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LABORATORY TEST RIG TO MEASURE CARRY-DOWN, RETENTIVITY, SPLASH AND PICKUP OF LUBRICANT IN WHEEL-RAIL LUBRICATION SYSTEM

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Abstract. One of the possible lubrication systems in wheel-rail contact is via a trackside applicator which deposits the lubricant (usually grease or friction modifier) on the rail; this lubricant is then carried down along the track by the passage of the wheels. Carry-down, retentivity, pickup, and splash are quantity indicators of lubrication performance, characterized as how efficient the lubrication system could provide lubricant to wheel-rail contact; recent results showed that these indicators could be crucial in achieving lubrication benefits. However, there is no consolidated methodology of simulating nor measuring these indicators, both in laboratory and field environments. Hence, new laboratory equipment is being developed to fill these gaps, consisting of a motorized scaled wheel that rolls over a 4.5 meters rail. The test rig final project, limitations and research opportunities are presented.

Keywords: Carry-down, Retentivity, Splash, Pickup, Wheel-rail

1. INTRODUCTION

One of the possible lubrication systems in wheel-rail contact is via a trackside (or wayside) applicator which is installed on rail and deposits the lubricant (usually grease or friction modifier) on it; this lubricant is then carried down along the track by the passage of the wheels. Figure 1 shows an schematic illustration of the mechanism of lubricant transportation in wheel-rail system when using a trackside applicator. The steps consist in:

- Step I: Lubricant is deposited on rail by applicator;

- Step II: Wheel passes by applicator and pickup lubricant (transfer from rail to wheel);

- Step III: Wheel carries lubricant along the rail ("re-transfer", from wheel back to rail); and

- Step IV: At certain distance (carry-down), no influence of lubricant can be noticed.

Carry-down is defined as the distance, starting from lubricant applicator, in which the effects of lubricant are still present (Harmon and Lewis, 2016). Retentivity (also called lasting effect) is analogous to carry-down, but refers to the number of cycles on same region of material when the effects of lubricant are still present. By these definitions, retentivity is related (and measured) to the wheels, while carry-down is related (and measured) to the rail. Usually both are intended to be as high as possible in order to extend the lubricant benefits in rail.
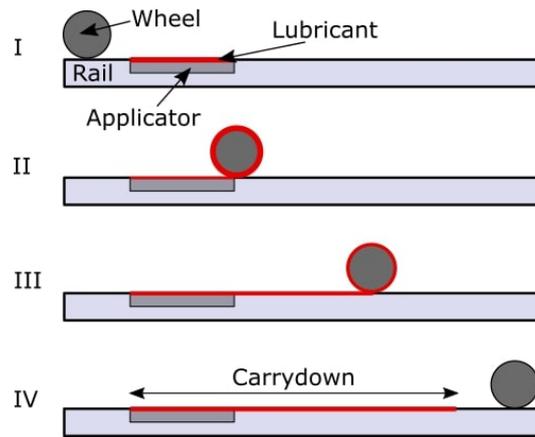
Figure 1. Schematic illustration showing the mechanism of lubricant transportation in wheel-rail system when using a trackside applicator.

The benefits of using lubrication in wheel-rail contact have been extensively studied both in laboratory and field environments. The most relevant benefits are reducing wear, energy consumption and noise (Lundberg *et al.*, 2015), rolling contact fatigue (Lu *et al.*, 2012) and corrugation (Eadie *et al.*, 2008). In 2007, Reddy *et al.* (2007) found that using proper lubrication could reduce total annuity cost per meter for rail maintenance in up to 62 % depending on curve radius.

Canadian Pacific Railway (2006) reported a derailment investigation and concluded that lubricator inspection and maintenance regime, along with the variability of lubricator performance and lack of friction measurement, did not ensure an effective lubrication program, which contributed to crack propagation, rail spalling, and the development of transverse defects, which lead to the rail breaking under the train (initiated from a shell at the lower gauge corner) and derailment.

Ferrer (2020) used pin on disc test rig to compare dry and lubricated contacts with 9 different greases and found that rail lubrication reduced friction and wear up to 10x and 5x, respectively. The performance between the tested lubricants however, were lower than 2x. Therefore, it was concluded that lubricating the rail for longer distances (higher carry-down) with whatever grease is always better than do not lubricate the rail.

