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Manuscript title: Vehicle-Based Cryogenic Rail Cleaning: an Alternative Solution to 'Leaves on the Line'

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Abstract

Contamination of rail lines with leaves and other organic matter and oxides can affect the traction of train wheels and cause safety issues, delays and schedule changes. The main solution in the UK is to use specialist rail-head-treatment trains that clean rails with high-pressure water jets. But these trains cannot cover all UK mainline infrastructure due to limited availability and gauging issues. As such, there is a need for a rapid-reponse mobile solution to expand this capability. This paper reports on successful field trials of a small road-to-rail vehicle fitted with dry-ice blasting equipment, and the effect this has on both cleaning rails and improving train braking.

1. Introduction

A long-term challenge for the railway industry is the effective cleaning of tenacious, low-friction, rail-head contamination. The University of Sheffield has been looking into a novel solution for remediating the issue involving dry-ice blasting of rail heads. Such cryogenic cleaning is widely used in a variety of industries already and is known to be effective at removing most surface contaminants. In addition, the operating pressure of the blast is much lower than that of the current standard rail-cleaning technique of pressure washing, and does not involve the transport of relatively heavy liquid consumables.

The field trials reported in this paper were preceded by tests at Sheffield to establish key parameters, and further validation tests were conducted on a twin-disc rig at another university. These initial tests were funded by the Rail Safety and Standards Board (RSSB) (Lewis, Lewis *et al.* 2018, Lewis Stephen 2018, Lanigan, Krier *et al.* 2019). The field trials were funded by Northern Rail, which would like to see the technology rolled out on a large scale.

Contaminant layers can be formed from a variety of substances, including leaves. The leaves are compressed and create what the rail industry generally refers to as ‘black layer’ on the rail head (Ishizaka, Lewis *et al.* 2018). Strictly the term means the mostly carbonaceous organic residue left from compressing leaves at high temperature and pressure (Olofsson 2007). Metal oxides on the rail are also a contaminant layer that require removal due to their ability to reduce adhesion (Gallardo-Hernandez and Lewis 2008, Arias-Cuevas, Li *et al.* 2010, Ishizaka, Lewis *et al.* 2017, White, Nilsson *et al.* 2017, Watson, White *et al.* 2020). These types of layers are known to cause safety and performance issues for train operation as they cannot support high shear stresses present in the wheel–rail contact.

In certain circumstances, typically involving small quantities of water, the contaminants can reduce the braking performance of trains. In the worst-case scenario, low adhesion can cause trains to pass a signal set to danger or over-run a station, which could result in a collision with another train. The annual cost of the low-adhesion problem, including delays and treatment methods, is reported to be £354 million in the UK and 100 million SEK (£8 million) in Sweden (Olofsson 2007, Lightoller; 2018). On some routes, timetable changes are made to accommodate delays caused by reduced traction or braking. While this may reduce incidents and the number of delay minutes, it is not good for passengers.

There are currently two main methods for removing contaminants from rails. Firstly, specialist staff can be sent out to assess a potential area of low adhesion and, if needed, treat the affected area of the rail head. This as-needed treatment would usually consist of time-consuming, mechanical cleaning using a petrol-powered wire-brush scrubber, possibly in conjunction with solvents or cleaning products (Swanson, Davis *et al.* 1995). Alternatively, a vehicle-based system can be used on either a multi-purpose vehicle (MPV) or rail-head-treatment train (RHTT). These systems use very-high-pressure water jets to clean the rail head.

While vehicle-based systems are capable of cleaning long stretches of rail efficiently, they are inflexible and have to travel along mainline track to reach problem areas. This adds to the time required for rail cleaning, creating higher demand than there is capacity. The cleaning vehicles are usually scheduled in advance of autumn. As such, last-minute changes to deal with local low-adhesion issues is not possible. In the UK, Network Rail staff are often deployed with traction-gel-applicator packs. This work involves being close to the mainline and is therefore a high-risk activity for workers. Reducing the need for manual cleaning will increase safety. In addition to the high costs of running RHTTs, their numbers are also limited. Consequently, their routes are planned to cover only the highest priority areas such as inter-city lines.

