail is likely to be. Adhesion is a word which is commonly used in the railway community and can be used incorrectly when referring to the wheel/rail contact as discussed in Olofsson et al. [3]. However, adhesion seems to be a useful term which can be used to refer to the general state of friction on the rail head. For example, "low adhesion conditions" refers to a rail head which has low friction and thus will give low traction between the wheel/rail interface.



(a) (b)

Figure 1: Relationships between creep and friction/traction/adhesion: (a) Creep curves in a twin-disc apparatus [4], (b) Definitions of friction/traction and adhesion

The traction force is determined by the traction coefficient μ between the wheel and rail and the normal force. It transmits both the accelerating force and the braking force from the wheel to the rail. Hence, the friction level in the contact patch is an important factor to determine the kinematic performance of trains. Generally, the traction coefficient between wheels and rails strongly depends on the condition of the contact area. Typically, the friction/traction coefficient in the contact area between wheel and rail is 0.3 in reasonably dry conditions [7]. However, the rail surface is often contaminated by various sources, such as water, oil and soil deposited at road crossings, and this contamination decreases the friction coefficient below that of dry levels. For example, fallen leaves in the autumn reduce the friction coefficient to approximately 0.1 or less [7, 8]. Leaves on the line are one of the main causes of the low adhesion problems [7, 9].

Low adhesion conditions cause problems in train operations, in terms of safety, service and cost. For instance, station overruns and collisions occur due to braking issues as a result of low adhesion levels [10, 11]. Moreover, service disruption can lead to low customer satisfaction. Additionally, low adhesion problems cause additional costs for the measures to maintain the adhesion level. For example, the annual cost due to the leaf problem is reported to be £50 million in the United Kingdom [12] and 100 million SEK in Sweden [13]. Low adhesion, therefore, has an impact on train operation and weakens the competitiveness of the railway in comparison to other transportation methods.

Leaf contamination on the rail surface has been studied by many researchers [4, 7, 12-22]. Studies reveal that leaves form a hard, black and "teflon-like" film on the surface. This layer reduces friction on the railhead when a small amount of water, such as light rain, frost and morning dew is present [7, 8]. From these results, various measures have been carried out to remove the leaf film, which is strongly bonded to the rail surface [7, 8]. For example, sanding from a locomotive has been used to increase adhesion and remove the leaf residue [7, 8]. However, sanding can damage the wheel and the rail, leading to an increase in maintenance costs [4, 17, 18]. Furthermore, it can cause isolation problems which affect track circuits used in train detection [23]. Other measures, such as vegetation management and high pressure water jetting of rails, are also carried out [8, 9, 22]. However, these measures also have an associated running/maintenance cost. Although, an effective method to remove leaf films has not yet been established.

Recently, new research approaches for the leaf film issue have been attempted, by analysing the bonding chemistry and mechanism between the leaf film and the rail surface [14, 15, 24-26]. Several techniques for analysis, such as FT-IR (Fourier-Transform Infrared spectroscopy), GD-OES (Glow Discharge Optical Emission Spectroscopy) and EDX (Energy Dispersive X-ray), have been carried out for leaf films obtained in both the laboratory and in the field. From these studies, it has been noted that leaf films have three important components, namely, pectin, cellulose and lignin [12, 15, 17]. Also, it is found that a leaf film contains a significant amount of iron, oxide, carbon, calcium and nitrogen [25, 26]. These results clearly show that the leaf components react chemically with the active Fe ions originated from the rail steel. This chemical reaction seems to cause the strong bond, thus, making the film difficult to remove.

However, the bonding mechanism of the leaf film has not yet been clarified [27]. The processes and parameters in the chemical reaction have not yet been revealed, although the key elements in the reaction have been defined. If this mechanism is determined, more effective methods to prevent the leaf film forming or to remove the leaf film could be developed. Thus, more detailed research in this field is required, including identification of the main parameters which affect the bonding condition.

The purpose of this review is to reveal the current understanding of the bonding mechanism between the leaf film and surface of the rail and key parameters which influence the formation of the hard, black and slippery layer, and to elucidate the manner in which it causes low adhesion. Gaps will be identified and further work defined to focus on the cause and propose an area to explore for mitigation.

2. Incident Analysis

Analyses were carried out regarding the data provided by Network Rail, which contains incident information for the autumn period, such as station overruns, track circuit failures and signals passed at danger (SPADs). These incidents are critical for train operators in terms of safety and service issues, and leaf contamination is considered to be one of the main causes of these incidents.

Figure 2 shows a relationship between the time of day and the total number of incidents (station overruns and SPADs), accumulated between 2010 and 2014. From this figure, a relatively high frequency of incidents is observed between the hours of 06:00 – 24:00, in which trains are frequently operated. In contrast, the incidents are dramatically decreased between 00:00 – 05:00 because of few train operations, and medium number is observed between 05:00 – 06:00.

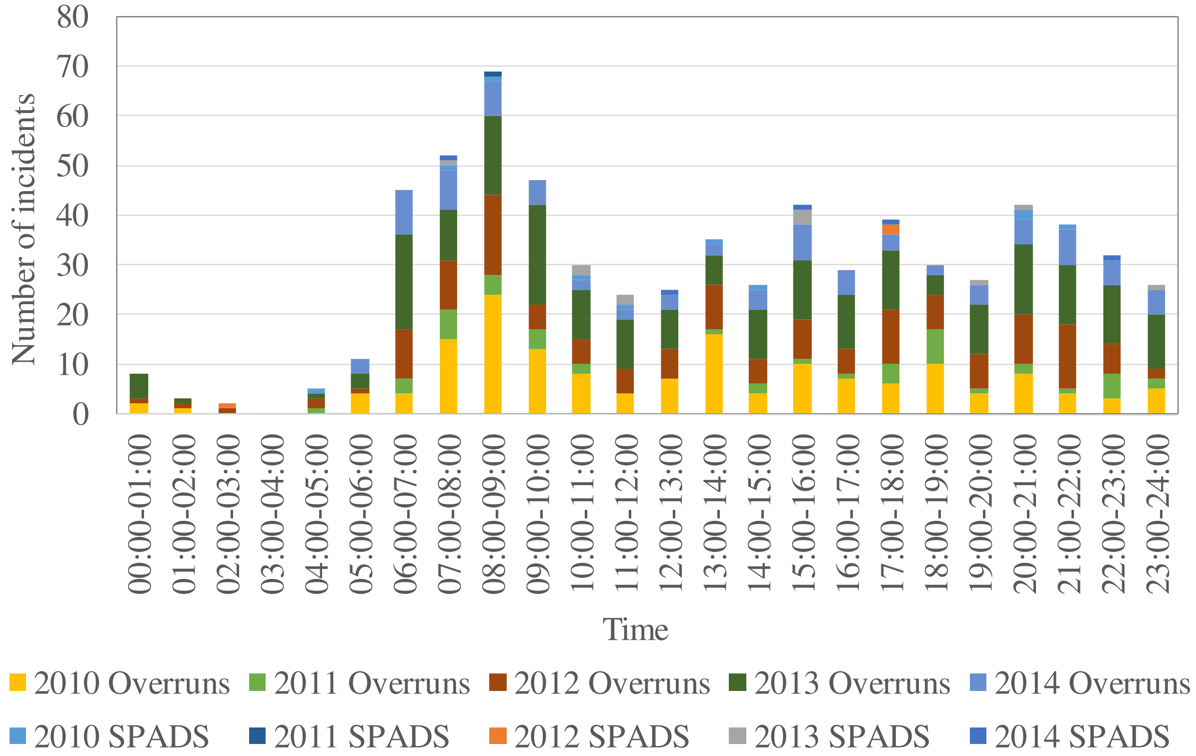


Figure 2: The relationship between the time of day and the total number of incidents (station overruns and SPADs) during autumns 2010 – 2014

Figure 3 shows a relationship between the time and the number of incidents between the hours of 05:00 – 24:00, normalised by the number of stopping attempts on average. The data between 05:00 – 24:00 is chosen because of the relatively larger number of incidents. The normalised number (N.N) is calculated by equation (1).

$$N.N = (station\ overruns + SPADS)/average\ number\ of\ stopping\ attempts\ in\ the\ hour \quad \ldots(1)$$

As can be seen, the high probability is confirmed between the hours of 05:00 – 10:00 and between 20:00 – 24:00, and the average values are $3.3 \cdot 10^{-3}$ and $3.1 \cdot 10^{-3}$, respectively. Conversely, the relative low possibility, $1.9 \cdot 10^{-3}$ on average, is confirmed between 10:00 – 20:00, although there are some fluctuations. This value is approximately 40 % lower than the values of 05:00 – 10:00 or 20:00 – 24:00. As a result, there is a distinctive relationship between the time and the incident probability.

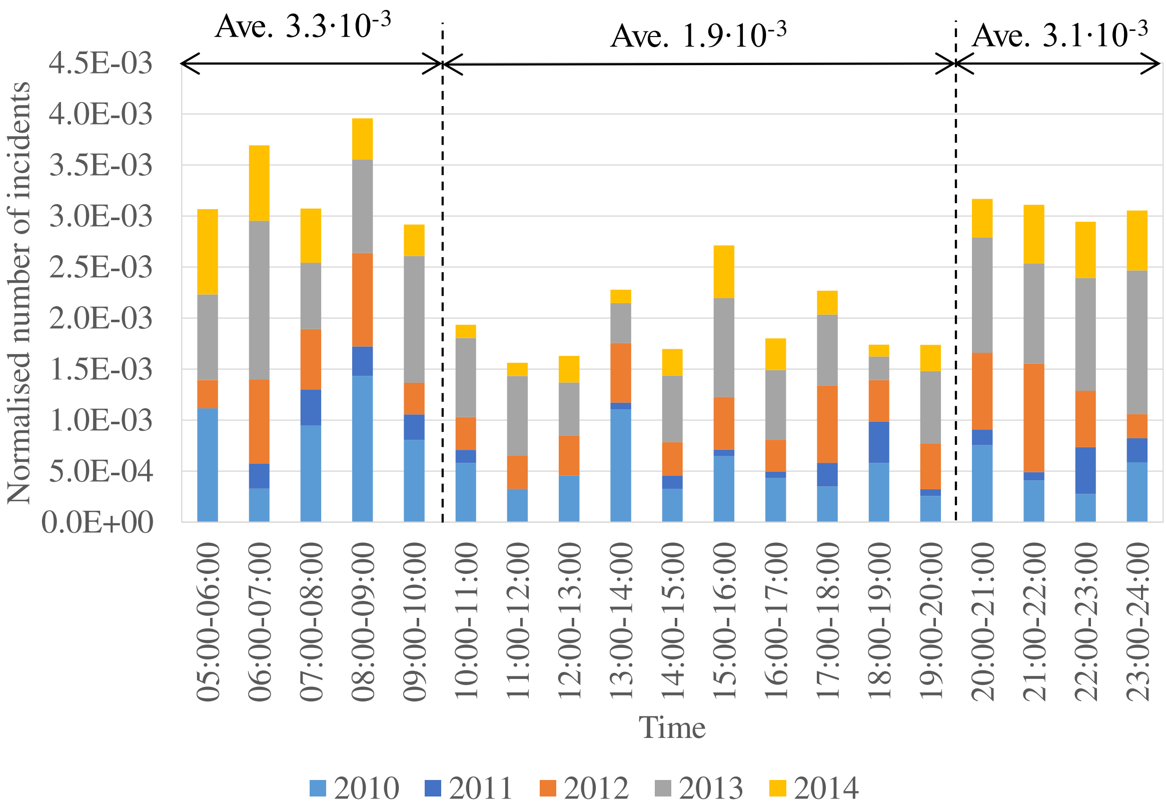


Figure 3: The relationship between the time of day and the normalised number of incidents

Figure 4 shows a relationship between the time of day and the normalised number of leaf-related incidents in the hours between 06:00 and 24:00, analysed from data recorded between 2010 and 2012. The data in 2013 and 2014 are excluded because of less data categorised as "leaf contamination". As can be seen, a relatively high possibility is observed between the hours of 06:00 – 09:00, in contrast, a lower possibility is confirmed in the other hours. The average value between 06:00 – 09:00 is $1.3 \cdot 10^{-3}$, which is twice as high as the average value between 09:00 – 24:00 i.e. $5.9 \cdot 10^{-4}$. A slight increase can be seen between 20:00 – 24:00, however, the difference is not clear. From this analysis, it is shown that the probabilities of incidents related to leaf contamination depend on the time of a day, namely, early morning from 06:00 – 09:00.

