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Simulation of Flange Lubrication for Digital Twin Application

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Abstract

This paper presents a simulation-based investigation of train passages through flange lubrication points positioned before curved track sections, aimed at predicting the evolution of friction conditions in the wheel-rail interface for digital twin application. Flange lubrication is commonly used to reduce wear, noise, and energy consumption in curves, but its effectiveness depends on complex processes including lubricant transfer and gradual consumption. The proposed approach combines simplified modelling of contact forces and creepage with experimentally derived relationships describing lubricant retention, redistribution, and the dependence of friction on lubricant quantity. A numerical algorithm simulates how lubricant applied at discrete locations is carried by successive wheelsets, spread along the track, and depleted by frictional work. The model enables estimation of changes in the coefficient of friction along track. The results demonstrate the capability to capture key trends in lubricant propagation and decay, providing a basis for optimizing lubrication point placement and dosing strategies and supporting future development of predictive maintenance and adhesion management tools. Beyond standalone analysis, the proposed model is formulated with integration into a digital twin of the wheel-rail interface in mind.

Keywords: wheel-rail contact, flange lubrication, friction modelling, digital twin, railway curves, numerical simulation, tribology, adhesion management.

1 Introduction

The interaction between a railway wheel and rail is a highly complex tribological system that plays a decisive role in vehicle safety, energy efficiency, noise emission, and the long-term durability of both infrastructure and rolling stock. In curved track sections in particular, the flange–gauge contact becomes a dominant mechanism governing vehicle guidance and stability. However, this contact is associated with elevated frictional forces, increased wear, and the generation of noise, especially in tight curves and heavily trafficked corridors. To mitigate these effects, railway operators widely employ flange lubrication systems, which apply small quantities of grease at selected points along the track or directly on the wheel. Although such systems are well established in practice, predicting their real effectiveness under operational conditions remains a challenging task.

When a train passes a lubrication point before a curve, lubricant is transferred to the wheel flange, redistributed in the flange–rail contact, and gradually consumed by friction during successive passages, causing friction conditions to evolve along the track. The local coefficient of friction depends on the applied amount of lubricant as well as contact forces, creepage, speed, and traffic history. Optimizing lubrication is therefore essential, as excessive amounts may reduce adhesion and increase maintenance demands, while insufficient lubrication leads to higher wear, noise, and energy consumption. Reliable models are needed to predict lubricant retention, spread, and depletion under repeated train operation.

This behaviour is strongly transient and has not been fully studied [1], which is why it holds a strong potential for development of future smart lubrication systems. Experimental research on flange lubricants [2, 3] has provided valuable insight into the tribological properties of flange lubricants, including their retentivity, friction-reducing capability, and sensitivity to load, speed, and slip. These laboratory studies on scaled contacts have enabled the identification of relationships between lubricant quantity and friction coefficient, as well as estimates of how quickly lubricant is depleted under given contact conditions. However, transferring these findings to real railway operation is not straightforward. Unlike laboratory tests, where the same contact area is repeatedly loaded, the wheel–rail interface in actual service is an open system. Lubricant is transported over long distances, exchanged between wheel and rail, and gradually redistributed across the track. This creates spatially varying lubrication patterns that cannot be captured by purely local measurements.

Experimental studies [4, 5] focused on redistribution of top of rail lubricant along a track using different methodologies. The results clearly show that the lubricant quantity decreases exponentially from the point of application. Experimental and numerical study [6] used parametrized results of twin disc testing to predict the evolution of coefficient of friction for top of rail lubricant on a simulated rail. Only after few hundred meters, the simulation shows a drop in the amount of lubricant on the rail considering 100 passes each with lubrication application. Simulation therefore represents a powerful tool for bridging the gap between laboratory experiments and field behaviour. By combining experimental knowledge with vehicle–track interaction models, it becomes possible to estimate how lubrication applied at discrete points influences friction conditions along extended track sections

This study presents a simulation-based framework for analysing train passages over lubrication points placed before curved track sections to predict how flange lubricant is distributed and consumed over time. Combining simplified modelling of wheel–rail contact forces and creepage with experimentally derived relationships for lubricant retention and friction behaviour, the model predicts lubricant transfer between wheel and rail during repeated train passing to describe the evolution of lubrication amount and coefficient of friction. By providing a computationally efficient representation of lubrication dynamics and friction evolution, the model forms a basis for data-informed and adaptive control of flange lubrication systems. This creates a pathway toward intelligent lubrication strategies that adjust dosing and placement in response to traffic conditions, track geometry, and predicted friction states, supporting reduced wear, noise, and maintenance demands in railway operation.