As well as scheduling and cost problems, cleaning with high-pressure water jets has inherent limitations. They are unable to operate over points, due to the possibility of moving lineside ballast into the point mechanism. Furthermore, these vehicles cannot be used on approaches to platforms during commuting hours. As such, there is a need for a more flexible cleaning solution that is able to cover long stretches of track on lines that do not generally receive treatment from RHTTs or MPVs.

The University of Sheffield has been incrementally developing a novel solution that employs re-captured solid carbon dioxide, also known as ‘dry ice’, as a complimentary technology to the current solution (Krier, Lanigan *et al*. 2020). As mentioned above, the cryogenic cleaning system operates at much lower pressures that conventional treatment. Water jetting takes place at up to 1500 bar, compared to an upper limit of 60 bar for dry-ice blasting (NetworkRail). This reduces the size of the equipment and the potential for damage to the rail head. A prototype has been mounted on a road-to-rail vehicle (RRV) and extensively tested in the field.

The aim of this work was to use the system to clean track at the Quinton Rail Technology

Centre (QRTC) at Long Marston to assess further the contamination-removal performance on leaf layers. The effect on deceleration of a modified class 117 diesel-multiple-unit train in brake tests on the cleaned rail were also conducted. The intention was to build confidence in the developed technology. The railway industry requires full-scale field tests in representative conditions before proceeding with implementation of new technology. The brake-testing method used at QRTC was developed and validated in previous work (Lanigan 2018, Lanigan, Krier *et al*. 2020).

2. Cryogenic cleaning procedure

To achieve effective rail-head cleaning, dry-ice particles are fired at the rail head in a supersonic stream of air (Figure 1). These particles have an immediate cleaning effect, removing contaminants that can cause low adhesion, thereby achieving a highly clean rail head as assessed by swabbing prior and post cleaning. The cleaning takes place via three different mechanisms (Spur, Uhlmann *et al*. 1999, Liu 2012, Máša and Kuba 2016), as follows.

- Surface cooling: the dry ice pellets are at −78°C and embrittle any surface contaminants on the rail head, which then shrink or crack to break down the adhesive bond between them and the rail surface.
- Kinetic energy: the energy of the pellets and the air contributes to contaminant removal. This removal through impact is enhanced if the surface cooling has weakened the adhesive bond between the contaminant and rail surface.
- Sublimation: as the dry ice pellets impact on the surface, they change from their solid state to a gaseous state, with an associated volume increase of about 800 times. This

creates a high-velocity gas flow that penetrates the interface between the contaminant and rail surface, breaking down adhesive bonds.

Due to the sublimation of dry ice from solid to gas, treated surfaces are left dry and clean, without residues of detergents or blasting materials. As the process is completely dry and non-conductive, dry ice can be used where other methods are unsuitable. For example, there is no danger of the loss of electrical contact for subsequent trains or unwanted contact with electrified rails.

Due to the low hardness of the pellets, the operating parameters can easily be tuned to avoid any surface damage from impact. There is also a limited exposure time of the low temperature upon the rail head, and low temperatures are unlikely to cause damage to the rail (Spur, Uhlmann *et al.* 1999). Low-temperature treatments of steel and similar allows are reported in the literature and are shown to positively affect material qualities, although this is typically conducted with the far cooler substance, liquid nitrogen (Manimaran, Pradeep kumar *et al*. 2014).

Unpublished research from Sheffield has shown that over the short durations required for cleaning, rail-head temperature is not affected much below a few microns into the material due to the large heat-sink capacity of the rail. Temperature data taken from thermocouples placed inside a rail were found to range between 0 to −12° C with 2.5 s of dry-ice blasting. At 16 km/h treatment from an RRV, the rail head is exposed to a dry-ice blast for around 0.005 s. As such, the cooling of the metal surface is very transient and likely would not exceed −12° C. Even after 35 s of blasting, the rail head was only found to be at −15° C. Thus, it can be safely assumed that the local levels of cooling are not sufficient to cause damage. This is a major advantage over technologies which seek to heat the black layer directly as it is of unknown thickness and property, such that the required thermal input is also unknown.

