Carrydown of liquid friction modifier

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Abstract
A small-scale laboratory apparatus was built to study liquid friction modifier (LFM) behavior in a top-of-rail application. A field experiment was also carried out to complement the laboratory findings. KELTRACK® (a water-based LFM) was used as the test fluid. Laser-induced fluorescence served to measure the LFM thickness left on the track after the passage of the wheel. The lab experiments show that the LFM cannot withstand the high wheel-rail contact pressure in the nip present in cargo rail situations. As a result, the liquid is squeezed out laterally and attaches to the edges of the wheel contact band. This “edge liquid” is then carried down the track on the wheel. Gravimetric measurements of the wheel contact band confirm this observation, and show that only a minute amount of liquid is carried through the nip in the valleys between surface roughness features. In the field experiment, the LFM is applied from a trackside unit on a tangent section of the track. About 500 m downstream of the application point, the track has a curved section. LFM cannot be detected anywhere on the track a short distance (~200 m) past the application unit. However, LFM is detectable on the curved sections of the track up to approximately 2 km from the application unit. This LFM on the curved track is believed to be due to transfer of the “edge liquid” from the wheel to the track, caused by the movement of the contact band as the train rounds a curve. The presence of LFM on the curved track far downstream is consistent with prior measurements of reduced lateral force on the curved track downstream of LFM application sites.

Keywords
Top-of-rail, friction modifier, carrydown distance, thickness measurement, optical technique

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Introduction
Top-of-rail friction control through application of liquid friction modifiers (LFM) is widely implemented in heavy haul freight railways.1,2 LFM changes the coefficient of friction between the wheel and rail to a value less than that of pure metal-to-metal contact, but are still sufficiently high to not compromise traction and braking. This reduced level of friction significantly reduces wear, curve noise, and the lateral force at the wheel-rail interface in a curve.3–8

Harmon and Lewis9 have recently conducted a review of top-of-rail (TOR) friction modifiers. They identify a gap in the literature—the lack of a thorough understanding of carrydown. Carrydown distance is defined as the distance from the application unit to the point where the LFM’s tribological benefits are no longer noticeable. TOR products are usually applied to the track via a trackside application unit. The trackside system is recommended when a long distance of the rail is to be coated with the LFM.9 When the wheel rolls over the LFM pool, the wet film splits between the wheel and the rail, with some remaining on the rail and some depositing on the wheel. The coated wheel then comes into contact with the rail at the next revolution, where the product is intended to be transferred back to the rail. LFM can be water-based, oil-based, or hybrid (mixed). The water phase of LFM has been shown to vaporize quicker than the oil phase in the wheel-rail contact (high-temperature zone),10 changing the carrydown performance.

One device that has been used to study carrydown in a laboratory is the twin-disc machine. The details of this device, along with test protocol and instrument discussion, are outlined in Gutsulyak et al.’s study.11 In this machine, the product is applied to the interface between two counter-rotating metal discs with an applied normal force, and the friction coefficient between the discs is measured as a function of the number of disc rotations. The variation in the friction coefficient (specifically, how long the coefficient remains below that of bare metal-to-metal contact) is then used to identify the carrydown distance. A friction modifying effect has been observed even 1000 rotations after application of the LFM to the twin discs. 1000 rotations approximately correspond to ~3 km travel of the train with minimal slip between wheel and rail (assuming a wheel diameter of 1 m). However, twin disc machines have a dramatically smaller size than a full-scale train wheel. In
addition, LFM on one disc interacts with a surface that has already been in contact with LFM, in contrast with LFM application in the field, for which LFM adhering to the first wheel interacts with the bare metal rail downstream of the application site. Stanlake studied the initial stage of carrydown, in which the wheel rolls over a pool of LFM, using an apparatus that consists of a ramp and a steel roller. The roller is released from a certain height and rolls over a patch of wet friction modifier at the base of the ramp. The mass of the liquid transferred to the roller was measured, and it was shown that a small change in the product formulation could lead to a drastic change in the amount of film transferred during film splitting.