Biazon *et al.* (2020) stated there is little information on the relationship between grease formulation, grease properties and field or lab performance either for full or small-scale tests. Also, in respect to friction modifiers, (Harmon and Lewis, 2020) affirmed that there is little published work that analyses how it is picked up from a wayside applicator to the wheel and there is a need for laboratory-based tests that mimic the wheel–rail interaction with a wayside applicator.

According to Biazon (2020), pickup is the mass amount (in absolute or relative terms) of lubricant picked up by the wheel when passing by applicator (step II of Fig. 1). According to the same author, splash refers to the amount of lubricant pushed away from the wheel mainly by centrifugal forces, which leads to various problems including lubricant wastage. Other disadvantages of high splash are: ground contamination (Park *et al.*, 2010), contamination of top of rail (Uddin *et al.*, 2014) and/or commitment of freight system (Lundberg *et al.*, 2015).

The infrastructure maintenance engineers need to establish a maintenance schedule for lubricators to ensure effective, non-excessive and even lubrication (Uddin *et al.*, 2014). Too few lubricant could raise carry-down problems while too much lubricant could raise splash problems. Fig. 2, adapted from Uddin *et al.* (2014), shows a undesired condition of severe waste of grease.

Figure 2. Severe waste of grease in wayside lubricator unit site, adapted from (Uddin *et al.*, 2014).

2. LUBRICATION PERFORMANCE MEASUREMENT

Appropriate performance measures should be implemented to accurately demonstrate the actual performance of the lubrication (Uddin *et al.*, 2014). A short review covering different methodologies for simulating and measuring carry-down, retentivity, pickup and splash, both in laboratory and field environment is presented ahead.

2.1 Current normatives

One specification published by European Committee for Standardization (CEN, 2019) proposed a laboratory methodology to determine the friction levels and the durability of top of rail products under simulated wheel-rail conditions. The justification is that the retentivity of top of rail products under high load and slip is used as an indicator of potential performance in the field, such as relative carry-down distances and required application rates.

In CEN (2019), a twin-disc machine is used with 1% creep, 600 rpm and 1090 MPa contact pressure; the retentivity is considered as the number of cycles before the coefficient of friction raise to the value of 0.4. The limitations of using a twin-disc machine to evaluate lubricant retentivity are further discussed in section 2.3.3

No other standard nor specification was found regarding carry-down, retentivity, pickup and splash in wheel-rail system.

2.2 Field measurements

When using trackside applicators, lubricant performance can vary widely depending on the climate, track characteristics, traffic type, operating patterns, dispensing equipment, type of lubricant, and lubricator maintenance practices (Canadian Pacific Railway, 2006).

The carry-down is generally checked by a finger test at a gauge corner in the curves, being a method of visual inspection of the presence of lubricant in rail. This is not a scientific method and does not provide any indication about the level of friction in the gauge corner area and the influence on rail/ wheel wear (Uddin *et al.*, 2014).

Another method with similar approach as the finger test was developed by Khan *et al.* (2018), which used cotton swabs in a mixture of alcohol and ester-based solvent to obtain the third body samples from different locations on the top of the rail and the running surface of the wheel. The samples were subsequently analysed for elements using an energy dispersive X-ray analyser equipped with a scanning electron microscope. The authors found lubricant-only elements (elements present in lubricant formulation and not on wheel nor rail composition) in cotton swabs up to 3 km from the applicator, indicating that the carry-down was, at least, this distance.

The finger test (Uddin *et al.*, 2014) and the cotton swab test (Khan *et al.*, 2018) are methodologies which use *direct* measurements to investigate carry-down, which means carry-down is evaluated by the presence (or absence) of lubricant at certain distances. Other type of methodologies evaluate the effect, and not the presence, of lubricant at certain distances, so called *indirect* measurement methodologies.

Indirect measurement methodologies involves measuring coefficient of friction with hand-push tribometer (Uddin *et al.*, 2014), lateral force reduction using different methods (Lu *et al.*, 2012) and vibration spectral distributions (Harmon, 2018).