It is important to note that carbon dioxide can be recaptured from industrial processes that generate it (Kim, Kim *et al*. 2014, Styring, Quadrelli *et al*. 2014, Ivanchenko, Balanov *et al*. 2021), and can be stored underground as part of a carbon dioxide capture system (Benson and Orr 2011). The Drikold dry ice used in these field trials was provided by Nippon Gases, which states it is recovered from fertiliser and bioethanol manufacturing (Nippon).

It is highly unlikely that industrial sources of carbon dioxide will be reduced over the coming years, even factoring in environmental legislation. The Netherlands Environmental Assessment Agency supports this prediction (PBL, 2020). Its found that in 2019 the growth in total global greenhouse gas emissions continued at a rate of 1.1%, reaching 52.4 Gt of carbon dioxide equivalent. Despite growth of 1.1% being only half that seen in 2018, it is a continuation of the average annual growth rate, which has been 1.1% since 2012 (Olivier, Peters *et al*. 2012). The recapture and use of carbon dioxide therefore does not impact upon overall global emissions. Instead, it can be regarded as a beneficial recovery process where a potential waste product can be put to a second use.

3. Test methodology

The methodology used in the field trials was the same as previously reported for creating leaf layers in the field for brake tests of a class 117 train (Lanigan *et al*., 2020), though for these tests only one car of the train was used. To create the leaf layer, leaves were fixed across the rail head with masking tape either side of the rail.

Previous work using the methodology showed little variation in traction performance over the first five tests on a leaf layer, with large variations between leaf layers. The cleaning was therefore applied between subsequent braking tests on the same leaf layer to compare results before and after cleaning. An outline of the testing protocol is given here with more details given in sections that follow:

1. Create a 3 m length of leaf layer, over both rails.
2. Vehicle brake test on the leaf layer.
3. RRV cleaning pass over the same area.
4. Vehicle brakes again on the line after cryogenic cleaning.
5. Repeat steps 3 and 4 (at least twice).

Increasing the length of leaf layer from 3 m was initially desired, however it was found to be prohibitively time consuming due to the manually intensive process of sticking the leaves to the rails. The success seen on the initial stretch of 3 m was considered a good indicator of the cleaning process working, which led to trials of the system in certain problem areas identified by Network Rail being carried out the following autumn (reported elsewhere?)

The entire protocol was repeated three times to ensure repeatability over a variety of leaf layers. The train wheels were effectively cleaned after each test by again using the brakes during transit around the test track.

3.1 Test site and vehicle

The test loop at QRTC in the UK was identified for the trials, access to a class 117 train car was arranged. This was adapted to provide sufficient data capture (see section 3.2 and Table 1). The track at QRTC is a 2.4 km loop with a 300 m straight where the vehicle can get up to a maximum speed of 40 km/h, though the vehicle speed was limited to 16 km/ in all tests. The reasoning behind this was that a large amount of rail incidents in the UK take place with a train moving at low speeds (Baysari, Caponecchia *et al*. 2009). This then allowed the authors to confirm if low adhesion conditions that can lead to such incidents could have been effectively prevented with cryogenic cleaning. The track on the straight is representative of that seen in the UK mainline. A loop of the entire track was employed to avoid the vehicle backing over the leaf layer between tests.

3.2 Onboard train measurements

On-board measurements of stopping time, location and velocity were recorded using a commercially available high-accuracy satellite-positioning system. This had a roof-mounted aerial to ensure the maximum number of satellites were used at any given time (Ruth and Brown 2010, Neale, Danaher *et al*. 2016, Racelogic). The location of the brake lever was recorded electronically to determine when braking was applied, though there was a variable, indeterminate delay before the system changed the pressure at the brake blocks.

