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# FRICTION MODIFICATION WITHIN WHEEL-RAIL CONTACT

# MODIFIKACE TŘENÍ V KONTAKTU KOLA A KOLEJNICE

*Shortened version of PhD Thesis*

Branch:           Design and Process Engineering

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Wheel-rail tribology, top-of-rail lubricant, friction modifier, adhesion, traction, braking, wear


**Klíčová slova:**
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# CONTENTS

# 1    INTRODUCTION

Rail transportation is one of the most reliable, safest and the most efficient way of transportation of passengers and goods. Since 1804, when the first steam locomotive was invented by Richard Trevithick, rail transportation has undergone a rapid progress. Today, trains are significantly more eco-friendly, safer, and, of course, faster. A current speed record for conventional trains is held by the French TGV bullet train which reached 574.8 km/h in 2007, and a common operating speed of high-speed trains is between 200 and 320 km/h. Besides trains, rail transportation has also become indispensable for public transport where subway and tram systems play an important role. In Brno (Czech Republic), trams annually carry nearly 200 million of passengers.

From the above lines, it is evident that rail transportation occupies a significant position in both intercity and public transport. However, there are some phenomena which considerably affect a success of rail transportation. A wheel-rail interface represents one of the key factors responsible for transfer of forces from the wheel to the rail. This transfer is usually expressed by a ratio between the normal and friction force acting in the contact. This ratio is usually called the adhesion or friction coefficient; a difference between these two coefficients is discussed in the following chapter. It should be emphasized that the actual value of friction coefficient is strongly weather-dependent because the wheel-rail contact is an open system. It means that acceleration and deceleration capabilities can be limited due to unfavourable environmental conditions and contaminants. One of the most critical scenarios occurs during the autumn when a combination of moisture and crushed leaves forms a layer providing a low adhesion. This layer limits traction and braking performances. Moreover, it can also lead to the difficulties with train detection due to its insulating effect. To overcome these difficulties, sand is applied into the wheel-rail contact; thus, a rapid increase in adhesion in the wheel tread–rail head contact is achieved. The second widely used approach for friction modification at the wheel-rail interface is a method of flange lubrication. This method becomes important for the vehicle running through a curve.

Besides the above mentioned traditional methods to control friction, substances for top-of-rail friction modification, the so-called TOR products, were developed in 1990s. These products can be applied to the wheel-rail contact to achieve the required adhesion level and shape of traction curve. It means that these products are able to control adhesion/friction at the specific value unlike sanding and wheel flange lubrication. Typical benefits of these TOR products are a reduction of wear, noise and rolling contact fatigue (RCF).

The aim of this doctoral thesis is to clarify the friction behaviour and impact of TOR products on friction in the wheel-rail contact while the main attention is paid to low adhesion issues associated with the application of these substances. So far, there has only been a limited knowledge about this potential risk.

# 2 STATE OF THE ART

## 2.1 FRICTION MANAGEMENT

Friction management includes different approaches to the friction modification between the wheel and the rail. These approaches are widely used all over the word in order to achieve a good transport efficiency, safety, noise reduction, and acceptable maintenance costs. According to the desired level of friction/adhesion, friction management can be divided into three categories [1].

- **Grease and lubricants** – typical representatives are grease and lubricants which are applied at the wheel-flange-gauge corner interface. These substances provide a friction coefficient lower than 0.1; thus, wear and noise are reduced. An application is mainly realized before a track and lubricant or grease are applied into the wheel flange-gauge corner contact of high rail as can be seen in Fig. 2.2. In some publications, these products are sometimes termed as *Low coefficient friction modifiers* (LCF).

- **High positive friction modifiers (HPF)** – these top-of-rail products (TOR products) maintain the friction coefficient at the intermediate level, which is usually the range from 0.2 to 0.4. Besides this, TOR products should provide a positive trend of the traction curve, see Fig. 2.1. In this case, a substance is usually applied only into the wheel tread–rail head contact of the high rail as is shown in Fig. 2.2.

- **Friction enhancers** - a typical representative is sand which increases adhesion, especially during traction and braking under poor adhesion conditions. The application of sand should ensure the friction coefficient higher than 0.4. Sanding or the so-called *Very high positive friction modifiers* (VHPF) can be used on both the straight and curved sections of track.
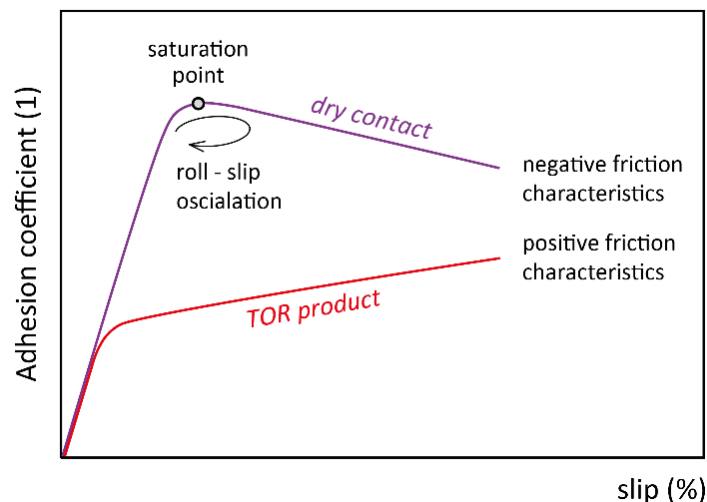