Recent discussions arose about the hypothesis that the presence of lubricant obligatory represents the presence of benefits (and vice-versa) and so the direct and indirect measurements would have same results. Khan *et al.* (2018) determined carry-down as the distance in which lubricant-only elements were found inside the wheel running-band, being the presence of lubricant pressed out of running band due to pressure and splashing non-significant, even being present on rail. According to this hypothesis, the presence of lubricant in specific regions of rail is not sufficient to bring the lubrication benefits, and lubricant carry-down should be evaluated by the lubricant effects (indirect measurement) over the presence itself (direct measurement).

By measuring the advantages of the lubrication, the indirect measurements are more reliable field testing than direct measurements, but other parameters could play important roles in effects and influence the results. Although being more reliable, Uddin *et al.* (2014) pointed that the monitoring of lubrication performance by measurement of coefficients of friction at the wheel/rail interface is not standard practice.

Regarding splash, Uddin *et al.* (2014) also showed a trial-and-error process which consists in qualitatively evaluate the occurrence of splash after a train passage, after each passage a condition of applicator system is altered, as applicator length, lateral distance or height, amount of lubricant pumped and/or number of applicators. The process is slow and qualitative terms as 'little splash' and 'significant splash' are used to rate the different lubricants and operating conditions.

A quantitative protocol of splash measurement in field consists in positioning a blanket underneath the rail and measure the mass of lubricant expelled from the wheel-rail to the blanket (Uddin, 2016). This is also a trial-and-error process, where operators incrementally raise the quantity of lubricant dispensed by applicator until an optimum quantity defined by higher carry-down and lower splash is achieved. Exploratory experiments with grease showed that both carry-down, measured by coefficient of friction reduction at certain distances and splash, measured by grease mass over the blanket,

increases for bigger amounts of grease dispensed; but the process found that carry-down can be improved by increasing dispensed grease amount up to a threshold, in which after that insignificant effect in carry-down is verified, the optimal dispensed grease amount is then assumed as this threshold value.

2.3 Laboratory test rigs

Different laboratory test rigs have been used to evaluate carry-down, retentivity, pickup and splash. Figure 3 shows some possible configurations used in recent studies.

These test rigs are, in general, efficient on ranking lubricants and predict field results in terms of friction, wear and rolling contact fatigue, however, such test rigs have relevant limitations in simulating the wheel-rail lubrication process when trackside applicators are used. These limitations could play important roles on overall results, generating erroneous conclusions about lubricants ranking and field performance prediction due to lack (or absence) of control in some parameters. Hence, the above mentioned rigs are not suitable of measuring retentivity, carry-down, splash and pickup in a reliable way. The limitations and benefits of these test rigs regarding *only lubricant performance* are discussed in more details in the following sections.
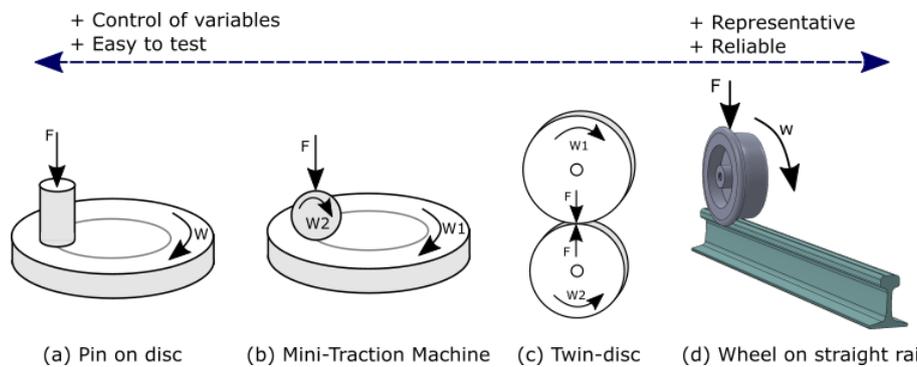

Figure 3. Laboratory test rig configurations currently used for measuring carry-down, retentivity, pickup and/or splash.

2.3.1 Pin on disc for lubricant performance evaluation

The pin on disc test rig configuration consists in a static pin loaded against a rotating disc (Fig. 3 (a)). Theoretically, this is the simplest laboratory test rig, which provides good control of variables at the price of being less representative of field conditions.