Carrydown has also been studied in the field. Chiddick et al. showed that the lateral force on the rail is reduced by 35% (with a decrease in wear and rolling contact fatigue) almost two miles downstream of a trackside LFM-dispensing unit. Other researchers questioned the accuracy of those handheld tribometer measurements as the friction level is also a strong function of the weather conditions and rail contamination. Khan et al. directly studied LFM coverage on the wheel and the rail. They used cotton swabs to collect samples from the wheel and the rail surfaces at various distances downstream. The samples were subsequently analyzed using the energy dispersive X-ray (EDX) method, searching for LFM elements such as molybdenum (Mo) and magnesium (Mg). Those researchers were unable to detect LFM on the rail more than ~100 m from the application site. In addition, they showed that the product could not support the high contact pressure at the wheel-rail interface and that it was pressed out of the contact band, limiting the carrydown distance. In an experimental trial, Eadie et al. showed there is an optimal amount for the LFM pool, beyond which increasing the initial pool volume barely changes the carrydown distance.

Although these studies give insight into some aspects of carrydown, other aspects of carrydown are not fully understood. For instance, we do not have a complete understanding of the mechanism by which the LFM functions at the wheel-rail interface and transfers down the track. The impact of the LFM rheological properties on carrydown is another open question that requires further attention. This information is particularly important for LFM manufacturers. Additional information is also needed to optimize the unit spacing and the application rate of the wayside systems. Motivated by these gaps in the literature, this research aims to enhance our understanding of the carrydown mechanism. The research comprises two parts: laboratory studies on a novel apparatus that mimics key aspects of realistic rail conditions, and field trials on an operating track. In the Methodology section, we describe the methodology for both types of experiments, and in the Results and Discussion section, we present the results and draw parallels between the laboratory studies and the field trials. Finally, in the Conclusions section we summarize the key findings and make recommendations for future work.

Methodology

Lab experiments

A custom rig (Figure 1) was developed at the laboratory scale to understand the LFM behavior at the wheel-rail interface and the mechanism for subsequent carrydown. The apparatus was not intended to accurately mimic all aspects of the full-scale wheel-rail contact, but rather represents a simplified geometry that is governed by the same physics. It consists of a highly modified woodworking band saw, chosen because the band saw provides a long and continuous moving surface. The original band saw was modified to incorporate various wheels, motors, pneumatic air cylinders, and sensors to model the wheel-rail contact and collect experimental data. The band saw blade represents the top surface of the rail. The blade is made of carbon steel and is 0.9 mm thick. To reduce the light reflection from the surface of the band saw blade (which is a requirement for the film thickness measurement technique, described next), the blade was chemically treated with black oxide.

The treated blade has an RMS roughness of ~850 nm (measured with an optical profilometer), close to the railhead’s typical roughness of 1 μm. The wheel design was based on the work conducted by Naemi et al., where they showed that a 1/5-scale train wheel under scaled loading could produce a contact pressure comparable to that at the wheel-rail interface. The wheel diameter is 0.2 m (roughly 1/5 of the actual wheel diameter). The wheel was driven by a separate motor than the blade to allow for independent speed control over the blade and the wheel, although in the tests described here the two surface speeds are the same (i.e., there is no creepage). Two magnetic Hall effect sensors were used to measure the speed of the blade and the wheel. A normal force was applied to the wheel by means of pneumatic air cylinders that are controlled by fast-acting solenoid valves. A backing wheel, which spins freely on its axle, was mounted opposite the driven wheel behind the blade, and was present to prevent deflection of the blade under the applied normal load. Both wheels were mounted on a linear rail guide to ensure smooth and accurate activation. A 12-kN load cell measured the normal force at the wheel-rail contact patch. The load cell measures the load on the wheel, and using Hertzian contact theory, the contact pressure at the wheel-rail contact is approximated, given Young’s modulus and Poisson’s ratio for mild steel ($E = 207 \text{ GPa}$ and $\nu = 0.3$). For the cylindrical wheel, the apparatus can generate wheel-rail contact pressures of up to ~1 GPa (based on the Hertzian contact model for a cylinder on a substrate), although the current load cell limits the measurements to ~0.7 GPa. For comparison, on a commercial wheel with a radius of approximately 400 mm, a load of approximately 40 kN is required to generate a ~1-GPa contact pressure, depending on the exact wheel-rail contact geometry.