2 Methods

The proposed methodology combines experimental characterization of flange lubrication behaviour with a numerical simulation framework describing the passage of railway vehicles through lubricated track sections. The approach is designed to predict the evolution of lubricant quantity and friction conditions in the wheel–rail flange contact during repeated train passages. The integration of the model into the overall framework of digital twin is shown in Figure 1.

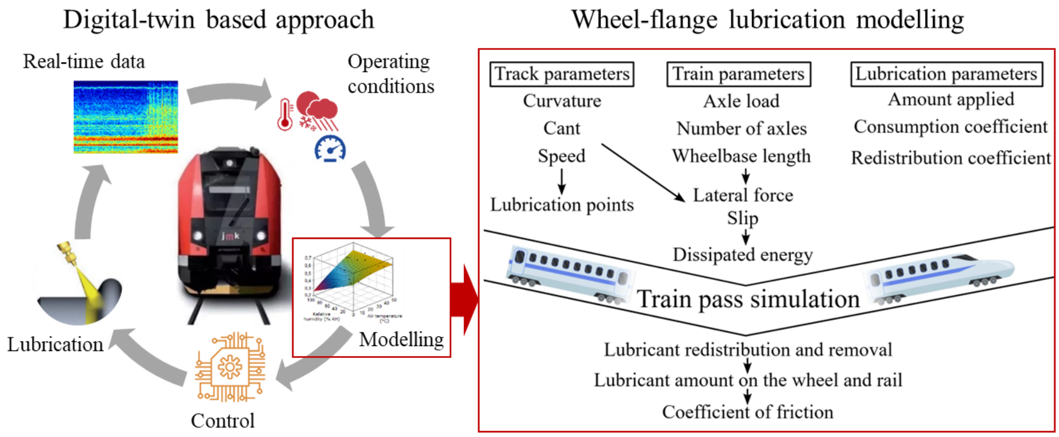

Figure 1: Overview of digital twin concept.

The main simulation of wheel-flange lubrication is performed separately for the left and right rails, while the computational procedure remains identical in both cases, differing only in the positions of the lubrication points. At the start of the simulation, the lubricant quantities on both the wheel and the rail are initialized to zero. The passage of a vehicle is then modelled by sequentially tracking the wheels that participate in flange contact along a discretized representation of the track.

Each wheel advances step by step along the track. When a wheel reaches a predefined lubrication point, a prescribed amount of lubricant is applied to the wheel flange. If lubricant is present on either the wheel or the rail at a given track segment, the total amount is redistributed between the two bodies according to the adopted redistribution model. Based on the resulting lubricant quantity in the contact, the local coefficient of friction is updated. The frictional energy generated in the contact is subsequently calculated using the current friction coefficient and precomputed contact conditions, and the corresponding lubricant consumption is determined using an energy-based approach. After consumption, the remaining lubricant is again divided between the wheel and the rail, with the wheel portion transported to the next step of track segment and the rail portion stored locally to affect only subsequent wheel passages.

The foundation of the model is formed by experimental investigations of flange lubricant properties [3] carried out on laboratory tribological test rig Mini Traction Machine. These experiments were used to quantify the retentivity of flange lubricant and assess the relationship between energy input into the system and the amount of lubricant removed. The value describing how much lubricant is removed per Joule of energy is 0.003 mg/J. Transferring from amount of lubricant to coefficient of friction was done by parametrization of experimental result from high pressure torsion tests [7]. The measured data were fitted using an exponential function as described by Equation (1), providing a continuous mapping between local lubricant amount and friction coefficient. This relationship enables dynamic updating of friction conditions in the simulation as lubricant is consumed and redistributed. The fitted parameters are following $A = 0{,}45$; $B = 0{,}5$; $C = 0{,}127$. Where V is the mass of lubricant in milligrams.