The high probabilities between 05:00 – 10:00 and 20:00 – 24:00 in Figure 3 and Figure 4 could be attributed to the dew on the track [28]. Generally, mixtures of leaves and a small amount of water decrease the friction coefficient dramatically [7]. Dew, which lies on the ground because of the high relative humidity, seems to deposit water on the rail. Relative humidity tends to increase from night to morning, for example, the relative humidity between 22:00 and 10:00 is over 80 % in south east England [29]. This data needs to be measured using a standard method.

For example, relative humidity measured close to the rail might be higher because of the lower air temperature close to the ground. Therefore, dew is likely to be produced between 22:00 and 10:00, depending on other factors, such as geographic features. This time characteristic corresponds to the tendency in Figure 3, namely, the relatively high probabilities between the hours of 05:00 – 10:00 and 20:00 – 24:00. Furthermore, the high possibilities between the hours of 06:00 – 09:00 in Figure 4 suggest that dew is absorbed into the leaf films continuously from night to morning, and creates the low adhesion condition due to the high moisture level in the leaf films, which seems to reach maximum value in early morning.

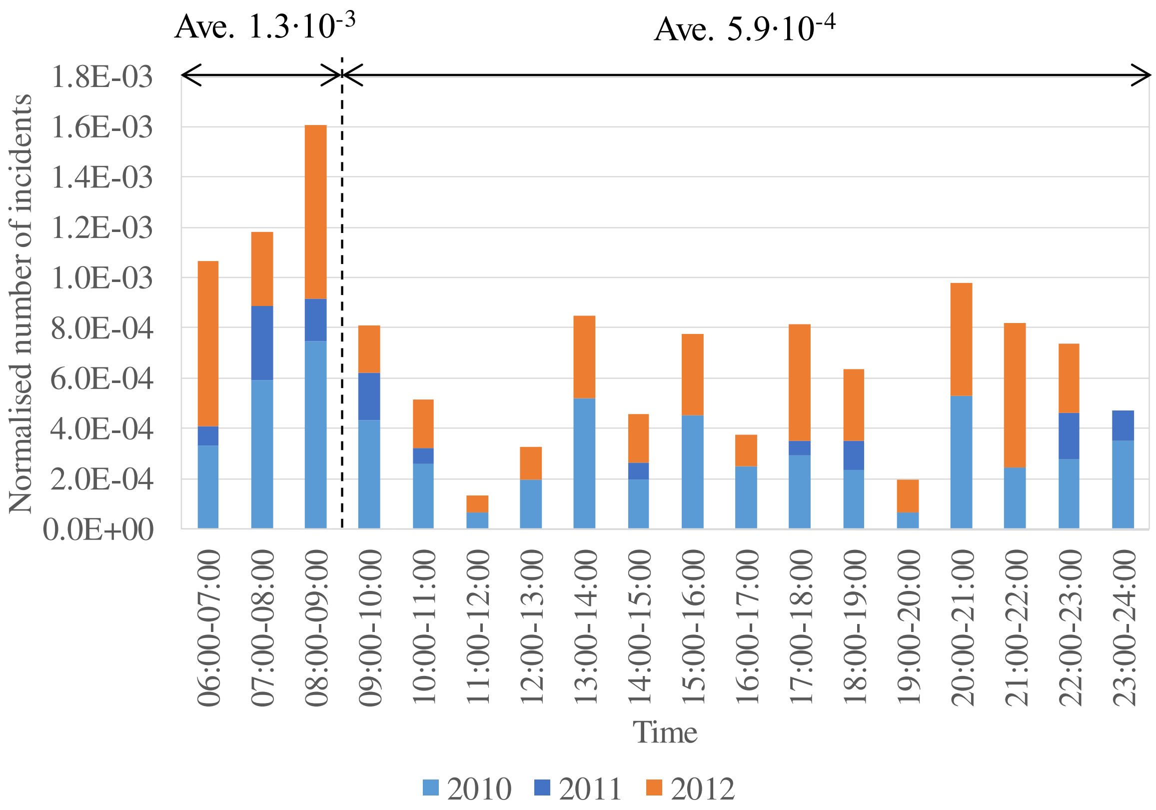


Figure 4: The relationship between the time of day and the normalised number of incidents related to leaf contamination causes

3. Low Adhesion due to Leaf Layers

The traction force is one of the most important factors for train control, in particular, for acceleration and braking. In dry conditions, the friction coefficient, μ, is 0.3 on average. Generally it is required to be 0.2 and 0.09 for safe traction and braking, respectively [7]. Low adhesion conditions can be produced by various factors. However, they are mainly caused by the mixture of surface contamination and a small amount of water [7, 8]. Low adhesion levels are classified into three groups as shown below [16].

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

- Exceptionally low: 0.02 < μ 0.05

Friction/traction coefficient values acquired during previous research are shown in Table 1. As can be seen, the friction/traction coefficients with leaf contamination are often below 0.1, although they are varied due to different test methods. It is also found that the leaf type (such as sycamore and elm) does not affect friction/traction values.

Table 1: Friction coefficient values acquired by the previous research

Authors	Test Method	Leaf type	Test conditions	Friction Coefficient
Gallardo-Hernández, *et al.* [4]	Twin disc	Mixture (Mainly maple and oak)	Dry/Wet 1 m/s with 0.5, 1, 2, 3, 5 % slip 1.5 GPa	< 0.05 (Dry, for all slip values) < 0.02 (Wet, for all slip values)
Arias-Cuevas, *et al.* [12]	Twin disc	Cut Sycamore	Dry 1 m/s with 0.5, 1, 2 % slip 1.2 GPa	< 0.05 (Typically)
Olofsson, *et al.* [13]	Pin-on-Disc	Crushed Elm	RH = 40 ±5 and 95 ±5 % 0.1 m/s with 100 % slip 0.8 and 1.1 GPa	0.25 (RH = 40 %, mean value) 0.15 (RH = 95 %, mean value)
Cann [15]	Ball on disc (Mini traction machine)	Chopped Sycamore Soaked for 1-15 days	Wet 0.02-1 m/s with 1 and 50% slip 1 GPa	0.01-0.07 (Soaked brown leaf) 0.04-0.14 (Water-soluble component)
Vasić, *et al.* [16]	Twin disc	Unknown	Wet 1 m/s with 1 % slip 1.5 GPa	< 0.06 (with leaf films)
Arias-Cuevas, et al. [17]	Twin disc	Cut Sycamore	Dry 1 m/s with 0.5 % slip 1.2 GPa	< 0.02 (Minimum value)
Omasta, *et al.* [18]	Twin disc	Mixture + Extractes Soaked for 5 days (maple, beech, oak, birch)	Wet 0.8-3 m/s with 1-10 % slip 1 GPa	< 0.1 (Leaf mixture) ≈ 0.1 (Extractes, gradual drop)
Lewis, *et al.* [24]	Twin disc	Sycamore Paste (Chopped and soaked)	Wet 1 m/s with 3 % slip 1.5 GPa	0.05 ~ 0.15
Arias-Cuevas, *et al.* [19]	Field (Locomotive)	Unknown	Dry/Wet Axle load 21.5 t	0.06 (Dry, mean value in 1st run) 0.04 (Wet, mean value in 1st run)
Tamura, *et al*. [22]	Field (Tribometer)	Unknown	Dry 0.7 GPa	0.3
Oloffson, *et al*. [25]	Field (Tribometer)	Unknown	Wet (Light rain)	0.15 (Minimum value)
Nagase [30]	Field (Test bogie)	Pine needles	Dry/Wet 20 km/h (Maximum)	0.05 (Dry, minimum Value) 0.05 (Wet, minimum Value)

From Table 1, the testing methodology is found to have an effect on the measured friction coefficient values. For example, values measured by a twin disc apparatus tend to be lower than the value obtained by pin-on-disc equipment. A pin-on-disc test does not replicate the rolling-sliding conditions between wheels and rails but does offer greater controllability over parameters such as sliding velocity and contact pressure. Rolling-sliding conditions can be replicated by either twin-disc or ball-on-disc machine. Main difference between a twin disc machine and a ball-on-disc machine is that the former produces a line contact and the latter produces a point contact.

Figure 5 shows typical traction results of a twin-disc test performed under varying contamination conditions [24]. A leaf layer was created on the rail disc and then run against wheel disc. In Figure 5, it is observed that wet leaves produce lower traction conditions than dry leaves and the lower traction tends to remain for a long time. Figure 1 (a) shows a general relationship between the slip and the traction coefficient, obtained in twin disc apparatus [4].

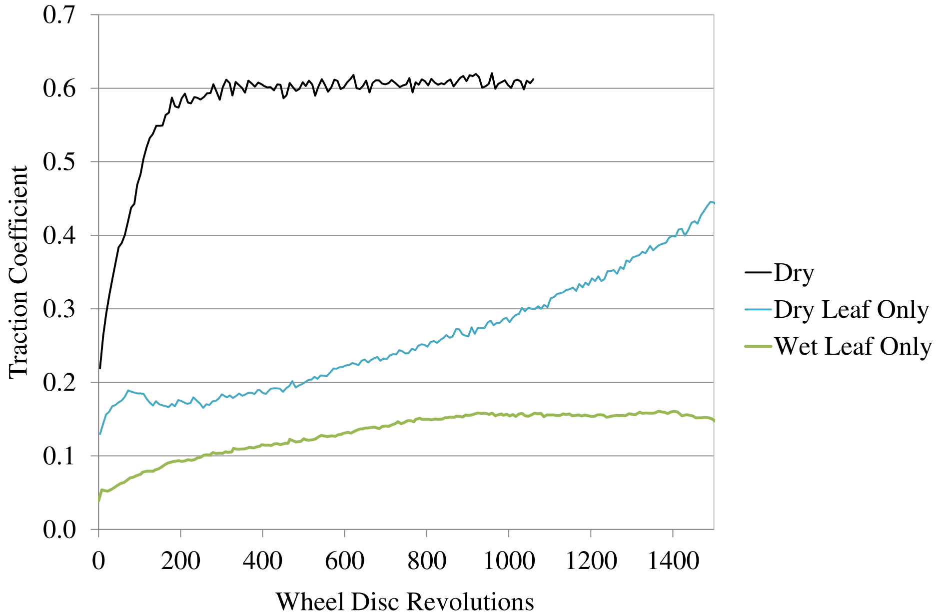


Figure 5: A general relationship between the rotational number and the traction coefficient in a twin disc apparatus, showing the long effect of wet leaves [24].

In [4], leaves were continuously fed into the disc contact, keeping the friction level low, in contrast to the method used in [24]. As can be seen, both dry and wet leaves yield low traction levels at slip ratios between 0.5 and 5 %. These results suggest that leaf films are not easily removed by the wheel rolling with slip once they have formed on the rail surface, confirming what has been seen in previous studies [7, 16].

4. Mitigation Methods

Several measures, which mitigate the low adhesion phenomenon due to autumn leaf films on the rail surface, have been carried out by train operating companies and infrastructure companies [7-9]. However, each mitigation method has a weakness in terms of practical applications, such as cost, time and labour. The specifications of representative methods are described below.

4.1 Sanding

Sanding is one of the traditional ways to increase the adhesion level [19]. The sanding effect on leaf-contaminated rails has been investigated by laboratory-based tests with various parameters, such as sand grain size and slip ratio [4, 17, 18]. According to these studies, sanding recovers the adhesion to near dry contact levels with optimised parameters, and it also contributes to the removal of leaf films. For example, in [4], adhesion is increased to the level of an uncontaminated contact in dry conditions. Furthermore, these recovering and removing effects are confirmed in field investigations [19]. In this investigation, the adhesion improvement was achieved even at the non-sanding axles due to the leaf film removal. Accordingly, sanding seems to have a lot of positive effects on adhesion improvements.

However, there are several drawbacks to sanding, namely, the damage to the wheel and the rail surfaces [4, 17, 18, 31, 33, 34] and the electrical isolation of the wheel/rail contact area [23, 32]. Generally, track circuit systems are used for train detection in signalling systems. Therefore, good conductivity between the wheel and the rail is essential for their successful operation. Sand in the wheel/rail contact increases the electrical resistance of the contact area [23, 32], and can cause temporary failure of track circuits. Track circuit failures cause unnecessary closure of the railway on safety grounds, leading to disruption and delays. Moreover, it is demonstrated that the applied sand damages the wheel and the rail, producing cracks and a large deformation layers in the surface [4, 18, 33, 34]. The wear of these components in sanding conditions can be 10 ~ 100 times greater than in normal conditions [31].