The wheel and rail geometries do not match the commercial geometries in some regards. The blade was flat, unlike the crowned cross-section of a railhead. Three wheels, which approximate railroad wheels, were fabricated from mild steel (grade AISI 1018 with surface hardness of Rockwell B). One wheel has no crowning (i.e., it is a simple cylinder), one has a constant crowning radius of $R_c = 200 \text{ mm}$, and one has a constant crowning radius of $R_c = 400 \text{ mm}$. These values of crowning radius are comparable to what has been measured in the field. The cylindrical wheel has the width $W = 10 \text{ mm}$ (to approximately
match the width of the train wheel running band) and the crowned wheels have the width $W = 20$ mm.

Water-based KELTRACK is the test fluid. It is a non-Newtonian fluid exhibiting shear thinning and elastic behavior with the measured viscosity of $\mu = 5.1 \text{ Pa} \cdot \text{s}$ at a shear rate $\dot{\gamma} = 100 \frac{1}{\text{s}}$. At the start of an experiment, a pool of KELTRACK with a known thickness and length (comparable to those used in practice) was applied to the blade. Then, the operating pressure and the speeds of the wheel and blade were set. Once a photo diode sensor detected a marker on the blade, the pneumatic cylinders were activated, driving the wheel into contact with the blade upstream of the pool of liquid. The wheel then rolls over the liquid pool, and picks up some of the liquid as it passes. One circumference downstream from the original pool, the liquid adhering to the wheel passes into the nip between the wheel and the blade, and the process repeats. The large length of the blade allowed six wheel-rail interactions before the wheel again approaches the initial pool location. Once the experiment was complete, the residual fluid thickness on the blade was measured using laser-induced fluorescence (LIF), described below. The wheel and the blade were run at a maximum speed of $\sim 30$ km/h, somewhat lower than typical freight train speeds.

**Carrydown measurements**

The thickness of the LFM layer deposited on the blade after the passage of the wheel, which is indicative of the amount of carrydown, is on the order of 100 $\mu$m or less. To measure the spatial distribution of the carrydown with sufficient resolution, trace amounts of a fluorescent dye (Rhodamine-B) were added to the LFM. Several rheological experiments confirmed that the minute amount of dye (0.04% by mass) does not change the rheological properties of the LFM. Laser-induced fluorescence (LIF) of the dyed liquid was then used to infer the carrydown thickness. The optical setup is shown in Figure 4(a). The light from a 1000-mW diode-pumped solid-state green laser (532 nm) was spatially expanded before passing it through an optical filter cube (Nikon 67007 gold-spectrum filter cube set, dichroic filter cut-off: 552 nm, excitation range: 530–554 nm, emission range: 570–613 nm). The light was then directed onto the liquid, causing fluorescence of the Rhodamine-B dye. The light emitted by the dye that passes back through the filter cube was collected by an intensified CCD camera (FLIR Blackfly S3 camera). A two-dimensional map of the film thicknesses was generated based on this fluorescence signal.

The LIF signal must first be calibrated against a standard. Shadowgraphy measurements of droplets of various sizes were chosen as the standard. The LIF signal is linearly ($R^2 = 0.998$) proportional to the film thickness for thicknesses below 200 $\mu$m, but at larger film thicknesses, the signal asymptotically approaches a maximum. The typical error and smallest thickness measurable using the LIF setup is 3.4 $\mu$m, although thinner layers can be measured if the dye concentration is increased.