$$\mu = A + (B - A) * e^{(-C*V)} \quad (1)$$

This procedure is repeated for all wheels, wheelsets, and successive vehicle passages. The primary outcome of the algorithm is the distribution of lubricant along the rail after each pass, together with the evolution of lubricant quantity on the wheels. During the simulation, additional variables such as frictional energy, lubricant consumption, and the coefficient of friction can be recorded for post-processing and evaluation of lubrication effectiveness.

At each discretized track segment, the total lubricant present in the contact is updated by applying the redistribution model, which divides lubricant between the wheel and the rail. This assumption is based on the redistribution model presented in [5]. The redistribution factor of how much lubricant is present on the wheel was set to 0.75. This was selected based on assumptions from experimental results and the predicted influence of flange contact patch.

To demonstrate the methodology, a real railway line with known geometric characteristics was selected. Track curvature, cant, and vehicle speed were defined as functions of position along the line. The track was discretized into segments of one meter length, which provides sufficient resolution to capture changes in curvature and lubrication effects while maintaining reasonable computational efficiency. The simulated vehicle consists of a 4-car electric unit, with each wheelset represented individually. Only leading wheelsets that are expected to engage in flange contact are considered in the lubrication model, as other wheels do not contribute to flange lubricant transport. Flange contact is assumed to occur when lateral forces exceed a predefined threshold, derived from simplified static equilibrium calculations and validated against preliminary vehicle dynamics simulations. For each wheelset passing through a curved track segment, normal and lateral contact forces are estimated using a quasi-static force balance that accounts for vehicle mass, speed, curvature, and cant. Based on wheel and rail geometry, the location of the flange contact point is determined, allowing estimation of local creepage values.

The frictional energy input into the contact q is calculated as the product of friction force, slip, and velocity as described in Equation (2). This then defines the frictional energy at each segment of discretized track. To improve computational efficiency, the maximum possible frictional energy (corresponding to a friction coefficient of one) is precomputed for each track segment. The resulting dissipated energy is shown in Figure 2, not accounting for flanging condition. During the simulation, the actual frictional energy is obtained by scaling this value with the current coefficient of friction, which depends on the local lubricant quantity.

$$q = \frac{F \cdot s}{v} \tag{2}$$

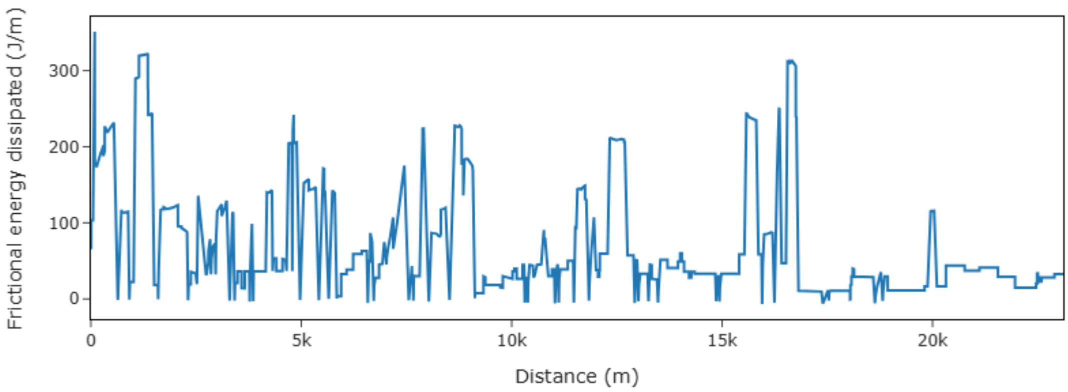

Figure 2: Frictional energy dissipated along the track.