3.3 Generation of leaf layer

Initially, the track was conditioned to ensure it was representative of normal rail. This conditioning consisted of five passes of the vehicle around the track. Leaf layers were then created using representative leaves gathered from a sycamore-rich location in Yorkshire. The leaves were fixed to the rail in the designated low-adhesion zone using adhesive tape (Figure 2(a)). The tape was kept away from the running band so it did not influence the datasets recorded. Similar methods have been successfully used to create leaf layers previously (Hyde, Fletcher *et al*. 2008, Chen, T *et al*. 2018). Five rolling vehicle passes were then used to condition the layer, with no traction or braking (Figure 2(b)).

3.4 Brake tests

During a brake test, the protocol was as follows: the leaf layer was sprayed with water as the vehicle approached the test area; the driver then accelerated the vehicle to 16 km/h, prior to entering the braking zone; the driver then applied the brake at a set position in the low-adhesion zone (Figure 3). This generated speed data from the vehicle. After this, an RRV cryogenically cleaned the line. This process was repeated several times to see if an improvement with additional cleaning occurred.

The vehicle had no wheel-slide protection so there was inevitable human error introduced by the driver. This was unavoidable and associated with the initiation and rate of braking. Braking was, however, kept as consistent as possible.

3.5 Cryogenic cleaning

Cryogenic rail-head cleaning was achieved through mounting the dry-ice blasting system on a Unimog RRV. The system consisted of an air compressor, electrical generator and dry-ice dosing rig. The generator and compressor were required for the functioning of the dry-ice dosing rig. The dosing rig allowed controlled addition of dry ice to a pressurised air stream.

The ice−air stream was then carefully positioned via high-pressure tubing so that the exit nozzle was directly in line with the running band (Figure 4).

The RRV performed a track-on manoeuvre initially, taking it from the concrete route access point to the rails. The rail wheels were then lowered and the cryogenic cleaning nozzles were checked to ensure accurate alignment with the rail head running bands. The cryogenic cleaning system was then triggered using the in-cab remote. The system initially vents compressed air before the dry ice is added to the air stream, so the trigger was pressed before entering the low adhesion area. The RRV was then driven between 8−16 km/h along the leaf layer.

4. Results of vehicle deceleration data

The velocity−time relationship of the train car braking on leaf layers before and after cleaning is shown in Figure 5. As shown, cleaning the rail results in an improvement in stopping time of roughly 1 s. This relates to an increased brake performance by 15% when compared to braking on a leaf layer.

In previous trials, it took on average 5 s for the vehicle to brake to a standstill (although weather and time of year can affect this). Weather data from this set of testing was obtained from a local weather station and is given in Table 2.

The cleaning process has shown to be effective here, as the stopping time is less than 5 s after cleaning. This increase is likely caused by the removal of rail-head contaminants by the cryogenic blast stream, confirming that RRV-mounted cryogenic cleaning is effective at improving adhesion levels.

The deceleration data from the braking tests at 16 km/h are shown in Figure 6. The initial pass on the leaf layer (without cleaning) shows a marked effect on vehicle performance. Subsequent passes after cleaning show significantly higher deceleration rates. Comparison to previously collected data shows cryogenic cleaning can also improve deceleration rates compared to those observed on a dry, clean rail head.

The cleaning of the rail head was monitored during testing with visual inspection. In addition, a RRV-mounted camera was able to capture images of the rail head's running band immediately after cleaning (see Figure 7). As shown, the majority of the contamination is removed by a single pass of the cryogenic cleaning system and removal is limited to the running band.

5. Discussion

The results of the field trials indicate that, using leaves, the test method is able to provide low adhesion that effects vehicle performance when braking from 16 km/h. It also confirms that RRV-mounted cryogenic cleaning can remove the leaf layers created for the trials, meaning it should be suitable for removing contaminants found on mainline railways.