**Field experiments**

Field experiments were performed on a track located in Delta, BC, Canada. The track was limited to freight and maintenance trains. A wayside unit (Figure 2) was installed on a tangent track located about 500 m upstream of the curved track. An applicator bar (visible in Figure 2(b) and (c)) was used to distribute the LFM on the railhead. The wayside unit was equipped with a magnetic sensor to detect train wheels. The sensor counted the number of passing axles, and for every seven axles, the unit pumped 2.8 mL of LFM onto the track, consistent with the supplier’s...
Experiments were conducted in two trials. In the first trial, Phase I, the westbound traffic (tangent track) was studied up to 150 m downstream from the application site under two conditions. In one condition, the application of dyed LFM coincided with the start of the trial. In other words, a single train with 628 axles carried the product downstream prior to measurement of carrydown. In a second condition, the track was pre-conditioned with LFM for several days before measurements of LFM on the track. During the conditioning period, approximately 33,000 train axles passed over the LFM pool. During this period, the application unit was in operation, so about 13 L of LFM were applied to the track during conditioning. In the second trial, Phase II, the eastbound traffic (both tangent and curved tracks) was studied up to almost 2 km from the application site when the track was pre-conditioned with approximately 40,000 axles. A handheld portable tribometer (Salient Systems) was used to measure the coefficient of friction along the track. We only investigated the carrydown at different distances downstream of the application unit.

Imaging of the LFM on the tracks after the passage of the train was done using a portable version of the experimental LIF apparatus used in the laboratory. The portable setup (Figure 4(b) and (c)) was clamped to the rail and imaged the track at different distances downstream of the application unit. Since no electricity was available on site, two car batteries, coupled with an inverter, were used to power the laser, camera, and computer. For the LIF setup to work properly, one needs to eliminate the ambient light, as it would otherwise interfere with the collected LIF signal. Accordingly, the whole optical setup was fully enclosed and covered by a dark cloth.

**Results and discussion**

**Lab experiments**

First, we present results for the cylindrical wheel. Henceforth, we refer to the location where the wheel rolls over the original LFM pool as Interaction One. Interactions Two to Five may show carrydown from LFM that adhered to the wheel during Interaction One. Throughout this paper, the Hertzian contact model is used to estimate the wheel-rail contact pressures. For a very lightly loaded wheel, with a Hertzian contact pressure $p = 46$ MPa (which is unrealistically low even for an empty freight car), the LFM forms a lubrication film under the wheel. The resulting film thickness contours are plotted in Figure 5(a), showing the deposited LFM on the rail after the passage of the wheel for initial contact (left panel) and subsequent carrydown (right four panels). In the left panel, the initial pool depth, 500 μm, far exceeds the saturation level of the LIF detection system, and hence, the entire pool outside the contact band is shown with a depth of 100 μm. For lightly loaded wheels, the hydrodynamic pressure generated within the fluid is sufficient to balance the applied load. The lubrication film carries down the track for the subsequent wheel-rail interactions (shown as Interactions Two to Five). The dynamics governing the lubrication film formation (which only occurs at comparatively low contact pressures) are quite different from those of the LFM interaction for a heavily loaded train, and are explored in detail in Rahmani et al. The figure 5(b) shows similar contours but for test conditions comparable to those in the real application. In the contact band, it is evident that the maximum thickness of the LFM layer is less than the 3.4-μm detection limit of the LIF system. The vast majority of the LFM, originally located in the contact band, cannot withstand the high contact pressure and is squeezed out of the nip laterally, where some of it adheres to the edges of the wheel. It is also apparent that some LFM is plowed ahead of the wheel as the wheel rolls over the pool, resulting in the two thin wedges of LFM (labeled as “Edge liquid”) extending downstream from the original pool. This edge liquid, in addition to the edge liquid picked up by the wheel as it passes through the original length of the pool, is carried forward on the rotating wheel, and some of it redeposits on the blade during subsequent interactions (apparent as two distinctive stripes on either side of the running band in Figure 5(b) right panels). The carried-down liquid reduces in depth with each interaction, weakening the observed pattern.