Hu *et al.* (2017) developed a model for the prediction of lubricant breakdown and calibrated the results with a pin on disc tribometer. The lubricant breakdown can be analogous to retentivity. The results clearly showed that retentivity increases with viscosity, speed and amount of lubricant, and it decreases with load.

The pin on disc configuration generates a pure sliding motion, this type of motion is representative of the contact between rail gauge face and wheel flange, where grease is usually employed as lubricant. However, on top of rail contact the motion consists in a rolling-sliding movement and friction modifiers are applied as lubricant; in this region, the pin on disc test is non-representative.

Limitations regarding pin on disc test rig on evaluating lubricant performance are: only pure sliding motion, different contact geometry, different body geometry, cyclic load and impossibility to use field lubricant application system.

2.3.2 Mini-traction machine for lubricant performance evaluation

In a mini-traction machine (Fig. 3 (b)), a ball is loaded against a disc and the ball and disc are driven independently to create a mixed rolling/sliding contact condition. The frictional force between the ball and disc is measured by a force transducer.

Even though the mini-traction machine is widely used to understand the influence of various parameters (e.g., creepage level) on friction coefficient, just one study focused on rail lubricant performance was found in the literature. Galas *et al.* (2018) used a mini-traction machine to evaluate the retentivity of top of rail friction modifier lubricants.

Comparing to pin on disc tribometer, the mini-traction machine is more representative of field due to creepage control, but carries within all other limitations presented for pin on disc test rig.

2.3.3 Twin-disc for lubricant performance evaluation

The most used test rig to evaluate retentivity is the twin-disc tribometer (Fig. 3 (c)). Some examples are the works from Li *et al.* (2009), Lewis *et al.* (2014) and Biazon *et al.* (2020).

Although the twin-disc test rig can provide a linear or elliptical contact with controlled creepage, normal force and velocity, the relation between twin-disc results and predicted field results is not robust. Eadie *et al.* (2015) showed the correlation between lab and field data was not straightforward when 11 different greases were compared. Also, one of the greases studied by Biazon *et al.* (2020) achieved retentivity of 31000 cycles, that represents approximately 9 km carry-down distance. Such long distances are never observed in field test.

Twin-disc test rig is not capable of simulating the wheel flange and rail gauge face contact, being an remarkable gap in grease lubricant performance. Besides that, even for top of rail lubricants, the twin-disc rig is not capable of overcoming all other limitations presented above for other test rigs regarding body geometry, such as impossibility of using lubricant application system and cyclic loading.

Figure 4 shows three examples of retentivity curves obtained by: (a) pin on disc (Hu *et al.*, 2017), (b) mini-traction machine (Galas *et al.*, 2016) and (c) twin-disc (Biazon *et al.*, 2020). There is few inter-rig and laboratory-field relation on the results found in literature when these three conventional test rigs are used to evaluate lubricant performance.

(a) Pin on disc
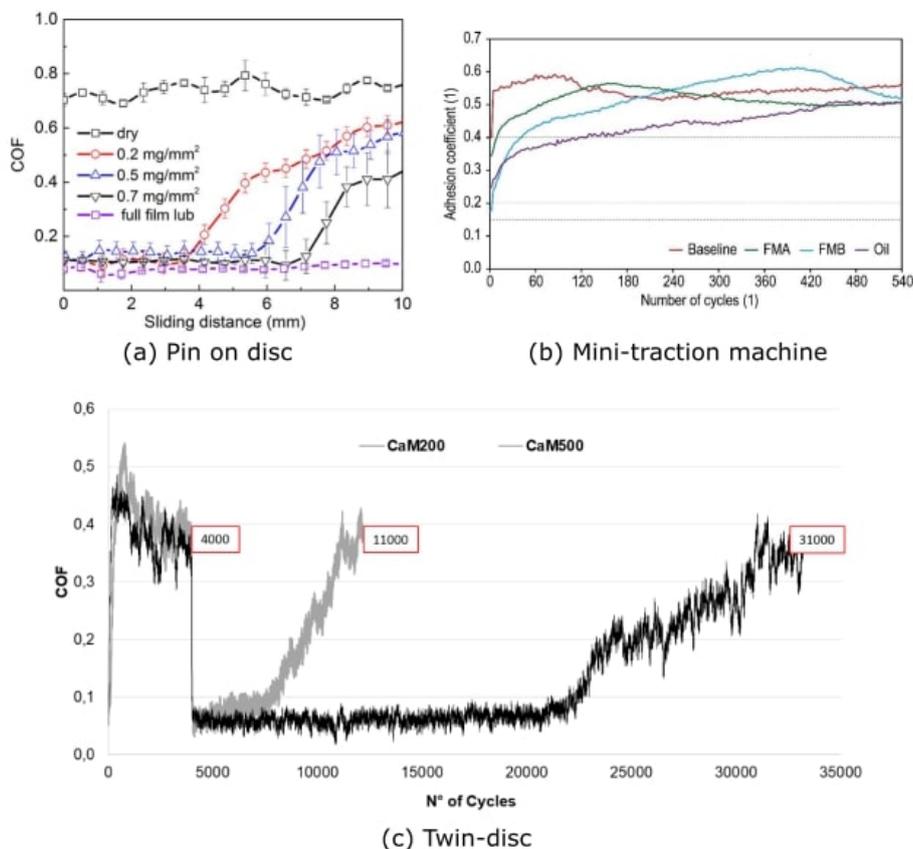
(b) Mini-traction machine