Lubrication points are defined at track curves with a radius below a threshold of 1000 m (curvature of 0.001 1/m) and after reaching 500 m in a single curve. When a wheelset passes a lubrication point, a 5 g amount of lubricant is added to the wheel flange at either left or right side. The simulation then tracks the movement of this lubricant as the wheelset progresses along the track. Lubricant remaining on the wheel is transported to the next track segment, while lubricant remaining on the rail is stored at the corresponding position and influences subsequent wheelsets. This process is repeated sequentially for all wheelsets and for multiple train passages, allowing accumulation, spreading, and depletion of lubricant to be captured over time.

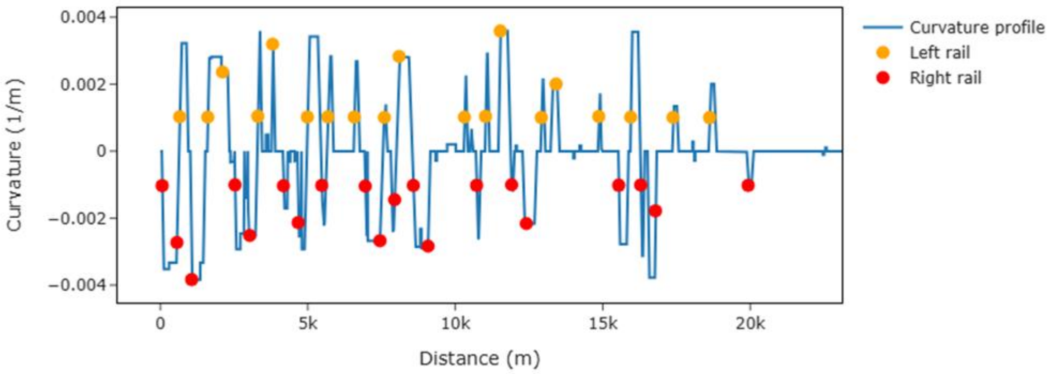

Figure 3: Definition of lubrication points.

The primary outputs of the simulation are the distribution of lubricant quantity on the rail and wheel, and the corresponding coefficient of friction along the track. Additional outputs include frictional energy input and lubricant consumption in each wheel step. These results enable evaluation of lubrication effectiveness, comparison of different lubrication strategies, and identification of zones with insufficient or excessive lubrication. The methodology is intentionally modular, allowing individual submodels to be refined as more detailed experimental or field data become available.

3 Results

The first set of results is presented for five vehicle passages numbered 1 to 5, all with active lubrication. Positive values correspond to the left rail, while negative values represent the right rail. Figure 4 shows the distribution of lubricant in the contact for individual passing wheels. In each case, the first wheel of the vehicle that participates in flange contact is shown, separately for the left and right sides. At all application points the amount of lubricant decreasses rapidly.

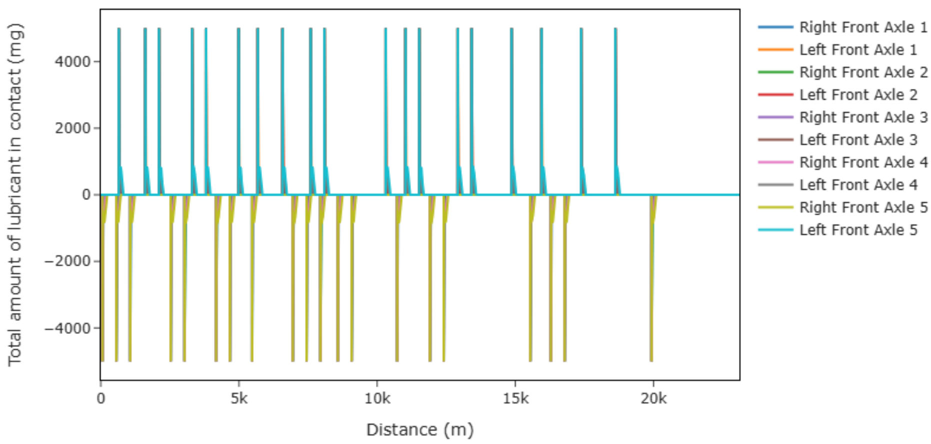

Figure 4: Amount of lubricant on the first wheel passing through the flange contact.