5.1 Created leaf-layers as low-adhesion simulants

A consistent low-adhesion situation was achieved throughout the braking distance at 16 km/h. Laboratory values studies show that the coefficient of friction of leaf layers can be between 0.01 and 0.04 (Li, Arias-Cuevas *et al*. 2008). These tests were carried out on a twin-disc tribometer, which is used to model the wheel−rail interface. Sycamore leaves were included in the leaf layer in these trails, which reduces the coefficient from around 0.33 to 0.05. These adhesion levels were maintained until the authors added friction modifiers.

A study into the characteristics of leaf layer contamination was undertaken on a full-scale wheel-on-rail test rig. It was established that the shear strength of the leaf layer was inversely proportional to the moisture level. The thickness of the layer ranged between 10−100 μm (Poole 2007), such that the metal surface roughness of the wheel and rail are not in contact in the presence of a leaf layer (Li, Arias-Cuevas *et al*. 2008).

As shown in Figure 8, the leaf layers rapidly generated black layer, which was found to transfer up to 9 m down the track. This layer was found to be tenaciously bonded to the rail head. Manual removal with a steel paint stripper was unsuccessful. To clean the rail head following the trials, a petrol powered, mechanically driven steel wire brush had to be used. It was clearly seen that this more labour intensive, slower and less effective than cryogenic blasting.

It has also been shown by other researchers on an mini-traction machine tribometer that friction curves for soaked brown leaf samples give a significant reduction in friction, particularly in the low-speed, boundary regime(Lewis, Dwyer-Joyce *et al*. 2012). Leaves exhibit low shear strength, which is suspected to be the source of low friction here.

The cryogenic cleaning process was demonstrated to remove artificially created leaf layers in a private rail track. The cleaning effect was confirmed beneficial as, after the initial cleaning vehicle pass, the deceleration values of the train car were significantly improved. The resulting deceleration values were within the standard deviation of values for clean, dry rail. Furthermore, the subsequent trials on Network Rail track confirmed that the cryogenic cleaning process is capable of removing other contaminants that are known to contribute to low adhesion, such as iron oxides (Krier, Lanigan *et al*. 2020).

Due to the nature of field testing on mainline rail, it is not possible to have advanced knowledge of which contaminants are present. Initially, optical inspection helps to identify some contaminants (e.g. black layer, sand) but they are not fully characterised until they have been taken to a laboratory for analysis. X-ray photon spectroscopy data from testing with Network Rail on certain lines shows the presence of silicon, which is a component of sand used in traction gels.

In addition, it was found that after cleaning, a post-test swab did not return an atomic percentage concentration for iron. Before cleaning, iron was detectable in the running band. The sampling technique demonstrates these are the more easily removed oxide debris, as opposed to iron still within the bulk steel.

5.2 Factors associated with field trials

Due to the nature of field testing, some factors were outside laboratory type, high-level control. For example, the brake applications could not be automated, so the data relied on the behaviour of individual drivers and their reactions to the braking events.

In addition, the effect of train passage and rail-head heating influenced the data to a certain degree. This was somewhat difficult to account for, as the leaf layers acted as a natural insulator and alter the thermal activity at the interface. For the leaf layers, thermal effects could be involved in the formation of a black layer.

Furthermore, the train wheels were not cleaned between runs. The action of the brake block on the running surface appeared effectively to control the wheel surface, removing contamination that could accrue between braking events.

Finally, accurately controlling the speed of the cleaning vehicle was difficult at low speeds. Road–rail vehicles typically operate at 16 km/h due to mainline restrictions, but the drivers hired in for these trials could have found it difficult to control the speed to a steady 16 km/h. As such, some of the cleaning passes may have taken place at a slower pace, resulting in a longer contact time of the dry-ice blast with the rail head.