(c) Twin-disc

Figure 4. Examples of retentivity curves for different conditions obtained by: (a) pin on disc (Hu *et al.*, 2017), (b) mini-traction machine (Galas *et al.*, 2016) and (c) twin-disc (Biazon *et al.*, 2020)

2.3.4 Wheel on straight rail

Wheel on straight rail (Fig. 3 (d)) is a test rig configuration in which a wheel is loaded against a section of rail.

Temple *et al.* (2018) investigated the effects of different trackside applicator, and the influence of parameters governing grease pickup, including lateral wheel displacement and pump duration using a scaled-wheel rig (SWR) and validated the results using a full-scale rig (FSR). Both configurations allows experiments using field trackside applicators with as-field body geometries, being more representative of field conditions.

The main limitation of both test rigs is regarding velocities. The SWR has no velocity nor load control, the movement occurs by gravity due to 1:20 inclination of rail and load is the wheel weight itself. FSR is capable of applying high contact pressure, but can achieve a maximum of only 100 mm/s, which is significantly slower than in field operation. The main advantage of SWR over FSR consists in a simpler set-up and the possibility of interaction between the wheel and different applicators to be studied (Harmon, 2018).

2.3.5 Other configurations

Some other laboratory methodologies to simulate wheel-rail contact were developed. Hibbert (2017) used an adapted band saw to evaluate friction modifier retentivity. Naeimi *et al.* (2018) built a scaled wheel on circular rail but did not investigate lubricant performance. Ferrer (2020) investigated the splash of greases by placing a quantified amount of it over a disc and measuring the maximum velocity the disc could rotate without initiating grease flow by centrifugal forces. Harmon *et al.* (2019) developed a grease tackiness test, being related to the required work to break grease strings in a approach-retraction movement. The results of tackiness could be related to friction modifier mass pickup in SWR experiments.

3. MOTIVATION OF TEST RIG DEVELOPMENT

By using laboratory test rigs, some simplifications regarding the wheel-rail contact are inevitably employed.

One first relevant limitation is regarding body geometries. Except for SWR and FSR, other test rigs make use of simplified specimen geometry to facilitate specimen production, which prevents the experiment to evaluate important conditions, e.g., the lateral distance between wheel-flange and rail gauge face. Fig. 5 (Temple *et al.*, 2018) shows that larger lateral displacement (lower wheel flange to rail distances) results in greater picked up mass of grease. It also shows the results are highly dependent on the grease applicator (MC4-GG vs MC4).
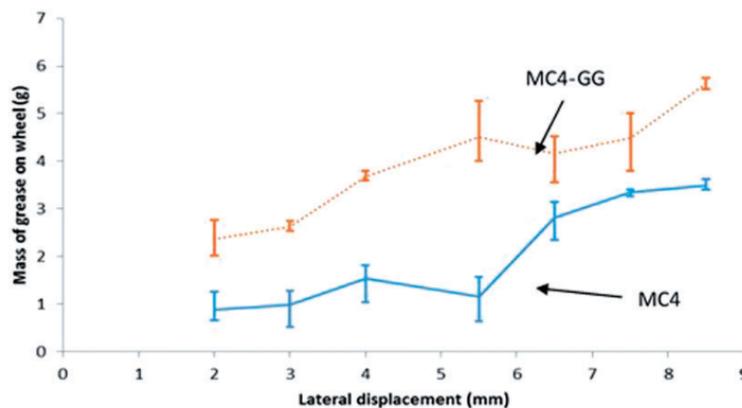