**Fig. 2.1** Traction curve for dry contact and contact with TOR product.

In the past, many authors used the term *friction modifier* (FM) for both the water-based and oil-based substances despite significant differences in the behaviour of these substances. In order to avoid confusions, in this doctoral thesis, the term *friction modifier* is used only for the water-based products while the oil-based, grease-based, and hybrid products (the base medium is a mixture of oil and water) are called *TOR lubricants* in accordance with the recently published articles [2],[3].
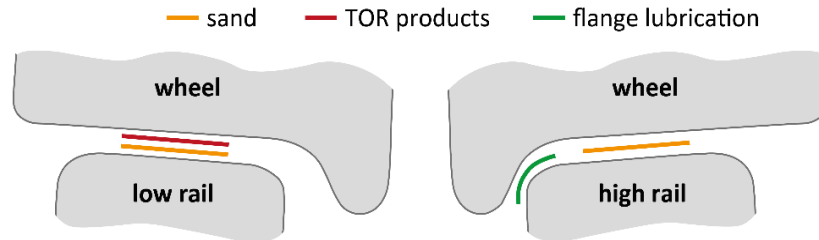


**Fig. 2.2** Friction management in rail transportation.

## 2.2  TOP-OF-RAIL PRODUCTS

The first TOR product was developed as a solid stick in the early 1990s. This solid modifier was subsequently used in the Vancouver mass transit system [4] where rail corrugations were developed as a result of wear and a roll-slip oscillation within six months following its opening in 1986. The study showed that the solid modifier enables to change a trend of the traction curve from negative to positive; thus, a roll-slip oscillation can be completely suppressed. Although a solid stick modifier proved to be a suitable method for reduction of roll-slip oscillation, this method does not easily allow to precisely control a dosing process which is one of the most important factor for top-of-rail friction modification. A large amount of TOR products can have a negative impact on traction and braking performance. Therefore, these solid stick products are more often employed for the flange lubrication where the requirements for dosing are not so strict. With respect to these strict requirements for application of TOR products, a liquid FM (water-based) was developed in 1996.

FMs, sometimes also called drying products, are usually applied directly to the top-of-rail in the targeted section of track. As was mentioned above, FMs should mainly generate a positive traction curve and provide an intermediate level of friction. In addition, there are some other FM benefits such as reduction of lateral forces leading to fuel/energy savings, wear reduction, and also a control of noise. All these benefits are significantly affected by the presence of the third-body layer which is naturally formed on the contact surfaces. After the application of FM, water is evaporated; thereby dry FM particles interact with the third-body layer consisting of wear debris particles, oxides particles, contaminants, etc. It means that FMs should be designed with respect to the composition of the third body layer. However, it should be noted that this composition can significantly vary due to changing environmental conditions. It means that these water-based products should

be beneficial in a wide range of both environmental and operating conditions. According to the patents [5]-[7], the following components contained in FMs exhibit a high positive friction characteristic (traction curve):

- **Base medium** – it is "only" a transport medium, which ensures a distribution of FM along the track or wheel circumference depending on the application method. The content of water is usually between 40 and 95 wt%.

- **Rheological control agent or binding agent** – this agent is a compound capable of absorbing base medium thereby a substance swells. This agent creates a continuous phase matrix which is able to bind solid particles such as lubricants, particles for friction modification and other compounds to a metallic surface of a rail or a wheel. Moreover, this agent has a function of a thickening agent, so it controls the flow properties and the viscosity of the composition. The typical representatives are e.g. clays such as bentonite, casein, starches, etc. The content of thus control agent is from about 1 to about 10 wt%.

- **Particles for friction modification (PFM)** – in patents, this compound is usually termed as a "friction modifier" as well as the whole substance. In order to avoid confusions, this compound is called herein *particles for friction modification*. Particles for friction modification, if any, are usually mineral particles such as magnesium silicate (talc), silica, ground quartz, etc. Apart from mineral particles, some oxides can be used, e.g. zinc oxide, aluminium oxide, zinc oxide, antimony oxide, etc. These particles should ensure a desired level of adhesion and a positive friction characteristic. The size of PFM is usually in the range from 0.5 to 10 microns. In the case of HPF FM (hereinafter FM), a preferable size of PFM is in the range from 1 to 2 microns whereas VHPF FM has a desired PFM size about 10 microns.

- **Solid lubricant** – the following solid lubricants are preferably employed: molybdenum disulphide (molyka), graphite and aluminium, or zinc stearate.

- **Wetting agent** – this agent helps to reduce a surface tension of liquids. Furthermore, this agent ensures a better adhesion of FM on the rail surface. One of the most common wetting agents is nonyl phenoxypolyol, which is usually contained in the amount less than 2 wt%.

- **Other additives** – antioxidant, retentivity agent for lifetime increase, etc.

Based on the patents [5]-[7], it is clearly evident that the main difference between HPF and VHP FMs is a size of PFM and a concentration of solid lubricant. In the case of VHPF FM, the size of PFM is significantly larger compared to (HPF) FM; moreover, VHPF FM does not contain a solid lubricant.

Besides the above-described FMs, TOR lubricants represent another possibility of friction management with similar benefits as those of FMs [3]. In this case, friction behaviour is much more affected by the applied amount than in the case of FMs. Representative constituents of TOR lubricants are base oil (usually plant oil),

thickener (e.g. calcium or lithium soap), PFM (e.g. metal and oxides), solid lubricant (e.g. molyka or graphite) and other additives such as antioxidant or extreme pressure additives.

## 2.3 LUBRICATION REGIMES

Fig. 2.3 shows a Stribeck curve describing the relationship between the adhesion coefficient and the Hersey number or the parameter of lubrication *Lambda*, which is a ratio of a film thickness to a combined surface roughness. Four following regimes of lubrication can be distinguished on the Stribeck curve:

- **Boundary Lubrication** – film thickness is too thin to separate the contact surfaces; therefore, the contact between the opposing asperities occurs. These asperities are covered with adsorbed molecules of the lubricant and oxide layer.

- **Mixed Lubrication** – loading is carried out by a combination of the contact pressure between the surface asperities and hydrodynamic pressure of lubricant, created as a consequence of higher speed. This lubrication regime is sometimes referred to as partial elastohydrodynamic lubrication.