6. Conclusions

Data from train brake testing on track with simulated leaf layers before and after cryogenic cleaning confirmed that representative low-adhesion layers created on the rail head were successful in compromising vehicle brake performance. Leaf layers were effectively removed by dry-ice blasting of the rail head, with a specific focus on the running band, and the cleaned running band provided braking comparable to dry uncontaminated conditions. The solution represents a mobile, lower-cost solution to cleaning mainline track which does not currently receive high-pressuring-washing treatment from an RHTT or an MPV.

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Table 1. Class 117 train car details

Parameter	Value
Car length: m	19.51
Width: m	2.82
Height: m	3.87
Tare weight: t	30.25
Bogie load: t	15.13
Axles	4
Brakes	8 x tread braked (2 per wheel)
Maximum speed: km/h	110 (40 on site)

Table 2. Weather station measurements over the test dates

Date	Wind speed: knots	Humidity: %	Temperature: °C	Rain: mm	Dew point: °C
12/02/2019	4	97	10.2	40	6.9
13/02/2019	8	92	11.2	40	6.8

Figure 1. How the cryogenic cleaning process works

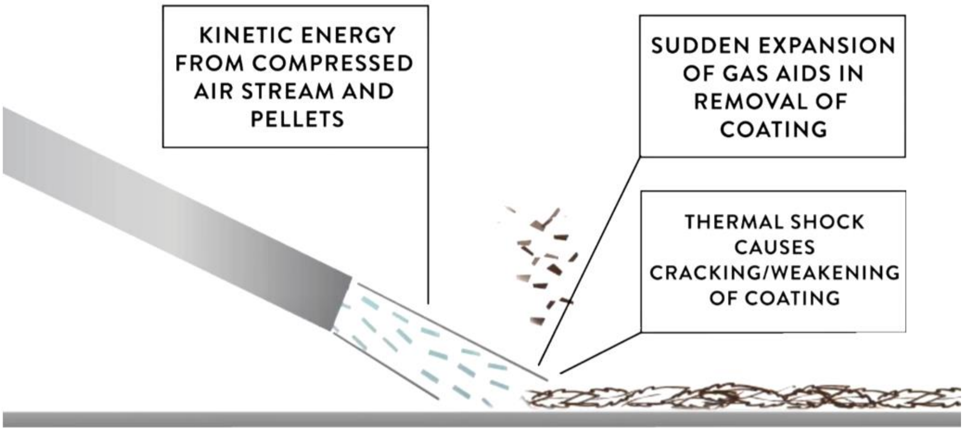

Figure 2. Leaves were fixed to the rails using tape at the sides (a), then compressed using five passes of the train car (b) to create a 3 m long low-adhesion zone (c)

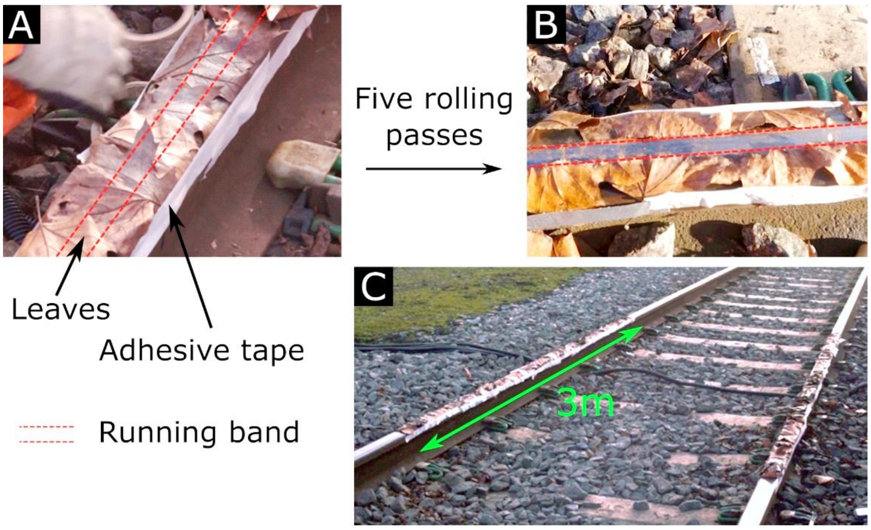

Figure 3. Test set up: the train car started braking to a stop from 16 km/h when its front bogie wheels were in the low-adhesion zone (shown in green)