Figure 5. Pickup mass of grease for different lateral distances between wheel and rail (Temple *et al.*, 2018).

The possibility to conduce experiments using a lubricant application system similar to field is crucial on evaluation of lab results. Galas *et al.* (2018) verified that retentivity of friction modifiers increases with increasing amount of lubricant supplied to the contact. Temple *et al.* (2018) verified that bulb (i.e., grease shape when deposited on rail) size and shape have influence on grease pickup; also verified pump duration would affect grease pickup. Temple (2015) and Uddin *et al.* (2014) concluded that different applicators and pump configurations influence drastically the grease pickup.

Due to the presented rig limitations, splash phenomena is still poorly studied. It is suggested that splash is governed by a combination of two phenomena: flow induced by centrifugal force, and flow induced by contact dynamics. The influence of contact parameters and application conditions on both types of flow has not being studied so far and therefore, its impact on field performance is unknown.

Other limitations are regarding the contact area geometry, relative motion of surfaces, magnitude and distribution of stresses. These parameters should alter significantly the lubricant transportation system and flow, being an important test condition when investigating lubricant performance.

Laboratory test rigs usually avails of cyclic loading to fit small rooms. Taking the rail as reference, the lubricant dynamics in field are non-cyclic and the flow of lubricant should behave accordingly. For instance, the process of grease pickup occurs always in a clean wheel; and the process of transfer of lubricant back to the rail occurs always in a 'clean' rail for the first wheel. These limitations are overcome by SWR and FSR, but both these test rigs showed limitations on reproducing the wheel-rail contact and speed.

The SWR doesn't have load nor velocity control, Fasihi *et al.* (2021) obtained different results on retentivity when varying creepage level, Hibbert (2017) found that the contact pressure have an effect on the initial friction modifier pickup. Also, according to Temple (2015), the biggest limitation of SWR is that velocity effects cannot be studied for being too slow, and excess grease can flung from the interaction at high speeds. Additionally, in the SWR is not provided any friction measuring system; being the carry-down and retentivity evaluations made difficult or even unable.

The FSR main limitation is also regarding velocity but additionally the lateral position of the wheel is poorly controlled, hence it can vary from one wheel pass to another (Temple *et al.*, 2018). Also, the experiments are hard to be set-up and, as presented by Harmon and Lewis (2020), some applicators may not fit the rig.

Table 1 shows a summary of new test rig requisites and which of them are achieved by the test rigs present in state of art.

Table 1. Parameters required in lubricant performance test for each state of art test rig

Parameter	Pin on Disc	Mini-traction machine	Twin-disc	Scaled-wheel rig	Full-scale rig
Body geometry				✓	✓
Application system				✓	✓
Non-cyclic load				✓	✓
Load control	✓	✓	✓		✓
Lateral distance control				✓	
High velocity (5 m/s)	✓	✓	✓		
Friction measuring	✓	✓	✓		✓

4. TEST RIG SELECTED CONFIGURATION

The scaled-wheel rig was selected as the constructive configuration to simulate carry-down, retentivity, pickup and splash.

4.1 Test rig overview

The main limitations of the SWR used in the works presented above are: low velocity, no velocity control, low contact pressure, no contact pressure control, no friction measurement. In the present project design, these conditions were overcome by using an electric motor coupled to the wheel, which provides the horizontal motion (along rail); and a linear actuator that moves vertically the wheel in relation to rail (lifting). Figure 6 (a) shows a image of projected test rig. A concrete structure in two levels was built; in the first level (lower), a TR68 rail (as-field) is fixed using screws; in second level (upper), guides are fixed using screws and a car is assembled in such guides. The car has three functions: be the coupling between a scaled wheel (4:1) and the guides; provide linear motion along the guides and provide a lifting system, further discussed in this section. Important to note that the wheel profile is kept the same as the original-sized wheel, the scaling occurs only on the diameters.