- **Elastohydrodynamic and Hydrodynamic Lubrication** – if the speed is sufficiently high, then the hydrodynamic pressure of lubricant increases and the film thickness becomes sufficiently strong and thick to completely separate the contact surfaces. It means that the film thickness is larger compared to the combined surface roughness.
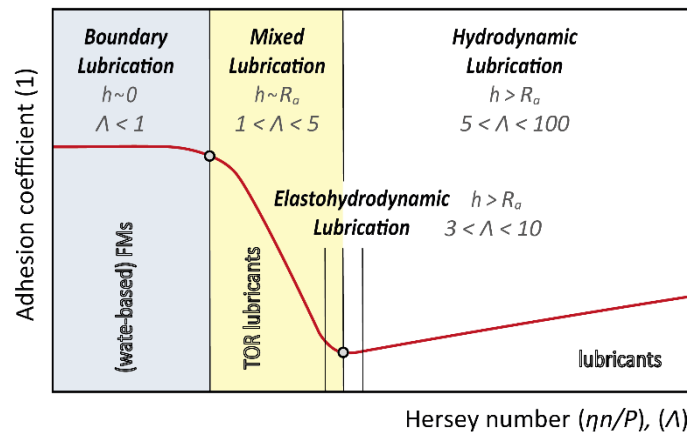


**Fig. 2.3** Stribeck curves showing different lubrication regimes.

Under dry conditions, the adhesion coefficient in the wheel-rail contact is given by the third-body layer, which is naturally formed on the contact surfaces. If the rail is wet, then the contact usually operates in the boundary or mixed lubrication regime. The elastohydrodynamic or hydrodynamic regime can occur when the contact is contaminated with oil or grease. In the case of TOR products, a boundary regime of lubrication is expected for FMs (drying materials), while TOR lubricants usually lead to the boundary or mixed lubrication [2], [3], see Fig. 2.3.

## 2.4  LABORATORY AND FIELD RESEARCH OF TOR PRODUCTS

Field research of FM was started in 1992 by Kalousek et al. [4] who proved a positive effect of solid modifier on corrugation. Since 1996, when a liquid FM was developed, field research has revealed that FMs are able to reduce or completely avoid the evolution of corrugation, see Fig. 2.4. This ability was gradually verified using different railway systems, such as metro [9]-[11], tram [10], commuter rail [11], and light rail system [8],[10]. Besides this, a roll-slip oscillation, occurring due to the negative friction after the saturation point (see Fig. 2.4), was identified as the initiation mechanism of short pitch corrugation [8].
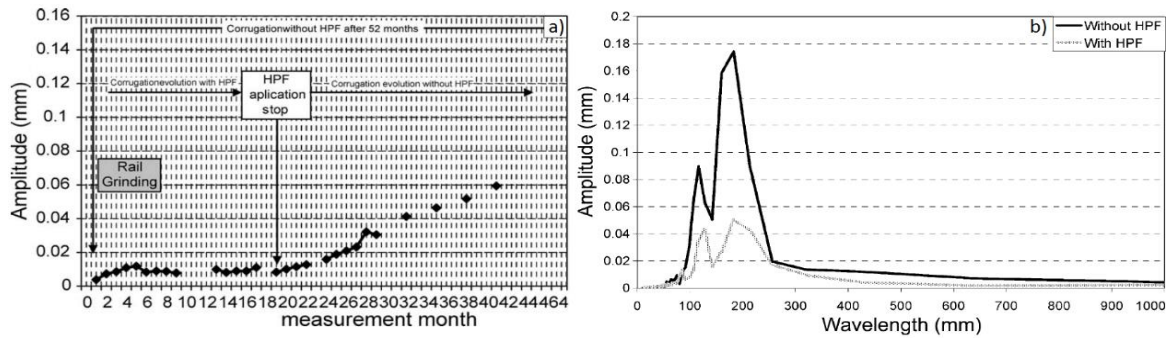


**Fig. 2.4** Evolution of rail corrugation amplitude (a) and wavelength spectrum comparison (b) [9].

Field studies also investigated how FM changes the spectral sound distribution and the level of noise emitted from the wheel-rail interface when the vehicle passes through a curve [12],[13]. It was observed that FM reduces both the TOR squeal and flanging noise across a wide range of railway systems, see Fig. 2.5. Note that more significant reduction of TOR squeal and flanging noise was observed when FM was applied on both rails [13]. However, another study gives the evidence that the flanging noise is not affected by FM [10]. Subsequently, other conflicted results showed that the flange lubrication is more efficient for TOR squeal reduction compared to FM and TOR lubricants [14]. Moreover, it was established that if FM or TOR lubricants were applied only to the low rail, there were no benefits associated with noise reduction.
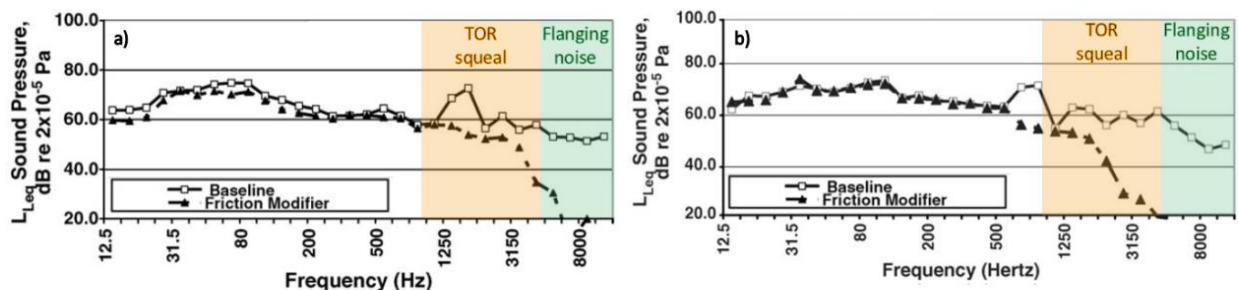