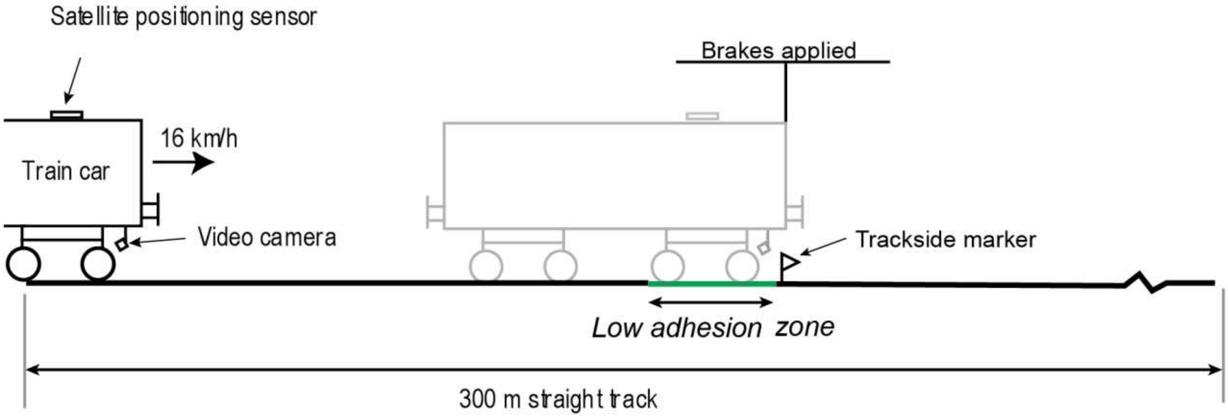

Figure 4. A road–rail vehicle was adapted to carry the cryogenic cleaning kit (a), with cleaning nozzles aligned with running band of the rails (b)

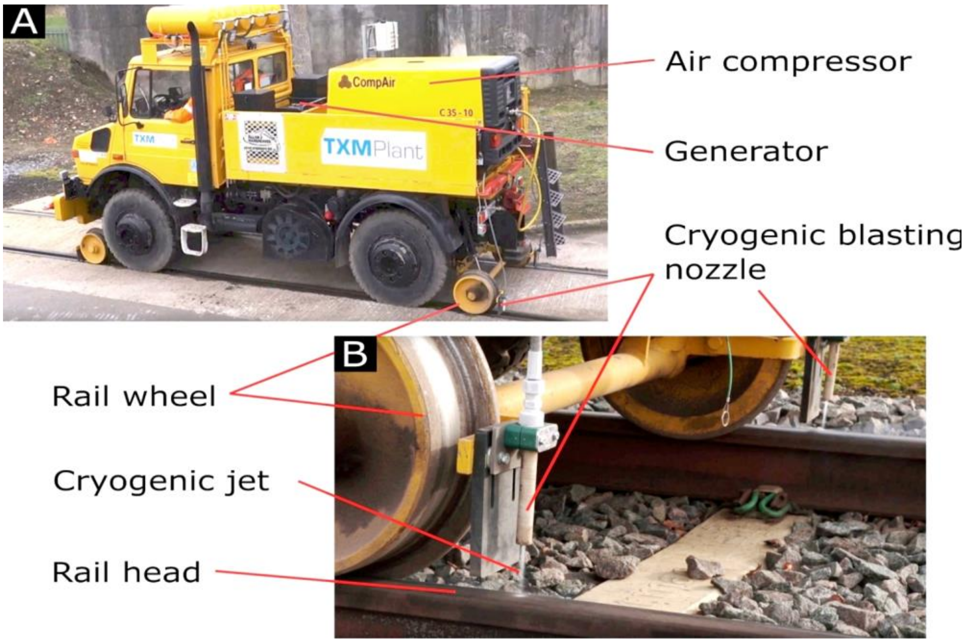

Figure 5. Braking times on leaf layers before and after cryogenic cleaning passes (dashed and dotted lines show repeated tests)