Therefore, sanding is effective for improvement in terms of adhesion and removal of the leaf residue. However, additional costs might be incurred, associated with operational issues and damage of track and infrastructure.

4.2 Traction Enhancer

Traction enhancers (Adhesion enhancers), a type of product have been developed and tested recently, [12, 24, 35]. Traction enhancers aim to overcome low adhesion problems, in particular, leaf contamination. Mainly, they consist of sand particles, steel particles, water or water-based gel, and usually they are applied to the top of the rail in liquid form [12, 24, 35]. The liquid/gel is designed to improve the particle adherence on the rail and thus increasing the efficiency of sand which reaches the contact patch, thus boosting friction/traction coefficients under low adhesion conditions [12, 35].

It is confirmed that traction enhancers can mitigate the low adhesion condition due to leaf contamination, recovering friction/traction levels close to dry conditions [12, 24]. For instance, the time to recover the friction/traction level can be shortened up to 70 % and 93 % in braking and traction, respectively [12]. Moreover, the wear rate of the rail material is lower than that of dry conditions, indicating less damage is caused to the wheel and rail compared to traditional sand application [24].

However, some traction enhancers cannot remove leaf films completely [12]. Some types of traction enhancer can cause damage both the rail and wheel surface, such as indentation due to sand particles [12, 35]. This damage might lead to an increase of maintenance cost. Moreover, they are reported to show a high impedance in the contact area immediately after their application [24]. Although the impedance becomes stable after a few seconds, this high impedance could cause a signalling problem.

Thus, traction enhancers are one solution for the leaf contamination problem, however, they have several drawbacks, such as surface damage and increased contact resistance.

4.3 High pressure water

High pressure water is often used to remove leaf films on the rail surface [7, 8, 16, 22], and it is usually used in combination with sanding [7, 8]. Special trains equipped with sanders and high pressure washers are routinely operated on areas of track where low adhesion conditions due to leaves are common. Although there is little work on the performance of high pressure water when used for the removal of leaf films, it is confirmed to be effective to some extent, as reported in [9]. However, the leaf films on the rail cannot be removed completely by this method, evidence showing that there is a 10 – 15 micron thick leaf film left on the rail after cleaning [7]. This residual film could still produce low adhesion phenomena. In addition, the operational cost of rail cleaning trains is relatively high, estimated at £25 million per year [16].

4.4 Prevention of leaf film formation

Some methods used to prevent the formation of leaf films include patrolling around hot spots and vegetation management, however, a promising measure is the application of a controlled pH solution to the rail head [14, 21]. According to a previous study, an alkaline environment (pH 9) prevents leaf films from forming, resulting in the improvements in leaf film properties, such as a reduced thickness, less coverage and increased skid resistance [21]. However, an acidic environment (pH 3) shows less effect on prevention than an alkali one [21]. These effects are closely related to the activation of ions, for example, $FeOH_2^+$ or FeO^- ions, which are from the Fe-oxides and believed to be key factors for the chemical reaction between leaf components and rail steel [14, 27]. The different results in varied pH values indicate that less H^+ ions deactivate the chemical reaction and prevent the formation of strong bonds between the leaf residue and the rail.

However, the leaf film formations are not completely prevented by this method. For instance, there is only a 17% reduction in the film thickness when using a pH treatment compared to no treatment [21]. One downside of pH solutions need to be continuously dispersed around the low adhesion area, incurring additional costs with regard to chemicals, equipment and labour.

Overall, the pH control method mitigates leaf film formation and also has some effect on removal, however, the prevention effect is limited and as such may not provide the most cost effective solution.

In conclusion, several measures have been conducted to overcome low adhesion problems due to leaf contamination, and they are effective to some extent. However, the improvements are limited, in particular, leaf films cannot be removed completely in a way that is not destructive to either the rail or the wheel.

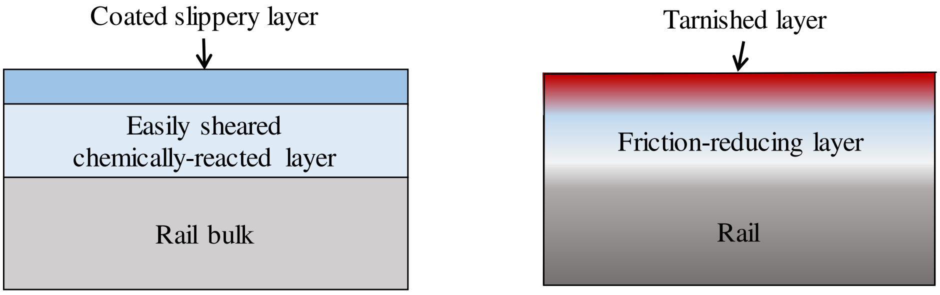
5. Leaf Layer Chemistry and Bonding Mechanism

Recently, new approaches to the leaf contamination problem have been implemented, to reveal the chemical and bonding conditions between the leaf layer and the rail surface [14, 15, 25, 26]. Important findings have emerged from analysis techniques such as FT-IR (Fourier-Transform Infrared spectroscopy) [14, 15], GD-OES (Glow Discharge Optical Emission Spectroscopy) [25, 26] and ESCA (Electron Spectroscopy for Chemical Analysis) [25]. Two representative models, which explain the chemical and bonding conditions between leaf layers and rails, are derived based on the previous research [25, 26], as shown in Figure 6. The details of these two models and other hypotheses are described below.

5.1 A laboratory-based model [26]

Figure 6 (a) shows a schematic view of the laboratory-based model presented in [26]. This model consists of the three layers, which are a coated slippery layer at the top, an easily sheared chemically-reacted layer in the middle and a rail bulk at the bottom. In the case of the leaf contamination, the coated slippery layer is a leaf film, and the easily sheared chemically reacted layer corresponds to a bonding layer between leaf films and rails. GD-OES analysis shows relatively high levels of calcium and phosphorus in rail samples which had been prepared in the laboratory by rolling with a leaf. These samples did not have a visible leaf layer, and these substances (Ca, P) are likely to have been deposited on the rail by the leaf. This result suggests the existence of a chemically-reacted layer.

However, a detailed chemical reaction process between leaf films and rail bulk materials has not yet been clarified. Furthermore, the mechanism of how leaf contents, such as Ca and P, bond leaf films to rail materials has not been revealed. Hence, this model needs more detailed research in chemical and bonding conditions, in particular, a chemical reaction process and a strong bond mechanism.



(a) (b)

Figure 6: Representative models of the bonding condition between the leaf film and the rail surface.
(a) A laboratory-based model with a three layer structure [26]
(b) A field-based model with a three layer structure [25]

5.2 A field-based model [25]

Figure 6 (b) shows a schematic view of the field-based model, explained in [25]. This model has been developed through analyses of a tarnished sample, taken from the actual tracks in Sweden. There are three layers in this model, i.e. a tarnished layer at the top, a friction-reducing layer in the middle, and a rail bulk material at the bottom. In this model, the bonding mechanism can be explained in two steps: firstly, a leaf is deposited on the rail surface, providing carbon, nitrogen, calcium and other elements. Secondly, these elements and iron oxides chemically react and form the chemically reacted layer with strong bonds to the rail bulk.

The tarnished layer mainly consists of organic components from leaves, and the friction-reducing layer contains a high amount of iron oxides. ESCA analysis reveals that a tarnished layer has high carbon (48 wt%), oxygen (29.3 wt%), calcium (2.8 wt%), but less iron (13.2 wt%). These contents are not originally derived from the rail bulk material; hence, there might be a chemical reaction between leaves and rails at the surface. Moreover, GD-OES analysis clarifies that a depth profile of oxygen is significantly different from the other samples without a tarnished layer. The thickness of a friction-reducing layer is approximately 300 nm, which is four times thicker than the other samples. This thick oxide layer seems to decrease the friction/traction coefficient [36-38] and to be a result of more complete chemical reactions between leaf debris and rails. Therefore, the chemical reaction probably produces the strong bonds between leaf film and rail.

However, chemical conditions in the tarnished layer have not yet been clarified, because of charge-up problems during the ESCA analysis. Furthermore, the accelerator of a chemical reaction has not yet been revealed, which is the most important parameter to prevent leaf film formation. Therefore, this model might reflect the chemical and bonding conditions between leaf films and rails, however, more detailed analyses toward the clarifications of chemical and bonding conditions seem to be needed.

5.3 Other hypotheses

There are some other hypotheses for the bonding mechanism and the leaf layer chemistry. For example, pyrite (FeS_2) is expected to be one of the bonding materials, which is produced by active Fe ions (Fe^{2+} and Fe^{3+}) and sulphur included in the leaf [27]. Other components possibly react chemically and form the strong bond, namely, fatty acids from cutin and carbohydrates from pectin, cellulose and lignin [27]. All these hypotheses are based on the chemical reaction with radical Fe ions emitted from the steel surface iron oxides, and the high contact pressure seems to enhance or trigger the reaction. However, the proposed reaction processes have not yet been established experimentally. The chemical analyses carried out in previous studies support these ideas [15, 25, 26], thus, more detailed research is required to demonstrate them.

In conclusion, the bonding condition and leaf layer chemistry have been gradually clarified by new research approaches, and two representative models, a laboratory-based model and a field-based model, are proposed based on previous studies [25, 26]. However, the chemical reaction process between the leaf components and the rail materials has not yet been established. Further experimental work is needed to demonstrate the fundamental processes.

6. Expected key parameters

The chemical and bonding mechanisms of leaf film formation need to be determined as a first step. From the point of view that wheels slip on the leaves with high pressure, several parameters are expected to influence the formation of leaf films, namely, iron oxides, high temperature, high pressure and material from leaf residue. The specifications and effects of these parameters are described below.

6.1 Iron oxide

6.1.1 Iron oxide on the rail

The existence of Fe-based oxide on the rail surface has been recognised, particularly, in areas near to the sea, where the rail can be easily covered with rust [38, 39]. It is revealed that there are some types of iron oxides, such as a haematite (Fe_2O_3) and magnetite (Fe_3O_4), on the rail surface [37-39]. These oxides are deemed to form a mechanically mixing layer [37], presumably leading to the formation of third body layers [40]. As a result, Fe oxides are thought to be an important material to determine the tribological behaviour of the contact area, and the effects have been studied, particularly, in terms of adhesion problems [36-38, 41, 42].

Generally, iron oxides are easily formed by oxygen in the air, and the types of oxides strongly depend on environmental parameters, such as temperature, pH and oxygen level [27]. Fe_2O_3 (red oxide) is the most common oxide in nature [27, 43]. Fe_2O_3 exists in the form of iron oxyhydroxides as a result of hydration, such as α-FeOOH, β-FeOOH and γ-FeOOH [27, 39]. Another iron oxide, Fe_3O_4 (black oxide) can generally act as a passivation film to protect from further corrosion [44]. It is also detected on the rail head, in particular, at the gauge corner of the rail, where severe contact pressure and high sliding occur during curving [39].

Previous research in the material science field suggests that $Fe(OH)_2$ is converted into Fe_3O_4 and γ-FeOOH by dehydration and deprotonation, depending on the reaction condition (Fe_3O_4 production seems to need a relatively poor oxygen environment and a long reaction time) [43]. These results support the observations described above. Overall, both Fe_2O_3 and Fe_3O_4 can be produced on the rail surface, and seem to have a significant effect on tribological characteristics in the contact area [36-38, 41, 42].

6.1.2 Low adhesion due to the iron oxides

The decrease of friction/traction coefficient due to iron oxides on the rail surface has been reported by many researchers [37, 38, 41, 42]. Oxide films are considered to be the mixture of Fe_2O_3 and Fe_3O_4, and the relatively soft Fe_3O_4 reduces the friction although hard Fe_2O_3 increases or maintains the friction level [37, 38]. However, rust (Fe_2O_3) is also reported to have a tendency to decrease the friction coefficient compared to clean samples, depending on relative humidity [42]. Consequently, Fe oxides produce low adhesion conditions, although the magnitude depends on the oxide types.