**Fig. 2.5** Sound spectrum of two tram systems [12].

Afterwards, other authors proved that FM reduces contact forces [9], [15] and also the adhesion coefficient [8],[16],[17]. It was observed that FM is able to provide the intermediate level of adhesion for both rails [8], see Fig. 2.6; however, some cases indicate that a poor adhesion can occur under FM conditions [16],[17]. Low adhesion values were also observed when TOR lubricants were applied and the friction coefficient was measured using a hand-pushed tribometer [18],[19].
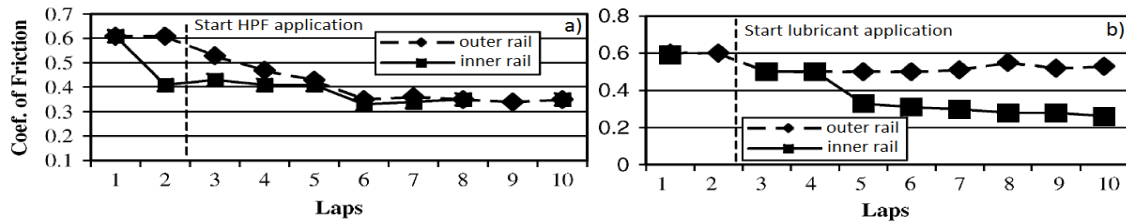


**Fig. 2.6** Performance of FM (a) and lubricant (b) [8].

In the case of laboratory studies, many authors were interested in the third body layer which is formed between the rail and the wheel [25]-[28],[20]-[31]. At first, Beagley et al. investigated the effect of railhead contaminants on adhesion under dry [25],[28], wet [25],[26],[28], and oil conditions[25],[27],[28]. It was concluded that the boundary lubrication model cannot be used for third-body layers containing solid particles; therefore, the so-called solid and viscous models were introduced [28]. The authors mentioned that if a solid behaviour prevails, then the railhead debris with high shear strength maintain adhesion at an acceptable level [28], even under oily fluids contamination [27]. In contrast, if a viscous behaviour dominates, then poor adhesion conditions can occur [26]. The exact adhesion value is mainly given by viscosity and shear strength of the third-body layer [28]. Later, the elastic-plastic rheological model of the third-body layer was introduced and experimentally verified for three types of third-body layers (negative, neutral, and positive) [20],[21]. Afterwards, a difference between the natural and artificial third body layer was specified [22], and three possible rheological behaviours of the third body layer, which are activated at different slips, were defined [23]. Many researchers dealt with the role of oxides in these layers [24]-[31]. These findings showed that the presence of oxide particles significantly affects adhesion and wear [24],[29], see Fig. 2.7.
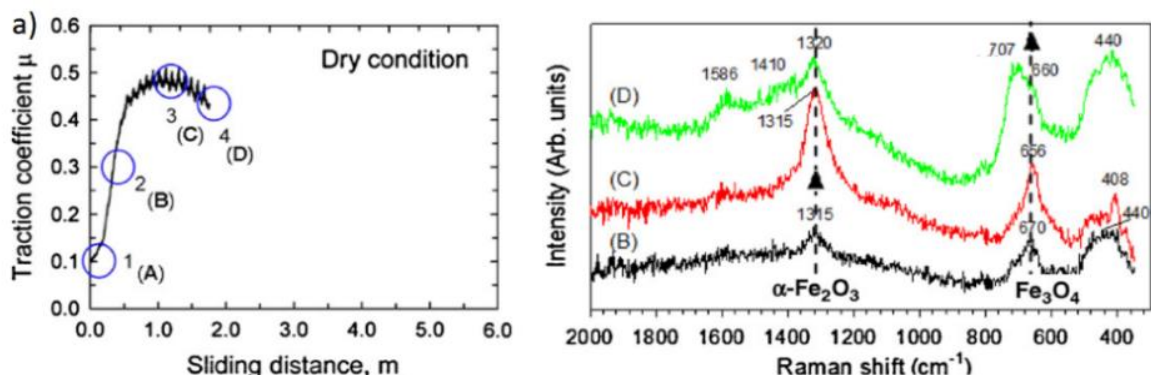


**Fig. 2.7** Trend of traction coefficient and Raman spectra of discs for worn surfaces from stage (B) to (D) for dry conditions (a) and for wet conditions (b) [24].

The ability of FM to provide positive traction curve was first proven by Matsumoto et al. [32], [33], whose findings showed that FM provides this positive trend in both the lateral and longitudinal direction [32]. Moreover, this study [33] showed that the shape of the traction curve can be controlled by the applied amount as is evident from Fig. 2.8. Subsequently, the study dealing with mixtures of FM and
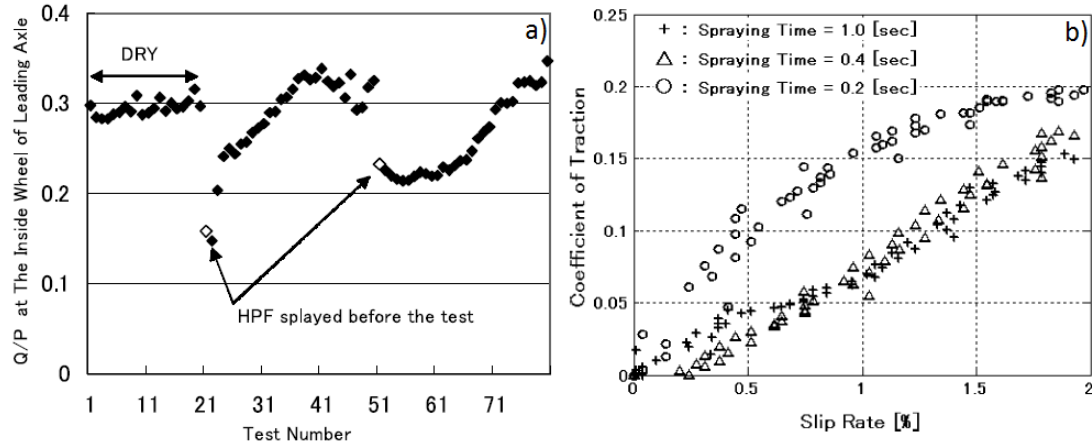