We posit that a minuscule amount of LFM passes through the nip in the valleys between surface roughness features (the rail surface has an RMS roughness of ~850 nanometers). This scale is certainly below the detection limit of the LIF measurement technique. To test this hypothesis, gravimetric measurements were performed. Aluminum strips were attached to the wheel and the blade,
and the samples were collected before and after each wheel-rail interaction. Subsequently, the samples were weighed carefully using an accurate analytical balance. An analytical balance with a readability of 0.01 mg was used for these measurements. These measurements were very sensitive, and special precautions were taken for accurate sample weighing. The samples were never touched with bare hands, and a pair of clean forceps was used to handle the samples. The balance was positioned on a horizontal surface, and the weighing chamber was in place to prevent the extremely small samples from being affected by air currents. The balance must be in a vibration-free environment.

In addition, several experiments (with no product applied) confirmed that the weight of the bare strip is unaffected by the passage of the wheel (i.e., possible wear) and the adhesive used to hold the strip in place.

For Interaction Two, the gravimetric measurements consistently showed an increase in the strip mass of $0.29 \pm 0.04$ mg for both wheel and rail. The equivalent film thickness, which we are confident is not in the form of a continuous film, is on the order of $\sim 520$ nanometers. Therefore, the gravimetric measurements confirm a minuscule amount of LFM is present on the contact band that cannot be otherwise detected by the LIF setup. Eadie et al.\textsuperscript{18} showed that the lateral force on the curved track 2 miles ($\sim 3.2$ km) from the dispensing unit is reduced by up to 37% using the same product, thus providing evidence that this minute amount of product (below the detection limit of LIF, i.e., $< 3 \mu m$) can still appreciably reduce friction. To further support this claim, we have conducted a separate experiment at LB Foster Rail Technologies using the twin-disc apparatus, and the results are provided in Figure 6. As apparent from this figure, the friction was consistently lower than that of bare metal-to-metal contact up to 1000 disc rotations after application of LFM. However, the fluorescence signals were not detectable after approximately 100 rotations.

Figure 7 shows the track left by the passage through the LFM pool of crowned wheels of width 20 mm. In (a) and (b), we show the results for the crowned wheel with $R_c = 200 \text{ mm}$, and in (c) and (d), we show the results for the wheel with $R_c = 400 \text{ mm}$. These values of $R_c$ correspond

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Figure 3. A top view of the studied track showing the location of the application unit, different phases of the trial, the relevant distances, and the observation regions. The shallow curve starts at about 450 m from the application site and the sharp curve extends to about 2 km downstream. Image source: google earth, 33MF+V7 Delta, British Columbia (49°05'05.0"N 122°55'36.5"W) [June 18, 2021].

Figure 4. (a) Schematic of the LIF setup used to measure the thickness of the carrydown LFM. (b) and (c) The portable LIF setup built to measure the LFM thickness on the rail.
respectively to gap size increase of 250 μm and 125 μm from the wheel centerline to the outside edge. Similar to the case of the heavily loaded flat wheel (Figure 5(b)), the images show that there exists a contact band (with a width of ∼4 mm) with dry contact between the wheel and blade for both crowned wheels. The experiments were repeated for different test conditions over a wide range of speeds (14.4 to 28.8 km/hr) and loads-per-width (9.2 to 450 kN/m), but in no case was a continuous film of LFM detectable across the entire wheel width. This contrasts with the case of uncambered wheels, for which wheel “liftoff” was observed at low loads (Figure 5(a)).

The lateral distribution of LFM film thickness is plotted for various speeds and loading cases in Figures 7(b) and (d). In these plots, film thicknesses are averaged in two steps. First, thicknesses are averaged in the direction of wheel motion. The resulting thicknesses are then additionally averaged over stripes symmetrically located on either side of the wheel centerline; therefore, the abscissa goes from z = 0 (wheel centerline) to z = 1 cm (wheel edge) for these wheels of width W = 2 cm. There is good agreement between the deposited film thickness and the dash-dot line representing half the gap size, which implies that the liquid filling the gap between the wheel and blade splits approximately 50:50.