6.1.3 Catalyst effects

Both Fe_3O_4 and Fe_2O_3 (transformed into Fe_3O_4 during the reaction [46]) are discovered to act as a catalyst in the decomposition of biomass materials, which contain a high amount of cellulose [45, 46]. Although relatively high temperatures and pressures are required (e.g. 300~400 °C and 3.5 MPa) [45], these iron oxides enhance the chemical reaction, and also production of gasification or dissolution into an organic solvent [45, 46]. They might assist the migration of ions, such as active hydrogen, and promote the reaction. Furthermore, Fe_3O_4 seems to act as a catalyst more than Fe_2O_3, because the transformation from Fe_2O_3 to Fe_3O_4 is observed after the reaction [46]. However, the detailed process of the chemical reaction related to the catalyst has not been clarified.

6.2 Temperature

A high slip ratio between the wheel and the rail causes a rise in temperature in the contact patch due to frictional work in the contact [47-49]. Examples of contact temperature are shown in Table 2. As can be seen, the maximum temperature is estimated to be over 727 °C in real tracks, forming a white etching layer with martensite transformation [49]. Temperature is an important parameter in chemical reactions, which activates ions and enhances the reaction process. From this viewpoint, the thermal energy must be considered for chemical reaction between the leaf residue and the rail.

As a result, the thermal energy induced by the wheel slip is expected to be a significant parameter which controls the chemical reaction between the leaf residue and the rail material.

Table 2: Achievable contact temperature

Reference	Temperature	Features
47	100 ℃	Twin disc with 5 % slip
48	200 ℃	Pin-on-disc with 100 % slip
49	Over 727 ℃	Field, Martensite transformation observed

6.3 Pressure

Generally, the contact pressure between wheels and rails ranges from 0.6 to 2.7 GPa [50], and this high pressure seems to compact the leaf layer and bond it to the rail surface tightly. The black leaf films have been formed both in laboratory-based tests and field tests, where high pressure is applied in the contact area [4, 12, 14, 16, 17, 19-21, 24]. Although there are many parameters, this fact suggests the significance of high pressure for leaf film formation on the rail surface.

Another effect of high pressure is refinement of material micro-structure [51]. This phenomenon is confirmed in a third body layer, where the structure of a third body is very fine or sometimes nano-crystalline with long sliding distance [52]. Although such a refinement seems to depend on the material combinations, a rolling-sliding contact between the wheel and rail induces similar phenomenon, leading to reduction in grain size at the surface, 20 nm on average [53]. Accordingly, these investigations [51, 52] show that high contact pressures affect the formation of leaf layers with severe deformation of the rail surface, in particular, surface oxides. Furthermore, they might assist in the strong bond formation between leaf films and rails, providing the mechanically mixed layer.

6.4 Material

6.4.1 Cellulose

Cellulose is a glucose polymer and a predominant material in plant cells [27, 54], and it is one of the main components in biomass, which is recently re-evaluated as a green energy source [45, 55]. Cellulose is also contained in both leaves and leaf films, and it is expected to be one of the key materials which form a strong bond to the rail [14, 27]. Usually, cellulose is dissolved into water, however, it maintains a crystal structure and is not decomposed under normal circumstances [54, 55]. This suggests that special circumstances, such as high temperature and high pressure, are required to form a cellulose complex with other materials.

The usages of cellulose are varied, with cellulose being found in the manufacture of paper, foods, chemicals [55] and adhesives [56]. This usage suggests that cellulose can be transformed into adhesive if it is decomposed into appropriate forms, and may adhere the leaf residue to the rail.

6.4.2 Lignin

Lignin is a polymer that forms plant cell walls [27, 57, 58], and it accounts for 15-25 wt% of plant biomass material [59]. FT-IR analysis reveals that lignin is contained in leaf residue produced by laboratory experiments, and thought to be a main component of leaf films [12, 17]. However, it is suggested that lignin is a structural material as it is not easily dissolved in pure water [15]. Thus, lignin has not been the main focus of previous low adhesion research.

Recent studies in chemistry show that the long chain polymer structure of lignin can be broken down under high temperature and high pressure, which is sometimes a sub- or supercritical environment [58-63]. According to these studies, lignin is transformed into gas and dissoluble fragments in a relatively short time, e.g. within 5 seconds [58], depending on the experimental conditions. This suggests that decomposition of leaf lignin might be possible under the conditions in the wheel/rail contact, due to the high pressure and the high temperature.

Lignin can also act as an adhesive by forming a polymer through crosslinking with other components, such as furfural and phenol [64, 65]. For example, a glass fibre strip immersed in a lignin-based adhesive has been shown to give a good tensile strength, achieving approximately 90% the strength of a strip with phenol-formaldehyde resin, which is a commercially used adhesive in the wood industry [64]. These results indicate the possibility that the lignin-based adhesive could be formed with wet leaves on the rail, due to the high temperature and high pressure produced by the wheel/rail contact.

A hypothesis has been proposed, in which lignin has an important role in forming a strong bond between leaves and rails [27]. In this hypothesis, an iron carbohydrate complex is formed as an interfacial layer, and this carbohydrate is from lignin of the cell wall. Although there is no reported experimental research, lignin might be one of the key bonding materials.

6.4.3 Pectin

Pectin is a soluble chemical compound, which can exist in one of three forms, namely, protopectin, pectin and pectic acid [57, 66]. One of the main features of pectin is that it is easily transformed into a gel [57]. Divalent metal cations, such as Ca^{2+} and Cu^{2+}, change the pectin into gel with crosslinking effects [67, 68]. Studies of the leaf residue show that it contains pectate esterified to some extent and a relatively small amount of cellulose [15]. Due to the high solubility of pectin in water, pectin gel, which is probably crosslinked by Fe ions, is thought to produce low adhesion conditions [15]. The black colour of leaf films may be attributed to the chemical reaction between pectin and iron, and clusters agglomerated with cellulose fibres might form a bond [15]. This suggests that pectin is one of the key materials in the black layer, to form a strong bond between the leaf and the rail.

However, the effect of pectin has not yet been clarified, in particular, how pectin reacts with other components chemically or how pectin can be a bonding material. For example, the detailed reaction process is not determined for the black colour formation. Moreover, the bonding strength of pectin gel has not yet been evaluated, thus, further experimental work is required.

7. Discussion

7.1 Drawbacks of current studies and the derived models

Despite the significant progress in chemical condition analyses of leaf films [14, 15, 25-27], important parameters, which control conditions of the chemical reaction in the leaf film growth, have not yet been determined. For example, few experiments have been carried out focusing on parameters, such as temperature, pressure and material. More studies need to be implemented with various parameters to specify the key factors, which produce strong bonded leaf layers.

The models derived in this paper which are based on the previous studies have some drawbacks, in that, the detailed process of the chemical reactions has not been demonstrated. For instance, the elements of the friction-reducing layer are clarified in the field-based model [25], however, it is not confirmed how the detected elements are bonded chemically. Moreover, few experimental works have been implemented to verify the other hypotheses of the bonding mechanism. As a result, the bonding mechanism cannot be fully explained by these models or hypotheses. Hence, there is a need to establish the chemical reaction process to reveal the bonding mechanism.

7.2 Paper Grading

The citations used for this review have been graded to visualise the research area and determine which research has been carried out and what published research is lacking, using the same evaluation method as used in [69].

The citations are divided into four categories, namely, "General adhesion", "Prevention", "Fundamental research" and "Mitigation". Each category has several groups, for example, the "General adhesion" category has groups such as academic research, laboratory testing and field testing. Some citations have several aspects, and as such belong to several groups. This is shown in combination forms with numbers and letters, such as 1A and 1B, which means paper 1 and aspect A or B, as shown in Appendix Table 3.

After grouping, the paper is evaluated in seven areas as described below.

1. Is the citation peer reviewed?
2. Does the paper contain theory supported by testing?
3. Is the test small scale?
4. Is the test full scale?
5. Does the citation contain real world measurements?
6. Are the conclusions in the citation evidenced within the data?
7. Are the conclusions validated by operational experience?

All the questions are "yes or no" interrogatory sentences, and "yes" obtains one point. Then, the citations are ranked into 3 categories by the accumulated points, namely, C (0-2), B (3-4) and A (5-7). For example, the citation obtains 3 yes scores, then the citation will get 3 points. In this case, the paper is ranked as "B". The summary of this evaluation is shown in Appendix Table 3. The score is not a reflection of research quality, but a measure of how well the research contributes to the particular field under investigation (i.e. in this case the adhesion problem due to leaf contamination) according to the above criteria set by the author. For example this criteria gives higher weighting to full-scale testing rather than small-scale testing alone. Finally, the ranking results are shown as a knowledge map, which visualises the different research areas and research quantity/impact in each particular area. In this map, research gaps are shown as the areas marked with less density of circles, which means that there is no work or little work in this area.

Figure 7 shows the knowledge map obtained in this evaluation process. As can be seen, general adhesion and mitigation groups have many previous studies on their sub-categories. In contrast, there has not been much published work in the prevention or principle research areas. Therefore, it might be reasonable that new research is attempted in the prevention and principle research areas.

7.3 Research Gaps

Bonding mechanisms have not been clarified yet, thus, there are research gaps in the specification of bonding parameters and presumption of bonding mechanisms, as described below.

- Parameter specifications

Expected parameters, such as temperature, pressure and leaf components, should be examined separately. The evaluations could be carried out in terms of mechanical/tribological properties (friction coefficient, hardness, shear strength, etc.) and chemical analysis (LRSS, ESCA, EDX, etc.). Subsequently, the effective parameters required for the formation of strong bonds can be determined.

- Reaction process presumptions

The reaction process between the leaf layer and the rail should be considered with input from the parameter investigation, and confirmation experiments should be carried out to establish the theory.

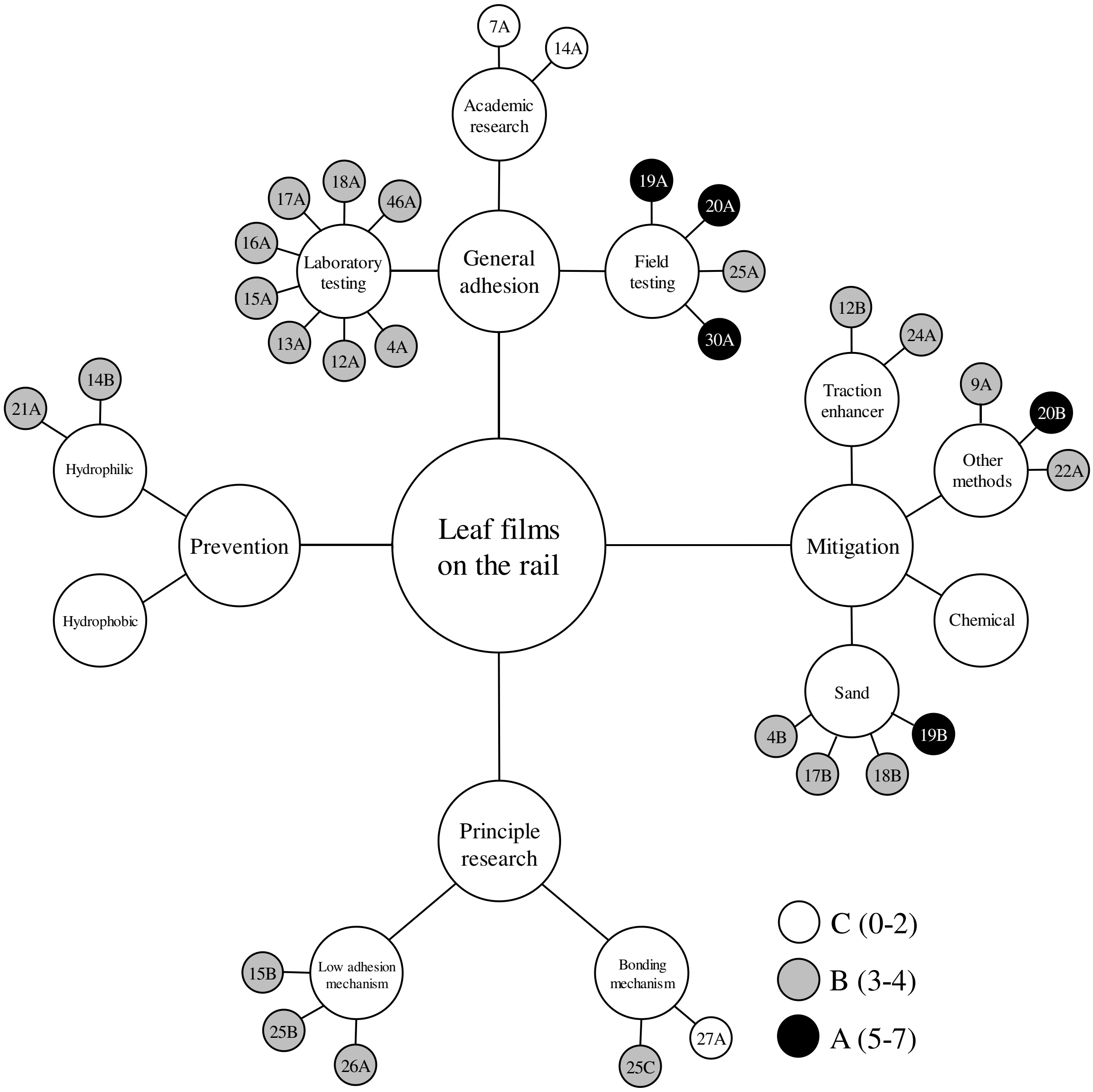


Figure 7: A knowledge map in previous studies regarding leaf films on the rail, based on the total scores in evaluation.