**Fig. 2.8** Effect of vehicle passes on adhesion (a) and traction curve for various spraying time [33].

oxide particles [34],[37] proved the hypothesis that FM is able to control friction over a wide range of iron oxide concentrations because of high wear resistance of FM particles [34]. In the study [34], the so-called N-shape behaviour, providing a longer lasting effect, was introduced. Other authors observed that, under dry [35], wet [35], and leaf [36] conditions, the lasting effect of FM is mainly given by the size and hardness of PFM. Besides this, experiments clarified that FMs can provide a required intermediate level of adhesion for tested conditions. While one of the latest publications [40] again confirmed that FM is able to provide the positive traction curve and the intermediate level of adhesion, a critically low adhesion occurred when TOR lubricants were applied, see Fig. 2.9. On the other hand, TOR lubricants were more efficient in the case of noise reduction; nevertheless, a squeal noise was not avoided due to thermal effects.
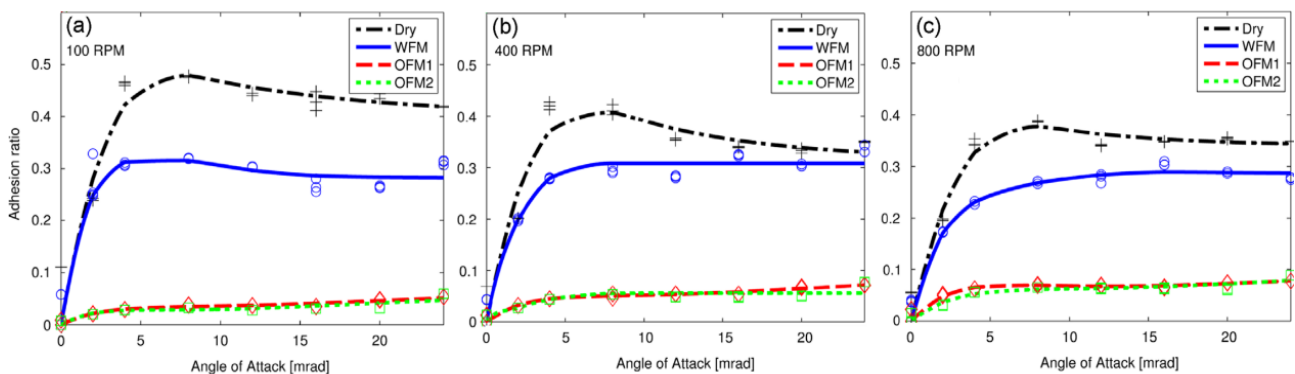


**Fig. 2.9** Traction curve at 100 RPM (a), 400 RPM (b), and 800 RPM (c) [40].

Apart from liquid TOR products, some authors used only PFM for top of rail friction modification [38],[39]. Although PFM are rather friction enhancers compared to typical TOR products, these findings can be useful because these particles (e.g. alumina particles) are the main part of TOR lubricants. Experiments showed that the alumina particles can ensure a required adhesion under water and oil-contaminated conditions and a wear rate is lower in comparison with sanding.

The following part of the literature review was devoted to the effect of TOR products on wear and surface damage [35],[36],[41],[42]. Using a twin-disc, it was proven that both tested FMs reduced wear and surface damage compared to dry conditions [35],[36]. As can be expected, FM with larger particles led to a higher wear rate and more serious surface defects. Experiments using a full-scale rig [41] revealed that FM is able to suppress changes in geometry occurring due to wear, see Fig. 2.10. In addition, FM reduced the number of head checks, plastic flow and surface roughness. A similar performance was observed for a premium rail [42].
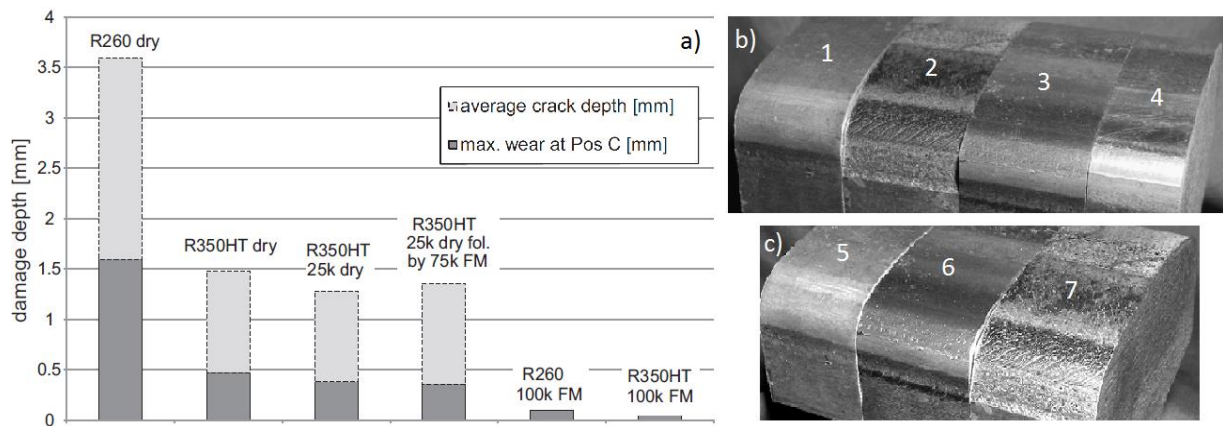


**Fig. 2.10** Combined damage of wear and RCF under various conditions (a), comparison of samples of rail R350HT (b): new rail 1, dry 100,000 passes 2, FM 100,000 passes 3, and FM 400,000 passes 4, and comparison of samples of rail R260 (c): new rail 5, FM 100,000 passes, dry 100,000 passes [41],[42].