As showing the whole track cannot show the localized changes, further figures are focused on the detail of first lubrication point on left side wheels at track distance of around 650 meters. Figure 5a presents a detailed view of the first wheelset in first lubrication point on the left rail. At the point of lubricant application, the amount corresponds to the applied dose, followed by an exponential decrease along the track. However, for subsequent vehicle passages, a slight increase in lubricant quantity and a stabilization over a distance of approximately several tens of meters can be observed. This stabilization is caused by the gradual redistribution of newly applied lubricant. It can be seen that each subsequent vehicle has access to a comparable amount of lubricant over a longer track section. A detailed view of the first lubrication point on the left rail for the last wheelset of each train is shown in Figure 5b. A similar trend to that observed for the first wheelset is evident, with a smooth initially higher lubricant amount that stabilizes at a slightly lower level of around 800 mg. For the fifth lubricated vehicle, the lubricant is distributed over a track length of approximately a few hundred meters, providing effective lubrication over a longer distance than for the first wheel passing through the section.

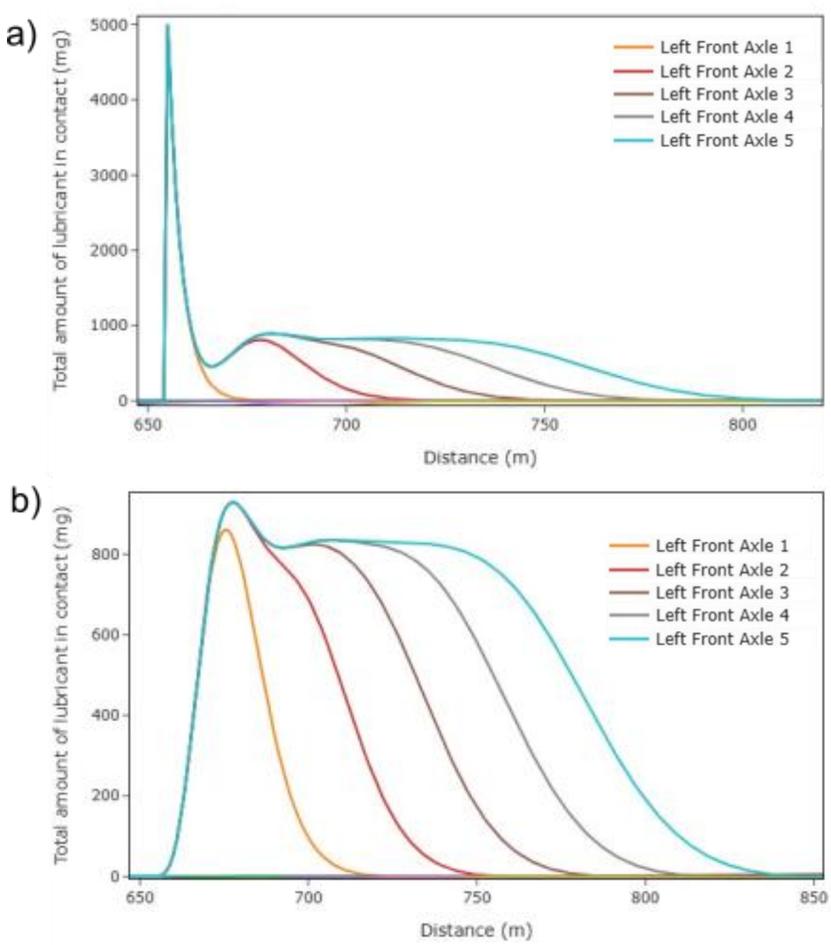

Figure 5: Detail of the lubricant amount on: a) the first wheel; b) the last wheel of a train passing through the flange contact.

The recalculated values of the coefficient of friction for the detail shown in Figure 5a is presented in Figure 6. As described by Equation (1) the maximum and minimum values of the coefficient of friction are 0.45 and 0.13, respectively. The figure shows the evolution of the coefficient of friction along the track downstream of a lubrication point for successive wheel passages. Immediately after lubrication, the coefficient of friction drops from the dry-contact level to a low value corresponding to a fully lubricated flange–rail contact. For subsequent wheelsets, the low-friction region extends progressively further along the track. This behaviour indicates that, in this case, lubricant redistribution along the rail is stronger than its consumption by friction, leading to an increasing effective lubricated distance with each passing wheelset. These results demonstrate that a subsequent lubrication events can progressively improve lubrication coverage downstream when redistribution effects dominate over consumption, emphasizing the importance of accounting for cumulative wheel passages in the assessment of lubrication effectiveness. To improve accuracy, especially the consumption factor needs to be evaluated in real track scenario.