Within a distance of 2 mm on either side of the wheel centerline, no LFM was detected. We conducted experiments with a higher tracer dye concentration (Figure 7(b) inset) to explore this region. The higher concentration...
improved the detection limit to 1.3 µm, allowing for thinner films to be detected. The measurements from higher dye concentrations were identical to those obtained from lower dye concentrations, but permitted us to detect the thin films present close to the wheel centerline. To confirm the presence of LFM even closer to the wheel centerline, narrow aluminum strips (70 x 2 mm) were adhered to the wheel centerline. The strips were weighed with a precision balance before and after the wheel-rail interaction. The measurements revealed that similar to the heavily loaded flat wheel, there is a 0.16 ± 0.05 mg increase, on average, in the mass of the aluminum strips, corresponding to an average film thickness of 800 nanometers (comparable to the blade surface roughness).

We could detect no carrydown from the crowned wheels, even with the high dye concentration. We posit that since the film splits evenly between the wheel and blade, the LFM adhering to the wheel is insufficiently thick to bridge the gap to the blade, and hence, there is no transfer back to the blade.

**Field experiments**

**Phase I.** In Phase I, the tangent track was studied up to 150 m from the application site to the west. Figure 8 displays coated rail images at various distances down the track. In this figure, the rail was pre-conditioned with approximately 33,000 axles. Similar images of the rail were also observed after passage of the first train with no pre-conditioning (not shown here, but film thickness data are plotted in Figure 9). It is clear that in most of the contact bands, the thickness of LFM is below the detection threshold of the experimental technique (about 3 µm). Within the contact band, the product is mostly visible in the grooves and cavities of the surface. We see a repeating pattern in all images: a minute amount of LFM on the contact band but significant carrydown of fluids from the edge of the contact band. We hypothesize that this carrydown on the (crowned) train wheels is due to modest changes in the location of the contact band, for example, due to lateral motion of the train or due to the variable geometry of different wheels.

Figure 9 presents the average measured film thickness as a function of the distance from the application unit for both single train passage and pre-conditioned rails. With the measurement system, it is possible to differentiate the LFM on the contact band from other parts of the railhead. Averaged over the entire top of the rail (Figure 9(a)), the LFM is present over the entire scanning distance (∼150 m, corresponding to the 47th wheel-rail interaction, assuming that the wheel diameter is 1 m). However, according to Figure 9(b), on the contact band, the carrydown distance is limited to approximately 100 m. When the rail is
pre-conditioned, the FM is often detected for slightly longer distances, which is intuitive. The magnitude of the film thickness and the approximate way in which it varies with distance from the application unit are consistent with the findings of Khan et al., who reported the deposited film thickness on the wheel contact band. However, it is unclear whether those authors studied the carrydown on a previously clean rail or a pre-conditioned rail. When interpreting these results, the detection limit of the measurement technique must be considered. For instance, after ∼150 m on the track, an undetectable fluorescence signal does not necessarily mean the complete absence of the LFM. As discussed above, the product may be present on the track if the thicknesses are below the detection limit.