7.4 Proposed Model

After reviewing the previous research in this area, a new model which represents the bonding condition between the leaf film and the rail surface is suggested, as shown in Figure 8. In this model, the leaf film is bonded to the rail surface via the bonding layer which acts as a buffer layer. This bonding layer has an intermediate characteristic between leaf films and bulk rails, and has a role to absorb the difference in material properties, leading to a strong bond. This bonding layer is analogous to a buffer layer. Buffer layers are a common technique used in the semi-conductor industry [70], to relieve the lattice mismatch between the substrate and film improving film quality. Although the conditions of film formation are different between semi-conductors and leaf layers, the use of buffer layers in industry supports the bonding layer model.

In this model, the concentrations of leaf components and Fe ions are gradually changed in the bonding layer. For example, the concentration of leaf components is highest at the surface, and lowest close to the bulk material. GD-OES results [25] support this idea, which shows gradual changes in oxide concentration from surface to bottom.

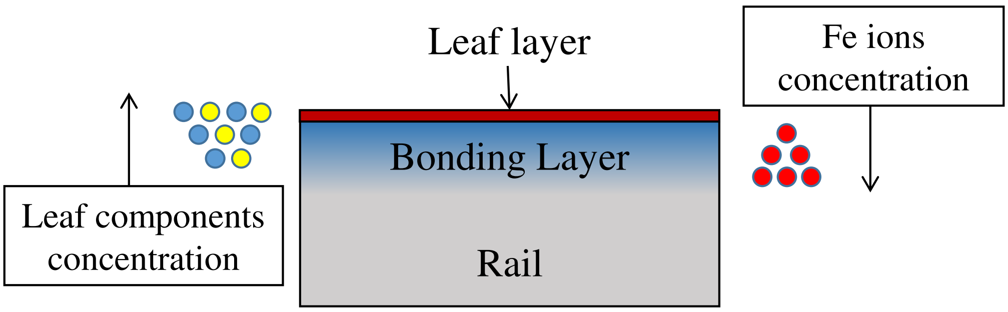


Figure 8: Schematic figure of proposed model, composed of leaf layer, bonding layer and rail bulk material. The bonding layer consists of leaf components and iron oxides, with this mixture forming the strong bond.

The generation mechanism of the bonding layer is shown in Figure 9. In this model, high pressure and high temperature are the main activators for the bonding layer formation. When wheels slip on top of low friction/traction leaves on the rail, thermal energy should be generated. This thermal energy is expected to be high enough to decompose organic components in leaves and to activate Fe ions on the rail surface, as shown in Table 2. Then, the leaf components and Fe ions are chemically reacted under a wet environment, which probably supplies reactive elements, such as oxygen, nitrogen and hydrogen. Finally, a mixed layer of leaf components and Fe ions is formed, and it possibly becomes a bonding layer after rapid cooling.

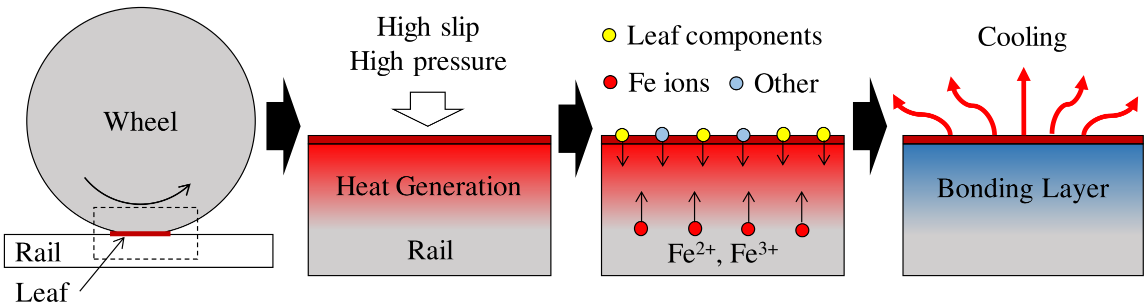


Figure 9: Proposed generation process of the bonding layer. High temperature generated in the wheel/rail contact due to the high slip and high pressure enhances the chemical reaction.

Temperature and pressure are important parameters used to control the properties of thin films in semiconductor manufacture. Thermal energy induced has a significant role, applying energy to ions and putting them into a radical condition. In terms of train operation, the continuous thermal generation at particular area of line could occur (for example wheel spin), leading to enough energy production for chemical reaction. This assumption is supported by the previous study [25], which shows a thick friction-reducing layer, approximately 300 nm in thickness (described in 5.2). Under other conditions, the oxide layer is thought to be less than 10 nm [25], so a layer of 300 nm indicates additional energy input, i.e. thermal.

The thermal energy generated in a wheel steel/leaf contact will be lower than the energy in the steel/steel (wheel/rail) interface due to the lower shear strength of the leaf film. However, high temperature could be achieved in a wheel/leaf contact by: a) some steel/steel asperity contact which penetrates the leaf layer, leading to very localised high flash temperatures in the contact and b) multiple wheel passes over the leaf layer as locomotives typically have 4 to 6 axles, so that the thermal energy due to flash temperature is accumulated. Additionally, leaf layers may form after many locomotive passes meaning that leaf layers could be formed by the gradual repeated application (i.e. many axle passes) of pressure and temperature.

Overall, the thermal energy due to high slip and high pressure of wheels activates the leaf components and Fe ions, and enhances chemical reaction between the leaf components and the rail bulk, forming a thick bonding layer.

7.5 Hypothesis of bonding mechanism

Based on the proposed model and process, some hypotheses are considered, as described below.

7.5.1 Sub- or supercritical water

Generally, leaf components, such as lignin, are stable and they are not easily decomposed into fragments. However, they can be decomposed under sub- or supercritical conditions as described in section 6.4.2, that is, temperature is greater than 374.2 °C and pressure greater than 22.1 MPa (Critical point). The schematic figure of this idea is shown in Figure 10. As described in section 6.2 and 6.3, high temperature (ex. over 727 ˚C [49]) and high pressure (ex. 0.6 – 2.7 GPa [50]) are achievable in the contact area, thus, this hypothesis seems reasonable.

The reaction process is divided into four steps. As a first step, the high pressure is applied to wet leaf films on the rail surface as shown in Figure 10 (a). Then, the contact temperature increases due to thermal energy induced by sliding in the contact, and the water in the leaf film becomes sub- or super critical. During the sliding, leaf components and Fe ions are released from leaf films and rail surface, respectively, and they are dissolved into the sub/super critical water as shown in Figure 10 (b). Subsequently, dissolved leaf components react with Fe ions, and a mixture of this material is formed. Finally, a bonding layer is formed after cooling.

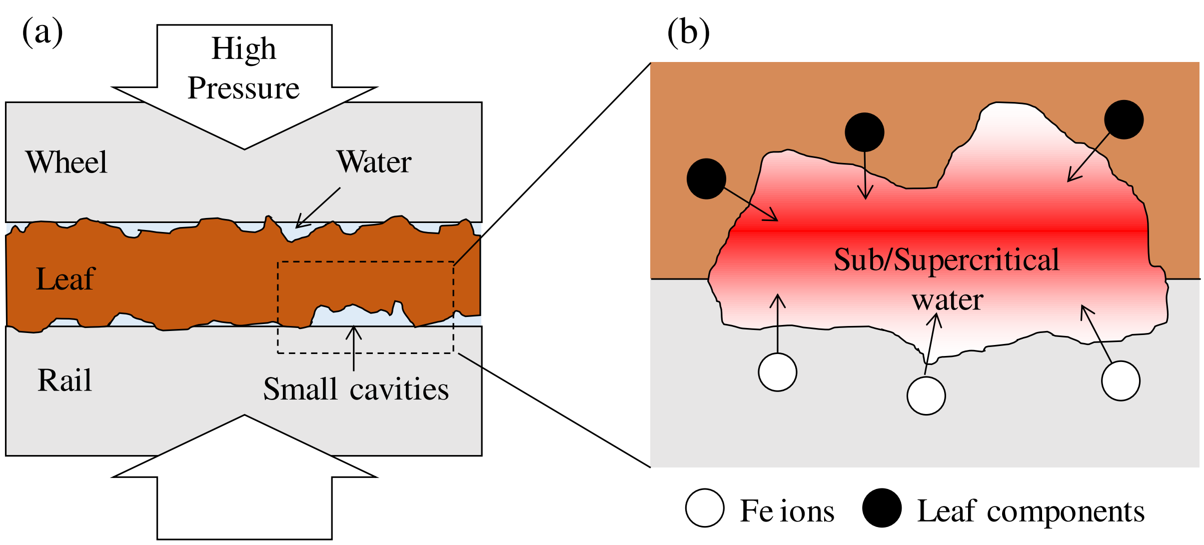


Figure 10: A dissolution process of cellulose and lignin
(a) Small cavities filled with water between the leaf and the rail under high pressure
(b) Zoomed in, leaf components and Fe ions dissolved into the water under sub/supercritical conditions (Pressure > 22.1 MPa, Temperature > 374 °C)

It should be noted that more careful consideration regarding temperature and pressure is needed for this hypothesis, for example, temperature calculation and pressure estimation during wheel slips. However, previous studies described in section 6 strongly support the hypothesis.

7.5.2 Catalyst function of iron oxides

Figure 11 shows a decomposition process of leaf components due to iron oxide catalyst. As mentioned in section 6, iron oxides have a catalyst function, which enhances the decomposition of cellulose or lignin under certain environments, namely, high temperature and high pressure. Although the magnitude of the catalyst function is not significant [45, 46], the active surface of iron oxides accelerates decomposition of leaf components more than under normal conditions.

There are three steps in the degradation process due to iron oxide catalyst. First of all, high temperature and high pressure are applied to wet leaf films on the iron oxide film formed on the rail surface as shown in Figure 11 (a). After that, leaf components, such as cellulose and lignin, are dissolved into the water, subjecting any water in the contact to sub/supercritical conditions as shown in Figure 10 (b). Immediately, dissolved components are decomposed into small fragments on the surface of iron oxides, such as Fe_2O_3 and Fe_3O_4, as shown in Figure 11 (b). In this step, iron oxides work as a catalyst. Finally, these fragments react together, or react with Fe ions discharged from the surface, and a bonding layer (mixing layer) is formed.