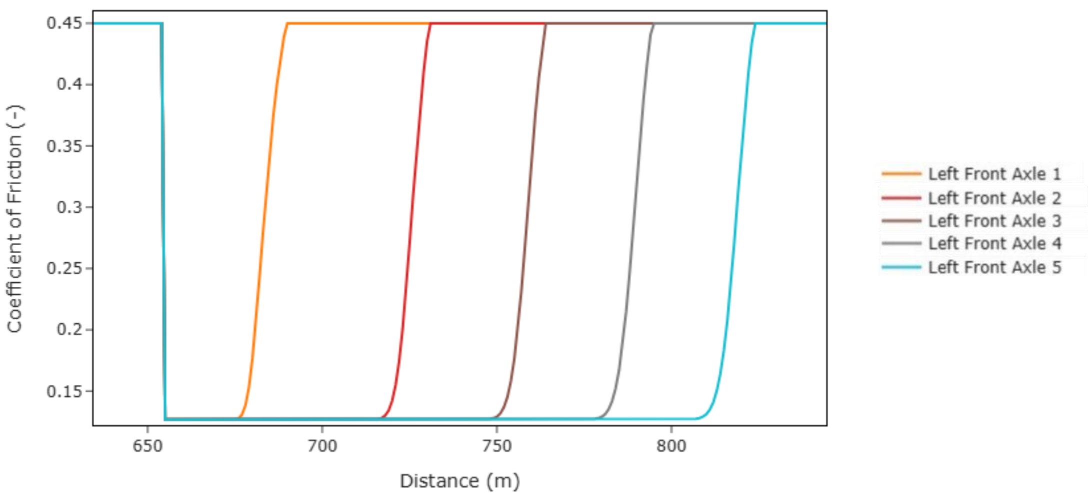

Figure 6: Detail of the coefficient of friction on the first wheel passing through the flange contact.

The results for the scenario in which lubrication is applied only by the first passing train, followed by four subsequent trains without active lubrication is shown in Figure 7. The results demonstrate the progressive depletion and redistribution of the initially applied lubricant. After the first lubricated passage, a distinct lubricated zone is formed along the track. During the subsequent non-lubricated passages, this lubricant is gradually redistributed and consumed by frictional work, leading to a continuous decrease in lubricant. Each successive train experiences a longer effective lubricated compared to the preceding one. The results show that a single lubrication event can still provide a measurable friction-reducing effect over several subsequent passages. However, this is true in this case where the removal of lubricant seems to have noticeably smaller influence than the lubricant redistribution. The approximate length of lubricated section is around 100 meters. Not even in this case an overlap of lubricated zones can be seen. This behaviour highlights the cumulative influence of traffic on lubrication effectiveness and underlines the importance of accounting for train sequence and traffic density when designing and optimizing flange lubrication strategies.