# 3    SUMMARY AND CONCLUSION OF STATE OF THE ART

The literature review shows that TOR products have been intensively studied since 1996. There are a lot of articles dealing with the performance of FMs (water-based products) in terms of adhesion [32]-[40], wear [35],[36],[41],[42], corrugation [8]-[11], and noise [8],[10],[12]-[14]. However, it should be highlighted that almost all these works investigated the performance of one particular commercial product with the trade name KELTRACK™. It means that only a little is known about the effect of FM composition on adhesion, wear, etc. Hence, FMs can be seen as "a black box". Apart from this, there is a very limited knowledge about the influence of FM amount on adhesion, e.g. when the contact is overdosed with FM. Particularly this may represent a possible risk for traction and braking. It should also be emphasized that the experiments with FMs usually started immediately after the application of FM in spite of the fact that FMs are designed as drying products. In this case, adhesion, as well as other parameters, are influenced by both solid particles and a base medium.  However, so far, the articles concerned have not discussed the effect of base medium evaporation on the performance of FMs. The literature review also reveals that only a little has been reported about TOR lubricants even though these products are widely used. Recently published articles [14],[40] have indicated that TOR lubricants reduce noise (squeal noise usually persists); however, adhesion can be reduced to low values with respect to braking/traction capabilities [18],[19],[40]. Based on this, it can be reasonably expected that the performance of TOR lubricants is strongly dependent on the applied amount and the application methods (low rail only or both rails). However, the reviewed studies did not discuss these effects in spite of the fact that a braking/traction performance can be limited. Therefore, it seems necessary to clarify the effect of TOR lubricant amount on adhesion, wear, noise, and other parameters. The aim of the present thesis based on these facts is defined in a greater detail in the following chapter.

# 4 AIM OF THESIS

The aim of this doctoral thesis is to clarify the friction behaviour and impact of the TOR products on friction in the wheel-rail contact, while the main attention is paid to low adhesion issues related to the application of these substances. For this purpose, adhesion and noise measurements were conducted considering both the laboratory and field conditions. Moreover, a wear rate and wear mechanisms were evaluated. To achieve the main goal of this thesis, the solution to the following sub-aims is necessary:

- Development of twin-disc machine allowing for adjustment of AoA (for noise measurements) and friction and normal force measurement.
- Selection of suitable track for field investigations.
- Selection of appropriate TOR lubricants and preparation of water-based substances (FMs).
- Design of experiments and approaches for evaluating the performance of TOR products.
- Series of laboratory experiments focused on the performance of TOR products considering various operating parameters.
- Verification of some laboratory results by field measurements.
- Data analysis.
- Discussion and publication of obtained results.

## 4.1 SCIENTIFIC QUESTION

*Q1.* *What is the influence of applied quantity and chemical composition of TOR products on their performance?*

*Q2.* *Can a safe braking distance be guaranteed when the contact is overdosed with TOR products?*

## 4.2 HYPOTHESES

*H1.* *The larger is the applied quantity, the longer is the lasting effect.*

*H2.* *The shape of friction curve can be controlled by the applied quantity of TOR products; thus, the beneficial friction behaviour can be achieved.*

*H3.* *TOR products are able to substantially reduce noise without the adhesion drop leading to braking and traction difficulties.*

*H4.* *When the contact is overdosed with TOR products, the required adhesion level for traction and braking is ensured by PFM.*

*H5.* *The most significant extension of braking distance can be expected during the first pass of vehicle after the application of TOR product.*

*H6.* *It is expected that the effect of PFM on adhesion will be much more significant compared to other constituents of TOR products.*

***H7.*** *The higher is the content of PFM, the shorter lasting effect can be expected.*

***H8.*** *Substances without PFM cannot provide stable adhesion in the intermediate level of friction.*

***H9.*** *When a base medium of FMs is evaporated before the experiment, the shorter lasting effect and higher wear rate can be expected.*

## 4.3  THESIS LAYOUT

This doctoral thesis is composed of two papers published in journals with impact factor (Paper A and C) and one paper published in a peer-reviewed journal (Paper B). These three papers dealt with the performance of TOR products where the effect of applied quantity and chemical composition is mainly discussed with respect to possible risks associated with low adhesion. In Paper A, two commercial TOR lubricants, with a different content of PFM, were used in order to evaluate a dependence between the applied quantity and adhesion in the contact. Finally, the ability of both tested TOR lubricants to reduce wear and surface damage was clarified. The obtained results indicate that overdosing of contact with TOR lubricant can lead to adhesion losses. Following these findings, the inability of TOR lubricant to provide a sufficient braking performance in the case of larger applied quantities was verified under field conditions where a series of tram braking tests was carried out (Paper B). Besides this, the influence of TOR lubricant quantity on the noise level was studied under both laboratory and field conditions (Paper B). The last part of this doctoral thesis is focused on water-based TOR products (FMs) where the role of individual constituents of FMs on adhesion was investigated for the so-called "dry" and "wet" film (Paper C). In addition, the effect of FMs on wear and surface damage was discussed in this paper.

**A.**  GALAS, R., M. OMASTA, I. KRUPKA and M. HARTL. Laboratory investigation of ability of oil-based friction modifiers to control adhesion at wheel-rail interface. *Wear,* 2016, 368–369, 230-238.
*Author's contribution 50%*
**Journal impact factor = 2.531, Quartile Q1, CiteScore = 3.00**

**B.**  GALAS, R., M. OMASTA, M. KLAPKA, S. KAEWUNRUEN, I. KRUPKA and M. HARTL. Case Study: the Influence of Oil-based Friction Modifier Quantity on Tram Braking Distance and Noise. *Tribology in Industry*, 2017, 39(2), 198-206.
*Author's contribution 50%*
**CiteScore = 1.32**

**C.**  GALAS, R., D. KVARDA, M. OMASTA, I. KRUPKA and M. HARTL. The role of constituents contained in water-based friction modifiers for top-of-rail application. *Tribology International*, 2018, 117C, 87-97, *article in press*.
*Author's contribution 50%*
**Journal impact factor = 2.903, Quartile Q1, CiteScore = 3.16**

# 5    MATERIALS AND METHODS

## 5.1    LABORATORY MEASUREMENTS

### 5.1.1    Ball-on-disc tribometer for friction measurement

It is a commercial tribometer *Mini-Traction-Machine* (MTM) enabling to evaluate friction properties of lubricants or unlubricated materials. The main parts of MTM are a 19.05 mm ball which is loaded against a 46 mm steel flat disc. To evaluate the adhesion coefficient in the contact, MTM is equipped with two load cells enabling to detect both the normal and the friction force. Both contact bodies are independently driven in order to set the SRR value in the contact.