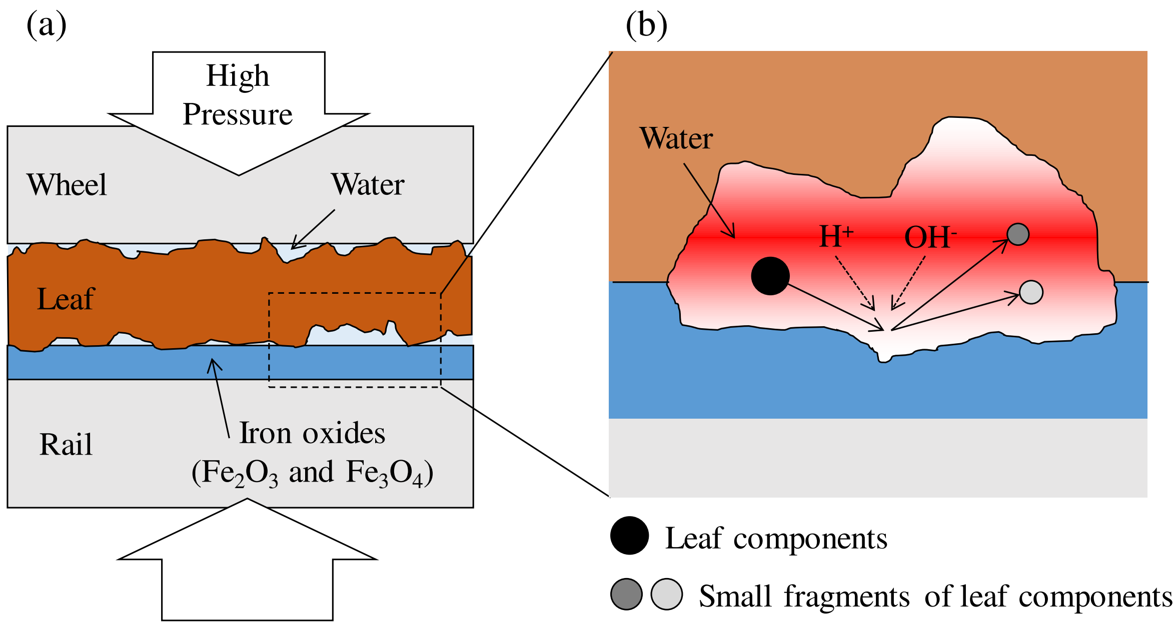


Figure 11: A decomposition process of leaf components with the catalyst of iron oxides.
(a) A contact condition with the surface iron oxides such as Fe_2O_3 and Fe_3O_4.
(b) Zoomed in, degradation process of leaf components into small fragments with the assistance of iron oxide catalysts.

It is noteworthy that this hypothesis has a close relationship to the sub/supercritical hypothesis, that is, both of them need high temperature and high pressure for chemical reaction. Lignin can be decomposed within 5 seconds or shorter under supercritical conditions (22.1 MPa, 374°C, see 6.4.2). The duration of a single wheel pass will be considerably shorter than this time. However, the pressure in a wheel rail contact is typically 900 MPa or more. This considerably higher pressure may reduce the time needed for the full decomposition of lignin. Also full decomposition could be achieved over many wheel passes as a single or multiple locomotives roll over the leaf.

7.5.3 Cellulose or lignin adhesives

Figure 12 depicts a schematic of the proposed mechanical interlocking mechanism of leaf adhesives. This hypothesis focuses on the basic bonding mechanism rather than the process of a bonding layer formation. In this hypothesis, dissolved leaf components and Fe ions are assumed to form an adhesive layer after the chemical reaction because cellulose and lignin have properties as an adhesive, as described in 6.4.1 and 6.4.2. Although there are many mechanisms regarding adhesives, one of the main theories is mechanical interlock theory, which explains that adhesive material fills surface asperities and anchor the two materials [71].

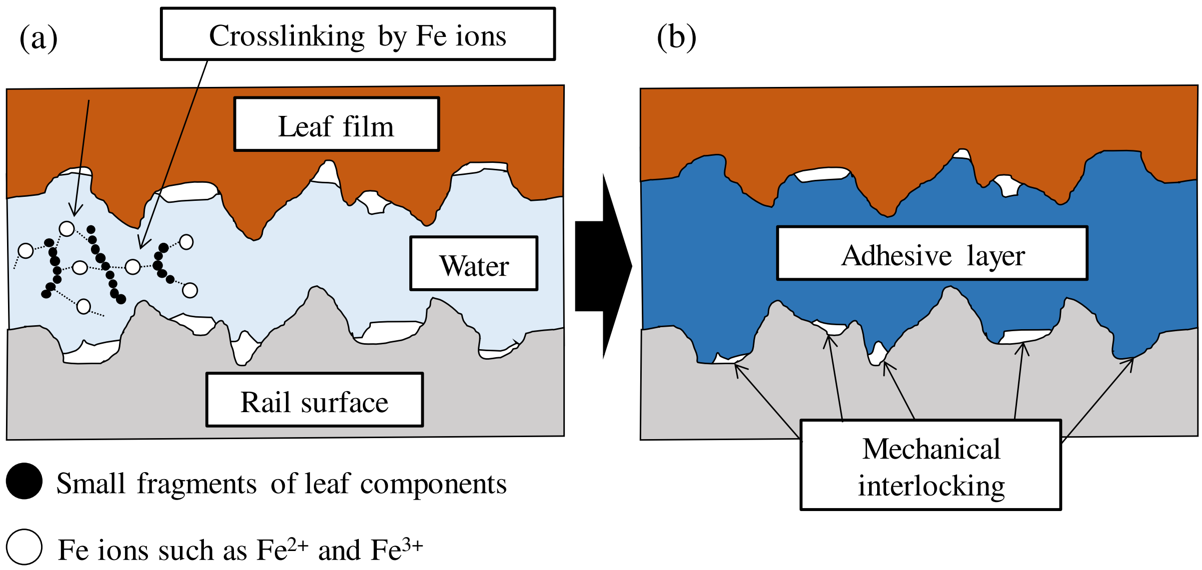


Figure 12: A schematic figure of adhesive layer formation, based on cellulose or lignin polymerisation.
(a): Re-polymerisation process through crosslinking by Fe ions
(b): Mechanical interlocking by adhesive layers produced by re-polymerisation

The process of adhesive formation can be divided into three steps. First, leaf components and Fe ions are dissolved into water, and leaf components are decomposed into small fragments, as described in 7.5.1 and 7.5.2. Following the decomposition, the small fragments are cross-linked by other elements, such as Fe ions as shown in Figure 12 (a). Through crosslinking, decomposed fragments are re-polymerised in the water. As a result, an adhesive layer is formed by the re-polymerisation process, filling the asperities on the rail surface as shown in Figure 12 (b).

7.6 Hypothesis of low adhesion mechanism

There are several arguments regarding the reason why the leaf residue causes low adhesion. However, the main cause has not yet been determined because of the many parameters, such as relative humidity, third bodies and temperature. Therefore, some hypotheses are proposed here to consider the main cause of low adhesion, focusing on how leaves work as a lubricant.

7.6.1 Bulk leaf

This hypothesis assumes that there are many fallen leaves on the line because of strong winds, as shown in Figure 13. If wheels pass over the leaves, leaves are compacted and adhered to the rail. During the wheel passages, leaves might act as a solid lubricant because the thickness will be large enough to prevent metal-to-metal contact. Consequently, the friction/traction coefficient on the contact area is lowered. After wheel passages, natural third body layers, namely, leaf films, are presumably formed, and the low adhesion problem continues for a long time.

Both laboratory experiments and experiences in train operation support this hypothesis. It is demonstrated that a continuous application of leaves into the contact area of a twin disc machine produce a low friction/traction coefficient (i.e. < 0.05) in both dry and wet conditions [4]. Furthermore, train operation is often suspended or delayed because of sudden and heavy leaf falls, which can be caused by strong winds.

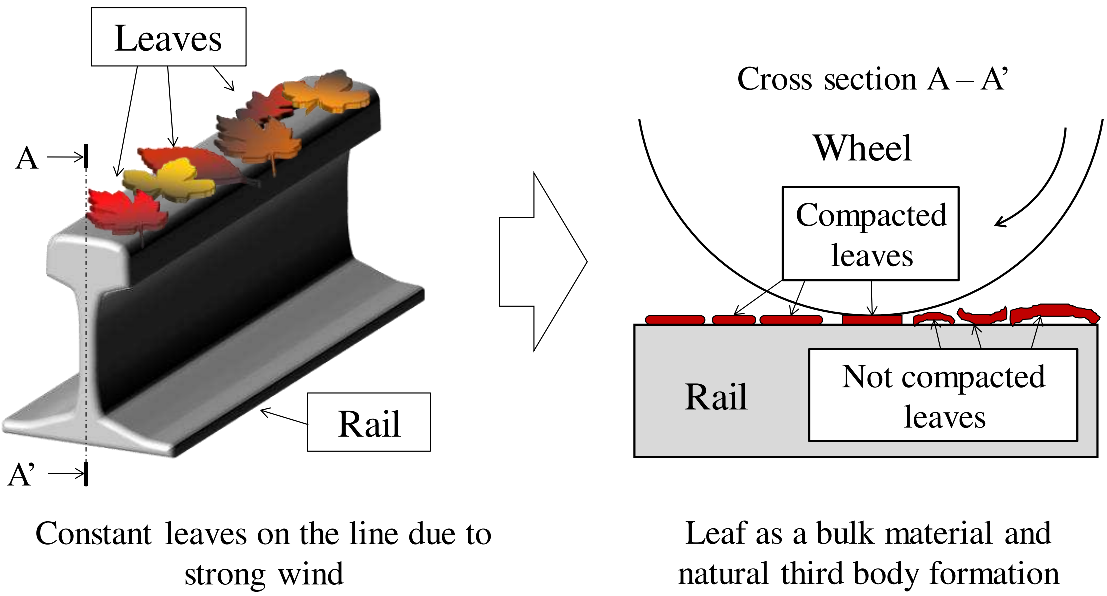


Figure 13: A schematic figure of the low adhesion mechanism due to bulk leaves, which have fallen on the line because of strong winds.

Figure 14 shows the classification of leaf conditions as a solid lubricant. Both wet and dry leaves are confirmed to produce low adhesion conditions, however, there are probably differences in friction/traction coefficients between green leaves and brown leaves. Further work is needed to demonstrate how this classification works for friction/traction coefficients.

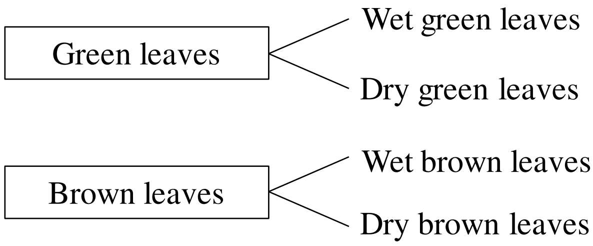


Figure 14: Classification of leaf conditions as a solid lubricant

7.6.2 Adhered leaf film

This hypothesis explains how leaf films adhered to the rail surface work as a lubricant, after compaction by wheel passages. Figure 15 shows a schematic view of the low adhesion mechanism of leaf films in dry conditions, based on a field-based model described in 5.2. The friction-reducing layer in the middle is created by a chemical reaction between the leaf and rail. This layer contains various elements from the leaf and rail, such as carbon and iron oxides [25, 26], working as a third body layer.

In this hypothesis, there are two factors which cause a decrease of the friction coefficient, namely, leaf films and the friction-reducing layer. First, leaf films are likely to become a solid lubricant due to their low shear strength. Previous studies reveal that leaf films created on test specimens produce low friction/traction coefficients [12, 16, 17, 24]. Furthermore, the friction-reducing layer also decreases the friction coefficient, because of the iron oxides in the layer. Iron oxides on the rail surface could be attributed to the decrease in friction/traction coefficients (see 6.1.2), thus, this hypothesis in dry conditions seems to be rational.

Figure 16 shows the low adhesion mechanism in wet conditions. In this hypothesis, leaf films absorb dew formed on the rail surface, and they are deteriorated, in particular, softened. The softened leaf films presumably have a lower shear strength, and cause low friction/traction.

Wet leaves are identified to decrease friction/traction coefficients in the wheel/rail contact [4, 7, 15-20], in addition, the statistical data of train operation suggests that morning dew affects adhesion condition and increases the number of accidents (see section 2).