The friction between wheel and rail is monitored by the resistance force in electric motor. Despite friction measurements using resistance force are inaccurate in absolute terms, the comparison between the dry and lubricated condition is the only interested effect, so the carry-down and retentivity can be measured.

Figure 6 (b) shows a free body diagram of wheel when moved by force driven by a linear motor (F_{motor}). R stands for wheel radius, m the mass of wheel, F_{ext} a force between wheel and rail applied by external source (e.g., electric actuator), $F_{friction}$ the friction between wheel and rail, F_{rolres} the rolling resistance force and N the reaction force from the rail.
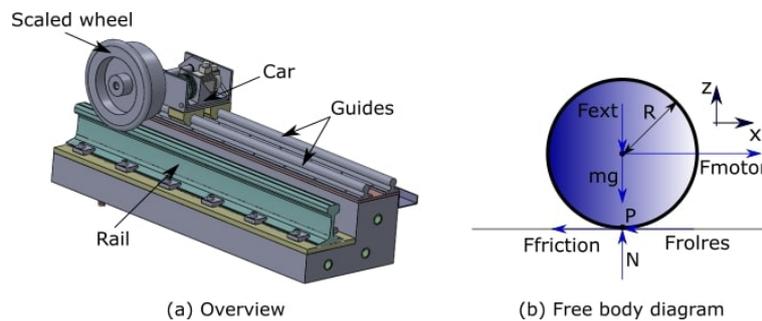

(a) Overview   (b) Free body diagram

Figure 6. Constructive configuration of new test rig.

The project main challenge is to achieve high velocity in a small course length (4.5 m). Heavy haul trains operate in a range of approximately 10 to 30 km/h depending on the sharpness of the curves. Therefore, an average speed was assumed as target velocity of 5 m/s (18km/h).

Considering the total rail length of the proposed test rig is 4.5 meters, the wheel would reach 5 m/s (v) in 2 meters (ΔS) for a linear acceleration (a_c) of 6.25 m/s^2, as shown in Equation 1.

$$v^2 = v_0^2 + 2 * a_c * \Delta S \rightarrow 25 = 4 * a_c \rightarrow a_c = 6.25 \tag{1}$$

Another limiting factor regarding to fast acceleration, besides motor power, is the desired non-slip condition between wheel and top of rail to prevent severe wear. To achieve the non-slip condition, the rolling resistance ($F_{friction}$ and F_{rolres})

must be high. To do not mischaracterize the contact, the coefficient of friction in the wheel-rail interface should not be changed. Therefore, it is needed to estimate the minimum normal force that minimizes the possibility of the occurrence of slip. This calculation is presented in details ahead.

The relation between F_{motor} and the desired linear acceleration a_c, considering I_P as the moment of inertia on point P, is:

$$\sum M_P = I_P * \alpha \rightarrow F_{motor} * R = \frac{3}{2}m * R^2 * \frac{a_c}{R} \rightarrow F_{motor} = \frac{3}{2}m * a_c \tag{2}$$

Being f_{rol} the rolling resistance coefficient, $F_{friction}$ can be computed as, substituting F_{motor} from Eq. 2:

$$\sum F_y = 0 \rightarrow N = F_{ext} + m * g \tag{3}$$

$$\sum F_x = ma_c \rightarrow \underbrace{\frac{3}{2}m * a_c}_{F_{motor}} - \underbrace{f_{rol} * N}_{F_{rolres}} - F_{friction} = m * a_c \rightarrow F_{friction} = \frac{1}{2}m * a_c - f_{rol} * N \tag{4}$$

Finally, it is possible to estimate the minimum normal force to achieve non-slip condition. Considering the coefficient of friction between wheel and rail μ, and a factor of safety FS, substituting $F_{friction}$ from Eq. 4:

$$\frac{\mu * N}{FS} > F_{friction} \rightarrow N > \frac{ma_c}{2 * (\frac{\mu}{FS} + f_{rol})} \tag{5}$$

The wheel is designed to have minimum weight, thus, the inside parts are made in composite and just the surface is machined with material commonly used in wheels, to preserve chemical affinity between lubricant and wheel.