### 5.1.2    Twin-disc machine for friction measurement

The main part of this machine is a pair of steel discs leading to the elliptical contact area according to Hertz theory, see Fig. 5.1b. Both discs are independently propelled using electric motors with shaft encoders; therefore, the slip in the contact can be accurately controlled. The cylindrical upper disc represents the wheel disc, while the lower disc, which is rounded with a radius of 50 mm, represents the rail disc. Load is applied using the spring-screw loading system which is mounted, as well as the load cell of a normal force, at the end of the loading arm. The lower disc is hung on the flexible linkages enabling a transfer of the friction force from the contact to the second load cell. Based on the data from both load cells, the adhesion coefficient is evaluated in real time. As is evident from Fig. 5.1c, the support of the lower disc enables to set different values of AoA in order to simulate a passage of vehicle through a curve. In the case of sound measurements, a hand-held analyser type 2270 was used for both laboratory and field experiments. In the laboratory, the microphone of analyser was oriented towards the contact of discs. It was mounted 10 cm above the contact of disc (1 m above the floor) and 50 cm from the contact in the horizontal direction.
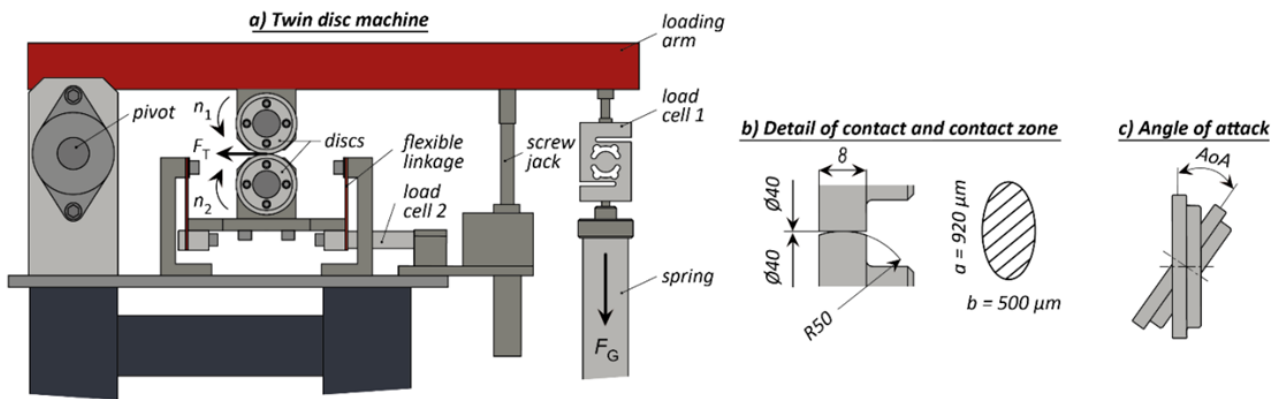


**Fig. 5.1** Scheme of twin-disc machine (a), detail of contact (b), and adjustment of AoA (c).

## 5.2 FIELD MEASUREMENTS

The ability of TOR lubricant to reduce noise and simultaneously to provide a sufficient traction and braking performance has been tested using the light rail system in Brno, Czech Republic. For this purpose, the curve section of the parallel track with the rail profile 49E1 and the curve radius of 200 m, depicted in Fig. 5.2, was chosen because of a high level of noise, corrugation, and heavy traffic.
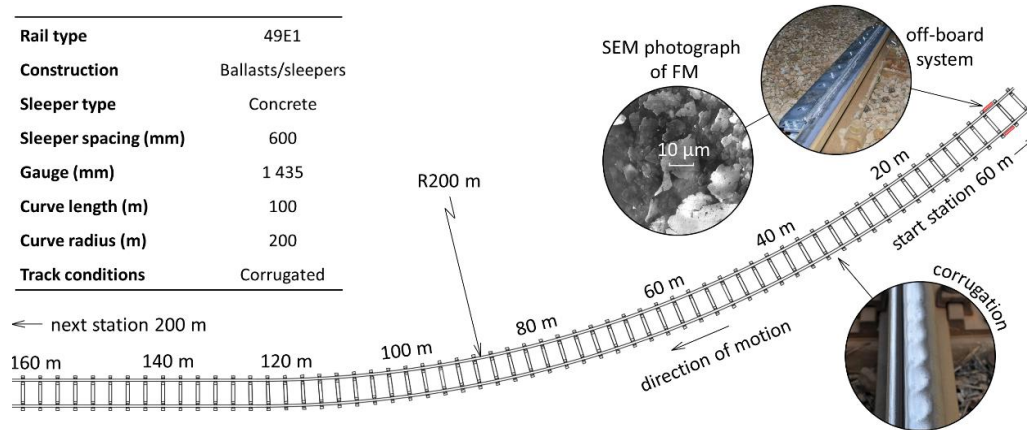


**Fig. 5.2** Tested curve of light and technical details.

A TOR lubricant application was realized using a commercial wayside lubrication system, which was located near the curve and also sufficiently far from the next tram station, see Fig. 5.2. The TOR lubricant is applied on the top of both rail using the application strips without the need to drill holes in the rails. A lubrication process is started by the vehicle-presence sensor detecting the vehicle on the track. This sensor also sends the information on the number of passing axles of vehicles to the control system, based on which the application interval can be set and controlled. The applied amount is controlled by the pump run time.

A level of sound was measured using the same analyser as in the laboratory. In this case, the analyser was placed 7.5 m from the centre of the track with the microphone of analyser 1.2 m above the ground.