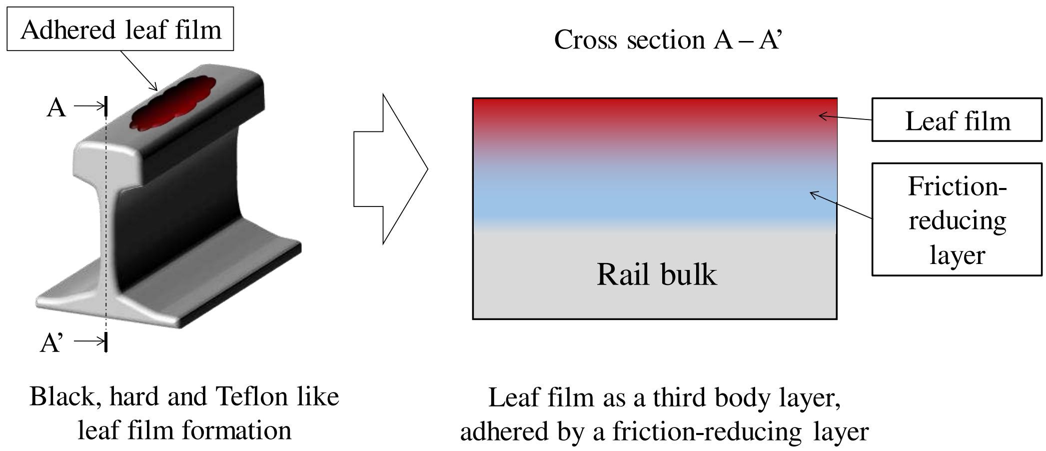


Figure 15: A schematic figure of the low adhesion mechanism due to adhered leaf films in dry conditions

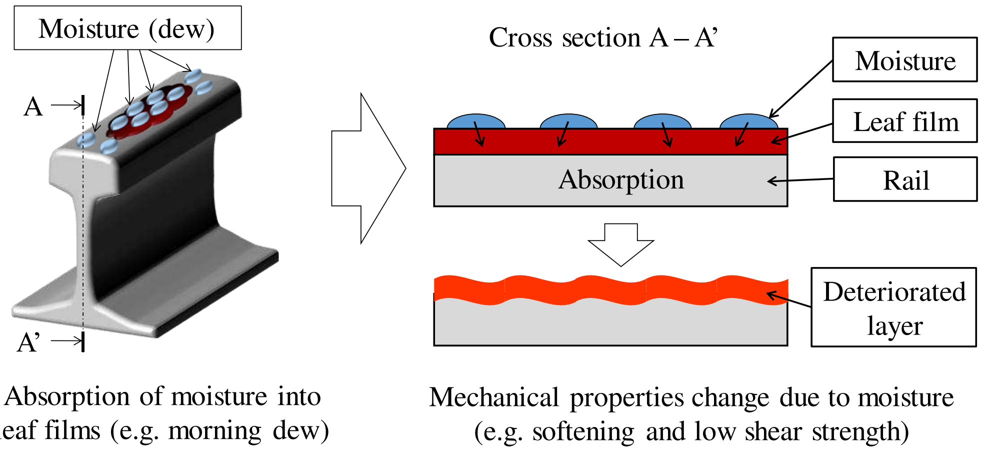


Figure 16: A schematic figure of the low adhesion mechanism due to adhered leaf films in wet conditions

7.6.3 Pectin gel

This hypothesis is based on the results that the pectin gel forms a slippery film on the surface, which is discharged from the leaf residue [15]. Figure 17 shows the low adhesion mechanism in the case of a relatively high amount of water, such as rain and heavy morning dew. FT-IR analysis demonstrates that there is pectin and cellulose as water-soluble components of the leaf, with pectin transforming into the pectin gel, presumably, by reacting with Fe ions [15]. Therefore, this pectin gel on the film surface is thought to prevent metal-to-metal contact by forming a lubrication film, leading to low friction/traction. Furthermore, EHL (elastohydrodynamic lubrication) films might be formed due to the gel's high viscosity, depending on the speed range [15].

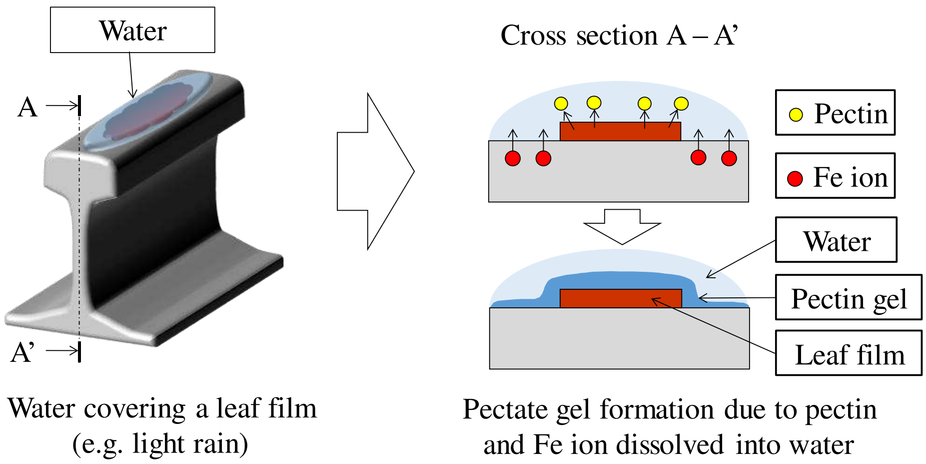


Figure 17: A schematic figure of the low adhesion mechanism due to adhered leaf films, forming pectin gel on the film surface.

In conclusion, a number of hypotheses are proposed based on previous works [4, 7, 15-20, 24-26], which are bulk leaf, adhered leaf film and a pectin gel model. Further works need to be carried out to confirm these hypotheses and establish the low adhesion mechanism due to leaves.

8. Conclusions

In this paper, low adhesion problems, which are presumed to be caused by leaves in the wheel/rail contact, were illustrated through a literature review and data analyses, focusing on the bonding mechanism, key parameters and the low adhesion mechanisms. This study is composed of six parts, namely, incident analysis, low adhesion, bonding mechanism, mitigation methods, key parameters and hypothesis proposals of bonding mechanism and low adhesion mechanisms. The conclusions are shown below:

- There is a relatively high possibility of station overruns and SPADS (signals passed at danger) between the hours of 05:00 – 10:00 and 20:00 – 24:00 (in the UK), which was confirmed in the incident analysis. This could be attributed to leaf films on the rail, which are moistened by dew produced by high relative humidity in the morning and at night.
- The friction/traction coefficient where leaf films are on the rail was identified as below 0.1 in both laboratory and field studies, which is categorised as a low adhesion level. Wet leaves tend to produce low friction/traction coefficients of around 0.05.
- Mitigation methods, such as sanding, friction modifiers and high pressure water, are thought to be effective for leaf induced low adhesion problems to some extent. However, there are still some issues with performance and cost.
- A laboratory-based model and a field-based model were derived as representative models for a bonding structure of leaf films based on previous studies. Chemical reaction between the leaf film and rail were considered to bond these materials, however, the detailed process has not yet been established.

- Key parameters that affect the bonding mechanism were investigated and assumed as iron oxides, temperature, pressure and material (leaf components). Further work is needed to identify which parameter is more predominant to form a strong bond between the leaf and the rail.
- Several hypotheses were proposed to explain the bonding mechanism, based on the results in the material and biochemistry fields: sub- or super critical water, catalyst function of iron oxides and adhesives of cellulose or lignin. Additionally, low adhesion models were also assumed including: bulk leaf, adhered leaf film and a pectin gel models. Theses hypotheses need to be demonstrated now by experiments.

9. Acknowledgments

The authors would like to thank the University of Sheffield, UK, and East Japan Railway Company, Japan, for their financial support to carry out this research.

10. References

1. Chester, M.V., Horvath, A., 2009. *Environmental assessment of passenger transportation should include infrastructure and supply chains.* Environmental Research Letters Vol. 4, 024008 (8pp)

2. *Baseline energy statement – energy consumption and carbon dioxide emissions on the railway*. Published by the ATOC, 2007

3. Olofsson, U., Zhu, Y., Abbasi, S., Lewis, R., Lewis, S., 2013. *Tribology of the wheel-rail contact – aspects of wear, particle emission and adhesion*. Vehicle system Dynamics Vol. 51, pp 1091-1120

4. Gallardo-Hernández, E.A., Lewis, R., 2008. *Twin disc assessment of wheel/rail adhesion.* Wear Vol. 265, pp 1309-1316

5. Lewis, S.R., Lewis, R., Olofsson, U., *An alternative method for the assessment of railhead traction*. Wear Vol. 271, pp 62 – 70

6. Harrison, H., MacCanney, T., Cotter, J., 2002. *Recent developments in coefficient of friction measurements at the rail/wheel interface*. Wear Vol. 253, pp 114 - 123

7. Fulford, C. R., 2004. *Review of low adhesion research*. Report published by the Railways Safety and Standards Board
8. Pearce, T., Watkins, D., 1987. *Adhesion and leaves - A review of the problem and potential solutions.* Report published by the British Rail

9. Voges, W., Spiess, P., 2006. *Optimising Services with EMU ET42x in Autumn 2004 and 2005*. In Proceedings of the 7th World Congress on Railway research, Canada

10. *Buffer stop collision at Chester station 20 November 2013.* Rail accident report published by the RAIB, 2013

11. *Station overrun at Stonegate, East Sussex 8 November 2010.* Rail accident report published by RAIB, 2010

12. Li, Z., Arias-Cuevas, O., Lewis, R., Gallardo-Hernández, E. A., 2009. *Rolling-Sliding Laboratory Tests of Friction Modifiers in Leaf Contaminated Wheel-Rail Contacts.* Tribology Letters Vol. 33, pp 97-109

13. Olofsson, U., Sundvall, K., 2004. *Influence of leaf, humidity and applied lubrication on friction in the wheel-rail contact: pin-on-disc experiments.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 218, pp 235-242

14. Poole, W., 2007. *Characteristics of Railhead Leaf Contamination*. Report published by the Railways Safety and Standards Board

15. Cann, P. M., 2006. *The "Leaves on the line" problem – A study of film formation and lubricity under simulated railtrack conditions*. Tribology Letters Vol. 24, pp 151-158

16. Vasić, G., Franklin, F. J., Kapoor, A., Lučanin, V., 2008. *Laboratory simulation of low-adhesion leaf film on rail steel.* International Journal of Surface Science and Engineering Vol. 2, pp 84-97

17. Arias-Cuevas, O., Li, Z., Lewis, R., Gallardo-Hernández, E. A., 2010. *Laboratory investigation of some sanding parameters to improve the adhesion in leaf-contaminated wheel-rail contacts.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 224, pp 139-157

18. Omasta, M., Machatka, M., Smejkal, D., Hartl, M., Krupka, I., 2015. *Influence of sanding parameters on adhesion recovery in contaminated wheel-rail contact.* Wear Vol. 322-323, pp 218-225

19. Arias-Cuevas, O., Li, Z., 2011. *Field investigations into the adhesion recovery in leaf-contaminated wheel-rail contacts with locomotive sanders.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 225, pp 443-456

20. Arias-Cuevas, O., Li, Z., 2011. *Field investigations into the performance of magnetic track brakes of an electrical multiple unit against slippery tracks. Part 1: Adhesion improvement.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 225, pp 613-636

21. Hyde, P., Fletcher, D., Kapoor, A., Richardson, S., 2008. *Full Scale Testing to Investigate the Effect of Rail Head Treatments of Differing pH on Railway Rail Leaf Films.* Proceedings of the World Congress on Railway Research, May 18-22, 2008, Seoul, South Korea.