For instance, supposing wheel weight of 5 kg, wheel radius 0.105 m, f_{rol} 0.001, μ 0.1 and FS 1.2, the normal force N should be at least 185 N to avoid slipping between wheel and rail, according to Eqs. 1 to 5.

The lifting system assembled in the car makes use of an actuator to apply the normal force. The system also provides the capability of lifting the wheel to avoid contact on backward movement. This capability is important to simulate the train passage, which is uni-directional and not bi-directional/reciprocating. An illustrative scheme of lifting system is presented in Fig. 7, in such scheme the parts responsible for movement in "x" direction (motor) are not shown.

By controlling the velocity and contact pressure, the developed laboratory test rig is able to simulate the wheel-rail lubricant transportation system in laboratory. The rig project is finished and exploratory tests will be conduced.
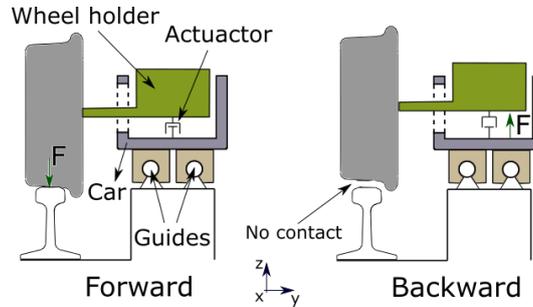

Figure 7. Lifting system on developed test rig.

4.2 Suggested methodologies

To investigate lubricant performance, it is important that the wheel passes on just one direction on rail. One possible methodology consists in repeatedly roll the wheel in one direction and clean the wheel or the rail after each passage. One passage of wheel is presented in Fig. 8, the blue arrows are movement imposed by electric motor and the green arrows by lifting system:

The total carry-down or retentivity would be the course length times the number of passages in which the friction is still above the dry friction threshold (previously measured).

For measuring pickup and splash, lubricant must be collected and weighted for each passage. It is important to store all lubricant parts separately; the lubricant expelled to ground would account for splash, the lubricant cleaned from rail and wheel would account for pickup but the transfer and re-transfer mechanisms can be better investigated with separated weighting (from wheel and from rail).

Such separated weighting may be challenging when working with lubricants with low shear stress, as they behave more as liquids and the flow may continue in a short time after wheel passage, being hard to identify the initial location where the lubricant was expelled.
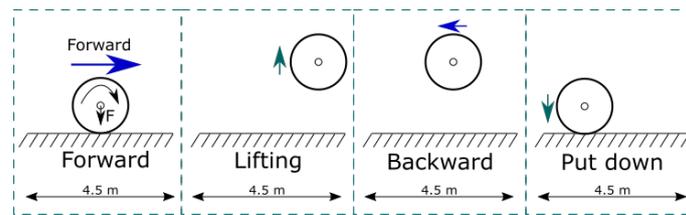
Figure 8. One passage of wheel over rail, the blue arrows are movement imposed by electric motor and the green arrows by lifting system.

To overcome this, other instruments may be used for evaluation the lubricant flow. High speed camera can provide important information on how the lubricant is being expelled. Also, graph papers (or similar) can be placed is various locations (e.g., under the test rig) to evaluate splashing distance more accurately.

5. CONCLUSIONS

A review covering carry-down, retentivity, pickup and splash concepts and test methodologies (both in field and laboratory environments) is presented, some literature gaps were detected and some conclusions are drawn:

- Conventional laboratory test rigs, as consequence of not using as-field trackside lubricant applicators and for lacking in control of fundamental parameters which governs lubrication performance when using trackside applicators, are inefficient to rank lubricants and predict field results in terms of the lubrication process;

- A test rig consisting in a motorized scaled wheel that rolls with contact force and velocity controlled over a 4.5 meters length rail was selected as the best configuration for lubricant performance testing. Caution was taken regarding high acceleration and required contact force to prevent wheel slipping;

- The test rig project is concluded, suggested methodologies and research opportunities are presented, and exploratory experiments must be taken to investigate operability and reproducibility of results.

6. ACKNOWLEDGEMENTS

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