**Phase II.** In this phase, the tangent and curved tracks were studied up to 2 km eastbound from the TOR application unit. The tangent track extends from the application unit to ∼450 m downstream, followed by two curved tracks extending to approximately 2 km downstream. For all tests, the rail was pre-conditioned with approximately 40,000 axles. Similar to Phase I, LFM was detected on the rail up to about 200 m from the TOR application unit. After that, no product was detectable on the rail until the end of the tangent section. Upon entering the curved section of the track, the LFM can again be measured on the railhead, which was a surprising finding. Some sample images of the LFM detected on the curved tracks are shown in Figure 10, and the LFM thicknesses are plotted in Figure 11. Although the average thickness of the LFM present on the curve is typically less than 15 μm, it is perhaps sufficient to reduce the lateral friction and wear, as claimed by the manufacturer of the LFM used in these trials. There is also some product on the wheel (not considered in this study), contributing to lower lateral forces and wear. Coefficients of friction (CoF) were also measured immediately downstream of the TOR application unit, and are plotted on the secondary axis in Figure 11. The trend in CoF is consistent with the measured thicknesses; it rises as film thickness decreases.
The surprising finding of LFM on the railhead on the curved track more than a kilometer downstream of where it was last observed on the tangent track requires an explanation. We hypothesize that as each wheel passes through the LFM pool at the application site, LFM is pressed out of the running band and adheres to the wheel adjacent to the running band. As the bogie hunts or sways on the tangent track, small excursions of the location of the running band on the wheel deposit the LFM onto the rail immediately adjacent to the running band. However, after a few hundred meters of motion, all the LFM near the nominal running band that can be transferred to the track has transferred, and none remains on the wheel at the edges of its tangent running band. However, when the bogie rounds a curve, centrifugal forces combined with wheel conicity substantially change the running band location, bringing fresh LFM into contact with the track, where it is deposited. This hypothesis is consistent with the experiments of Khan et al., who showed that LFM stays on the wheel for a distance longer than 3 km.

Conclusions

Laboratory and field experiments were carried out to study water-based TOR-LFM (KELTRACK) behavior at the wheel-rail interface and the associated carrydown. An optical technique, based on the fluorescence of a tracer dye, was used to scan the rail and generate a map of the film thickness. The key findings of this research are as follows:

1. Both laboratory and field experiments clearly show that the LFM cannot withstand the characteristic...
high contact pressure at the wheel-rail interface to form a lubrication layer. Therefore, the LFM is pressed out of the contact band in locations where the wheel and rail are smooth. This liquid adheres to the non-contact surface of the wheel. Careful gravimetric measurements show that unless there are significant surface irregularities, only a minute amount of LFM is carried through the nip. This LFM is believed to be carried in the valleys between surface roughness features.

2. The LIF technique is used throughout this study to detect and measure the deposited liquid on the rail. This technique has a detection limit of about 2.5 μm and has the advantage of providing the spatial distribution of the product on the track right after the train passage. However, this method is likely not a good choice for very thin LFM deposits (below 1 μm). In that limit, some other measurement choices, such as SEM or AFM (atomic force microscopy), could prove useful, but they require the collection of surface deposits, which is very challenging in the context of an operating track.

3. At a significantly lower contact pressure, the hydrodynamic pressure developed in the fluid is sufficient to balance the wheel load. However, this low-pressure condition is not expected to occur in practice for loaded or even empty freight trains.

4. The LFM adhering to the non-contact surface of the wheel can subsequently be transferred to the track if the location of the contact band on the wheel changes, for example, due to hunting or sway.

5. LFM has been measured on the tangent track for a distance up to ~200 metres from the application unit. On the contact band, however, this distance is limited to ~70 metres. LFM can be detected in track curves up to 2 kilometres from the application unit. The presence of LFM on curved track kilometers from the application unit is thought to be due to the lateral movement of the contact band as each bogie rounds a curve. Whether that small amount of product on the curved track can provide frictional benefits requires further investigation, but prior measurements of significant lateral force reduction 2 miles down from the application unit are an indication that this product transfer could prove useful.

6. It is also important to note that product layers thinner than the detection limit may reduce friction between the wheel and rail, as confirmed by the twin disc experiments. In addition, this study is only limited to rail coverage. Train wheels are capable of carrying products for longer distances.

In future work, it would be interesting to measure the spatial distribution of LFM coverage on the wheel, perhaps using LIF. Performing field experiments for an oil-based FM would aid in understanding the role of liquid evaporation on carrydown. Finally, carrying out additional laboratory experiments with fluids of different properties (e.g., shear thinning and elastic) would elucidate the role of non-Newtonian fluid behavior on carrydown.

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