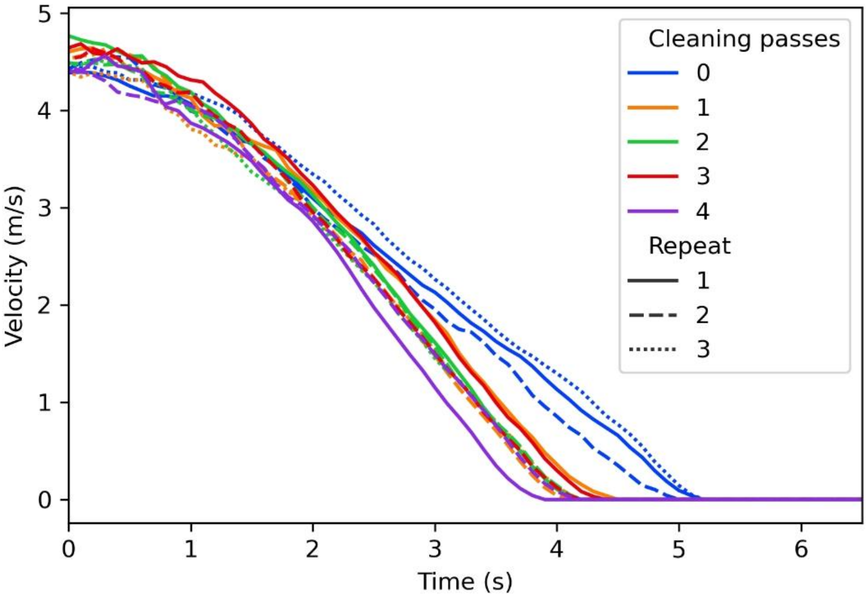

Figure 6. Deceleration rates on leaf layers before and after cryogenic cleaning passes (bars show standard deviations of repeated tests)

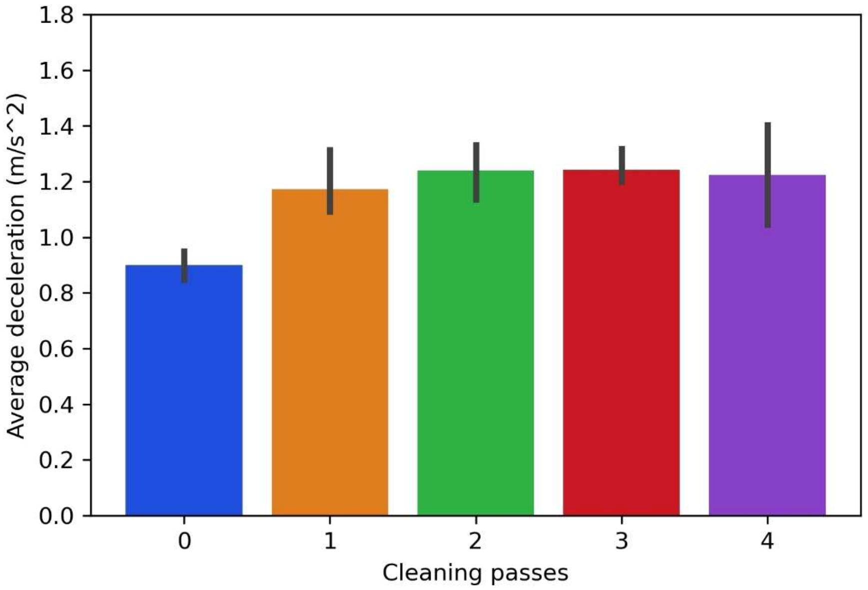

Figure 7. Example of a cryogenically cleaned rail

Figure 8. Attempted physical removal of 'black layer' transferred down to rail head from compressed leaves