22. Tamura, D., Numakura, A., Takigawa, M., 2007. *An effective measures for prevention against slipping/sliding problems of the wheel due to leaf contamination on the railways.* Proceedings of Japan Society of Civil Engineers Vol. 62, pp 4-226 (in Japanese)

23. Lewis, R. Masing, J., 2005. *Static wheel/rail contact isolation due to track contamination.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 220, pp 43-53

24. Lewis, S. R., Lewis, R., Cotter, J., Lu, X., Eadie, D. T., 2016. *A New Method for the Assessment of Traction Enhancers and the Generation of Organic Layers in a Twin-Disc Machine.* Wear, Vol. 366–367, pp 258–267

25. Zhu, Y., Olofsson, U., Nilsson, R., 2014. *A field test study of leaf contamination on railhead surfaces.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 228, pp 71-84

26. Olofsson, U., 2007. *A multi-layer model of low adhesion between railway wheel and rail.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 221, pp 385-389

27. Somashekara, N., Saiyed, Z. M., Ramchand, C. N., 2006. *Biochemistry of railhead leaf film contamination.* LD43562 263 Report published by the Railways Safety and Standards Board

28. White, B. T., Fisk, J., Evans, M. D., Arnall, A. D., Armitage, T., Fletcher, D. I., Lewis, R., 2015. *A study into the effect of the presence of moisture at the wheel/Rail interface during dew and damp conditions.* 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems Colorado Springs, Colorado, USA, 30th of August – 3rd of September

29. Brimblecombe, P., 2013. *Temporal humidity variations in the heritage climate of South east England.* Heritage Science Vol. 1, pp 1-11

30. Nagase, K., 1989. *A study of adhesion between the rails and running wheels on main lines: results of investigations by slipping adhesion test bogie.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 203, pp 33-43

31. Jenks, C. W., 1997. *Improved methods for increasing wheel/rail adhesion in the presence of natural contaminants*. RESEARCH RESULTS DIGEST Number 17Transit Cooperative Research Program Project C-6, pp 1-5

32. Lewis, R., Dwyer-Joyce, R. S., Lewis, J., 2003. *Disc machine study of contact isolation during railway track sanding.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 217, pp 11-24

33. Arias-Cuevas, O. Li, Z., Lewis, R. 2011. *A laboratory investigation on the influence of the particle size and slip during sanding on the adhesion and wear in the wheel-rail contact.* Wear Vol. 271, pp 14-24

34. Lewis, R., Dwyer-Royce, R. S., 2006. *Wear at the wheel/rail interface when sanding is used to increase adhesion.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vol. 220, pp 29-41

35. Arias-Cuevas, O., Li, Z., Gallardo-Hernández, E. A., 2010. *Rolling-sliding laboratory tests of friction modifiers in dry and wet wheel-rail contacts.* Wear Vol. 268, pp 543-551

36. Zhao, Y.W., Liu, J.J., Zheng, L.Q., *The oxide film and oxide coating on steels under boundary lubrication.* The 16th Leeds-Lyon symposium on tribology, Lyon, France, 5–8 September 1989, The Netherlands: Elsevier, pp.305–311.

37. Nakahara, T., Baek, K. S., Ishida, M., 2011. *Relationship between surface oxide layer and transient traction characteristics for two steel rollers under unlubricated and water lubricated conditions.* Wear Vol. 271, pp 25-31

38. Chen, H., Sone, Y., Baek, K. S., Nakahara, T., Ishida, M., 2007. *A Fundamental study on effect of rust upon adhesion coefficient between wheel and rail.* RTRI Report Vol. 21, No. 12, pp. 5-10

39. Suzumura, J., Sone, Y., Ishizaki, A., Yamashita, D., Nakajima, Y., Ishida, M., 2011. *In situ X-ray analytical study on the alteration process of iron oxide layers at the railhead surface while under railway traffic.* Wear Vol. 271, pp 47-53

40. Berthier, Y., Descartes, S., Busquet, M., Niccolini, E., Desrayaud, C., Baillet, L., Bailetto-Dubourg, M. C., 2004. *The role and effects of the third body in the wheel-rail interaction*. Fatigue and Fracture of Engineering Materials and Structures Vol. 27, pp 423-436

41. Zhu, Y., Lyu, Y., Olofsson, U., 2015. *Mapping the friction between railway wheels and rails focusing on environmental conditions.* Wear Vol. 324-325, pp 122-128

42. Zhu, Y., Olofsson, U., Chen, H., 2013. *Friction between wheel and aail: A pin-on-disc study of environmental conditions and iron oxides.* Tribology Letters Vol. 52, pp 327-339

43. Misawa, T., Hashimoto, K., Shimodaira, S., 1974. *The mechanism of formation of iron oxide and oxyhydroxids in aqueous solutions at room temperature.* Corrosion Science Vol. 14, pp. 131-149

44. Zhu, H., Cao, F., Zuo, D., Zhu, L., Jin, D., Yao, K., 2008. *A new hydrothermal blackening technology for Fe_3O_4 coatings of carbon steel.* Applied Surface Science Vol. 254, pp 5905-5909

45. Koriakin, A., Nguyen, H. V., Kim, D. W., Lee, C. H., 2015. *Thermochemical decomposition of microcrystalline cellulose using sub- and supercritical tetralin and decalin with Fe_3O_4.* Industrial & Engineering Chemistry Research Vol. 54, pp 5184-5194

46. Uddin, M. A., Tsuda, H., Wu, S., Sasaoka, E., 2008. *Catalytic decomposition of biomass tars with iron oxide catalysts.* Fuel Vol. 87, pp 451-459

47. Gallardo-Hernández, E. A., Lewis, R., Dwyer-Joyce, R. S., 2006. *Temperature in a twin-disc wheel/rail contact simulation.* Tribology International Vol. 39, pp 1653-1663

48. Sundh, J., Olofsson, U., 2011. *Relating contact temperature and wear transitions in a wheel-rail contact.* Wear Vol. 271, pp 78-85

49. Fletcher, D. I., 2012. *Thermal contact stress and near surface rail cracks.* 9th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems, Chengdu, China

50. Lewis, R., Olofsson, U., Basic tribology of the wheel-rail contact, *Wheel-rail interface handbook*, Woodhead Publishing in Mechanical Engineering, pp 58-90

51. Cao, Y., Wang, Y. B., An, X. H., Liao, X. Z., Kawasaki, M., Ringer, S. P., Langdon, T. G., Zhu, Y. T., 2014. *Concurrent microstructural evolution of ferrite and austenite in a*

duplex stainless steel processed by high-pressure torsion. Acta Materialia Vol. 63 pp 16-29

52. Rigney, D. A., 2000. *Transfer, mixing and associated chemical and mechanical process during the sliding of ductile materials*. Wear Vol. 245, pp 1-9

53. Baumann, G., Knothe, K., Fecht, H.J., *Surface modification, corrugation and nanostructure formation of high speed railway tracks.* Nanostructured Materials Vol. 9, pp 751-754

54. Crowe, J., Bradshaw, T., Monk, P., Molecular shape and structure 2: the shape of large molecules, *Chemistry for the Biosciences*, Oxford University Press, pp 241-266

55. Sakai, M., Fang, Z., Fukushima, Y., Adschiri, T., Arai, K., 2000. *Dissolution and hydrolysis of cellulose in subcritical and supercritical water.* Industrial & Engineering Chemistry Research Vol. 39, pp 2883-2890

56. Parker, R. S. R., Taylor, P., Natural products as adhesives, *Adhesion & Adhesives*, Pergamon Press, pp 59-75

57. Esau, K., The cell wall, *Plant Anatomy*, John & Wiley & Sons, Inc., pp 33-66

58. Yong, T. L. K., Matsumura, Y., 2012. *Reaction kinetics of the lignin conversion in supercritical water*. Industrial & Engineering Chemistry research Vol. 51, pp 11975-11988

59. Gosselink, R. J. A., Teunissen, W., van Dam, J. E. G., de Jong, E., Gellerstedt, G., Scott, E. L., Sanders, J. P. M., 2012. *Lignin depolymerisation in supercritical carbon dioxide/acetone/water fluid for the production of aromatic chemicals.* Bioresource Technology Vol. 106, pp 173-177

60. Nagamatsu, Y., Funaoka, M., 2001. *Structual control of lignin-based polymers and the design of recyclable lignocellulosic composites*. Journal of the Adhesion Society of Japan Vol. 37, pp 10-17 (in Japanese)

61. Yuan, Z., Cheng, S., Leitch, M., Xu, C., 2010. *Hydrolytic degradation of alkaline lignin in hot-compressed water and ethanol.* Bioresource Technology Vol. 101, pp 9308-9313

62. Okuda, K., Man, X., Umetsu, M., Takami, S., Adschiri, T., 2004. *Efficient conversion of lignin into single chemical species by solvothermal reaction in water-p-cresol solvent.* Journal of Physics: Condensed Matter Vol. 16, pp 1325-1330

63. Osada, M., Sato, T., Watanabe, M., Adschiri, T., Arai, K., 2004. *Low-temperature catalytic gasification of lignin and cellulose with a ruthenium catalyst in supercritical water.* Energy & Fuels Vol. 18, pp 327-333

64. Dongre, P., Driscoll, M., Amidon, T., Bujanovic, B., 2015. *Lignin-furfural based adhesives.* Energies Vol. 8, pp 7897-7914

65. El Mansouri, N. E., Pizzi, A., Salvado, J., 2007. *Lignin-based wood panel adhesives without formaldehyde.* Holz Roh Werkst Vol. 65, pp 65-70

66. Cosgrove, D. J., 1997. *Assembly and enlargement of the primary cell wall in plants.* Annual Review of Cell and Developmental Biology Vol.13, pp 171-201

67. Kawabata, A., Sawayama, S., Kamata, T., 1979. *On the mechanism of association of low-methoxyl pectin due to calcium ions (Studies on the gelling mechanism for pectin part 1).* Nippon Nogeikagaku Kaishi Vol. 53, pp 61-67 (in Japanese)

68. Wellner, N., Kacurakova, M., Malovikova, A., Wilson, R. H., Belton, P. S., 1998. *FT-IR study of pectate and pectinate gels formed by divalent cations.* Carbohydrate Research Vol. 308, pp 123-131

69. Harmon, M., Lewis, R., 2016, *Review of top of rail friction modifier tribology.* Tribology – Materials, Surfaces and Interfaces, Vol. 10, pp 150-162

70. Kawano, M., Yamada, S., Tanikawa, K., Sawano, K., Miyao, M., Hamaya, K., 2013. *An ultra-thin buffer layer for Ge epitaxial layers on Si.* Applied Physics Letter Vol. 102, 12908

71. Mittal, K. L., Pizzi, A., Theories and Mechanisms of Adhesion, Adhesion promotion techniques, Marcel Dekker, Inc., pp 1-26

11. Appendix

Table 3: Summary of paper grading

Paper	Grade	1st Category	2nd Category	Peer reviewed publication	Theory supported by testing	Scale test	Full scale test	Real world measurement	Conclusions evidence in paper	Conclusions operationally validated
4A	4	General adhesion	Laboratory testing	Y	Y	Y	N	N	Y	N
4B	4	Mitigation	Sand	Y	Y	Y	N	N	Y	N
7A	2	General adhesion	Academic research	N	N	N	N	N	Y	Y
9A	3	Mitigation	Other methods	N	N	N	N	Y	Y	Y
12A	4	General adhesion	Laboratory testing	Y	Y	Y	N	N	Y	N
12B	4	Mitigation	Traction enhancer	Y	Y	Y	N	N	Y	N
13A	4	General adhesion	Laboratory testing	Y	Y	Y	N	N	Y	N
14A	1	General adhesion	Academic research	N	N	N	N	N	Y	N
14B	3	Prevention	Hydrophilic	N	N	N	Y	Y	Y	N
15A	4	General adhesion	Laboratory testing	Y	Y	Y	N	N	Y	N
15B	4	Principle research	Low adhesion mechanism	Y	Y	Y	N	N	Y	N
16A	4	General adhesion	Laboratory testing	Y	Y	Y	N	N	Y	N
17A	4	General adhesion	Laboratory testing	Y	Y	Y	N	N	Y	N
17B	4	Mitigation	Sand	Y	Y	Y	N	N	Y	N
18A	4	General adhesion	Laboratory testing	Y	Y	Y	N	N	Y	N
18B	4	Mitigation	Sand	Y	Y	Y	N	N	Y	N
19A	5	General adhesion	Field testing	Y	Y	N	Y	Y	Y	N
19B	5	Mitigation	Sand	Y	Y	N	Y	Y	Y	N
20A	5	General adhesion	Field testing	Y	Y	N	Y	Y	Y	N
20B	5	Mitigation	Other methods	Y	Y	N	Y	Y	Y	N
21A	4	Prevention	Hydrophilic	N	Y	N	Y	Y	Y	N
22A	2	Mitigation	Other methods	N	N	N	N	Y	Y	N
24A	3	Mitigation	Traction enhancer	N	Y	Y	N	N	Y	N
25A	4	General adhesion	Field testing	Y	Y	N	N	Y	Y	N
25B	3	Principle research	Low adhesion mechanism	Y	Y	N	N	N	Y	N
25C	3	Principle research	Bonding mechanism	Y	Y	N	N	N	Y	N
26A	3	Principle research	Low adhesion mechanism	Y	Y	N	N	N	Y	N
27A	1	Principle research	Bonding mechanism	N	N	N	N	N	Y	N
30A	5	General adhesion	Field testing	Y	Y	N	N	Y	Y	Y
46A	3	General adhesion	Laboratory testing	Y	N	Y	N	N	Y	N