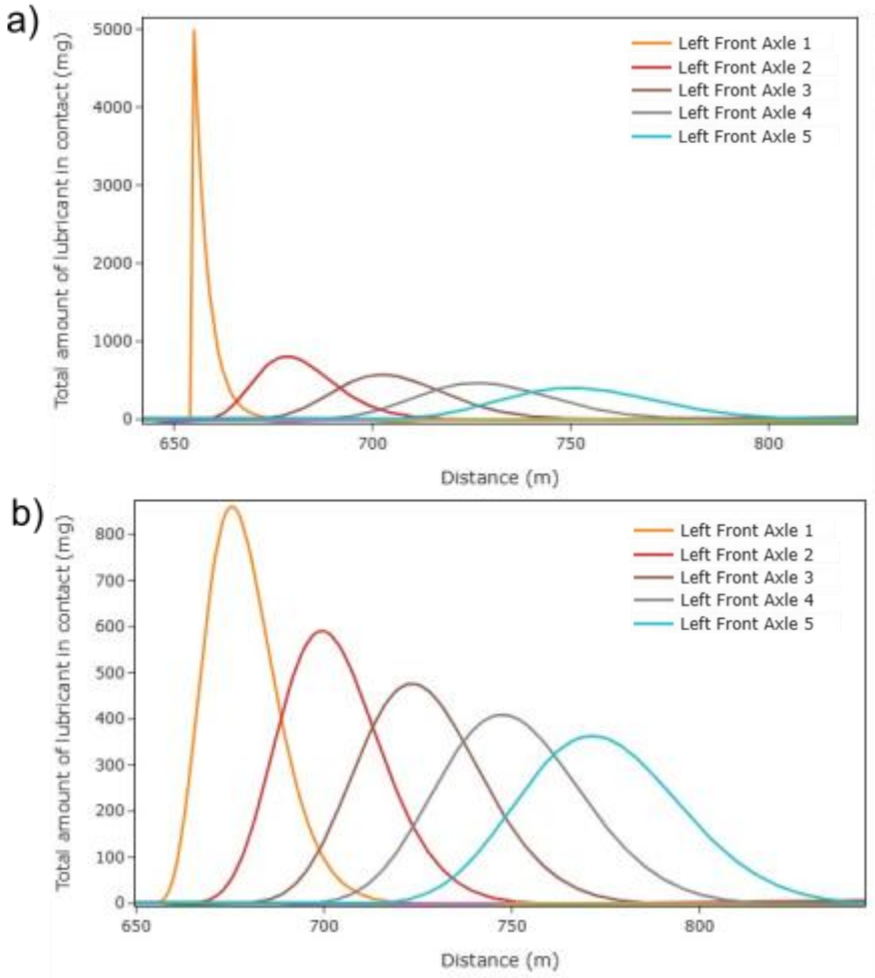

Figure 7: Detail of the lubricant amount on: a) the first wheel; b) the last wheel of a train passing through the flange contact. For case where only train number 1 provides lubrication.

4 Conclusions and Contributions

This study presented a simulation-based approach for predicting the behaviour of flange lubrication applied before curved track sections and its influence on friction conditions in the wheel–rail interface during repeated train passages. The developed methodology combines experimentally derived descriptions of lubricant retention, redistribution, and frictional behaviour with a numerical model of vehicle passage along a discretized railway track. This allowed the spatial and temporal evolution of lubricant quantity and the corresponding coefficient of friction to be evaluated in a physically consistent manner.

The results demonstrate that lubricant applied at discrete lubrication points is not consumed locally only, but is transported and progressively redistributed along the track by successive wheelsets. Depending on the balance between redistribution and frictional consumption, the effective lubricated distance may either decrease or increase with additional wheel passages. In the investigated cases, redistribution effects were shown to dominate over consumption, leading to a gradual extension of the low-friction region downstream of the lubrication point. This behaviour highlights the cumulative influence of wheel passages and explains why lubrication effectiveness cannot be assessed solely based on the first vehicle passing the lubricated section.

Although the model employs simplified contact force calculations and empirical relationships, it provides valuable insight into the key mechanisms governing flange lubrication performance. The proposed framework forms a suitable basis for further refinement, validation with field measurements, and future integration into predictive lubrication and adhesion management systems aimed at reducing wear, noise, and maintenance costs in railway operation.

In addition to its standalone predictive capability, the developed model is directly applicable as a core component of a digital twin of the wheel–rail interface focused on friction and lubrication processes. Its modular structure and low computational cost enable the repeated evaluation of lubrication scenarios in near real time, a key requirement for digital twin applications. When combined with track geometry data, traffic information, and experimentally calibrated lubricant parameters, the model can support adaptive decision-making regarding lubrication point placement, dosing amounts, and application intervals. This creates a foundation for intelligent flange lubrication systems that move beyond fixed dosing strategies toward predictive, condition-based control aimed at balancing wear reduction, noise mitigation, and adhesion safety.

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