## 5.3 TEST SAMPLES, EXPERIMENTAL CONDITIONS AND EXPERIMENT DESIGN

### 5.3.1 Paper A

In this paper, the friction behaviour of two commercial TOR lubricants and castor oil were investigated using the MTM device. In the Paper A, the tested TOR lubricants are identified as TORL-A and TORL-B. The base media of TORL-A and TORL-B are the plant oil and the ester oil, respectively. Both these products include PFM; particularly Cu and Zn particles are contained in TORL-A while TORL-B contains Cu and Al particles. The particles size distribution showed that the predominant size of PFM is between 4–10 μm for both TOR lubricants but

the number of PFM is significantly higher in TORL-A. Note that the content of PFM in TORL-A was approx. 44 times higher than that of TORL-B.

The MTM disc was made from C45; its chemical composition, as well as hardness, nearly correspond to the frequently used wheel steel R7T. Three different types of experiments are included in Paper A, namely: *friction test*, *Stribeck test*, and *lubricant volume test*, see Tab. 5.1. Moreover, a *run-in test* was performed at the beginning of each experiment to achieve a dry level of adhesion.

**Tab. 5.1** Experimental conditions for MTM tests – paper A

|  | **Run-in** | **Friction test** | **Stribeck test** | **Volume test** |
|---|---|---|---|---|
| Pressure, GPa | 0.75 | 0.75 | 0.75 | 0.75 |
| Speed, mm/s | 300 | 300 | 1 - 2500 | 300 |
| SRR % | 1, 3, 5, 10 | 1, 3, 5, 10 | 10 | 10 |
| Conditions | dry | TORL-A, TORL-B, oil | TORL-A, TORL-B, oil | TORL-A, TORL-B |
| Amount, μl | - | 1 | fully flooded | 1 - 4 |

The contact pressure of 0.75 GPa was chosen regarding to the real contact pressure in light rail systems. The values of SRR (1, 3, 5, and 10%) were chosen with respect to the actual shape of the traction curve measured with the MTM device where the SRR values (1, 3, and 5%) did not lead to the full contact saturation. In other words, if the contact operates at these slips (1, 3, and 5%).

The rolling speed of 300 mm/s was selected based on the calculation of the film-thickness parameter $\Lambda_1$. The rolling speed of 300 mm/s should ensure that the contact with castor oil/TOR lubricants operates in the boundary regime of lubrication where the film-thickness parameter $\Lambda_1$ is less than 1.

As was mentioned above, Paper A includes three types of experiments. In the case of *friction* and *volume test*, the performance of TOR lubricants/oil was evaluated regarding to the following points:

- *Lasting effect* – the time period from the application of TOR lubricant to the moment when adhesion reaches a high adhesion level according to Tab. 5.2.

- *Critically low adhesion* – the period when the adhesion coefficient is lower than 0.15 according to Tab. 5.2.

- *Intermediate (optimal) adhesion* – the period when the adhesion coefficient is in the optimal adhesion range according to Tab. 5.2.

- *N-shape behaviour* – the ability of TOR lubricants to provide the N-shape behaviour which was described by Liu et al. [40].

**Tab. 5.2** Adhesion levels for evaluation of TORLs performance – paper A

| **SRR** | **Critically low adhesion** | **Low adhesion** | **Intermediate adhesion** | **High adhesion** |
|---|---|---|---|---|
| 1% | μ < 0.15 | 0.15 – 0.20 | 0.20 – 0.25 | μ > 0.25 |
| 3% | μ < 0.15 | 0.15 – 0.20 | 0.20 – 0.35 | μ > 0.35 |
| 5%, 10% | μ < 0.15 | 0.15 – 0.20 | 0.20 – 0.40 | μ > 0.40 |

Stribeck tests were conducted under fully-flooded conditions in order to investigate if TOR lubricants can cause poor adhesion conditions when the contact is overdosed. Based on the obtained results, some additional experiments, which are not included in Paper A, were performed using the ball-on-disc optical tribometer described above. The aim of these additional experiments was to clarify whether the PFM particles contained in TOR lubricants can easily enter the contact under fully flooded conditions.

At the end of this paper, the discs were analysed using a 3D optical microscope and an analytic balance to evaluate the wear rate and mechanisms of wear.

### 5.3.2 Paper B

In this paper, both laboratory and field experiments were conducted to determine the ability of TORL-B to reduce noise without a significant impact on the braking performance. At first, laboratory measurements using a twin-disc machine were performed where both discs were made from the bearing steel 100CrMn6 with hardness of 60 HRC and the initial roughness of Ra 0.4 μm. This harder contact pair should ensure that the contact width remains almost constant during experiments.

**Tab. 5.3** Experimental conditions for twin-disc measurements – Paper B

| Pressure (GPa) | Speed (mm/s) | SRR (%) | AoA (°) | Quantity (μl) |
|---|---|---|---|---|
| 0.8 | 1 000 | 8 | 4 | 1, 2 , 3, 4 |

As in the case of Paper A, each laboratory experiment started with a run-in phase under dry conditions. Then, TORL-B was applied, using a micropipette, and the trend of adhesion and noise over the time was recorded at AoA of 4°, see Tab. 5.3. This value of AoA represents a typical value for reversing loops. The adhesion and noise measurements were stopped when the adhesion coefficient reached dry adhesion. In the case of noise measurements, the sound level $L_{AF}$ was recorded and A-weighting was applied to the signal. The adhesion performance of TORL-B was assessed with respect to the similar adhesion ranges as in the case of Paper A. Afterwards, the influence of TORL-B on adhesion and noise was studied under real operating conditions. At first, three sets of braking tests were conducted where different amounts of TORL-B (1, 2, and 4 g per single rail) were successively examined to evaluate a suitable amount for long-term testing. Each particular braking test started at the tram station with acceleration of tram to 40 km/h. Once the tram reached this speed and the position of the off-board system, see Fig. 5.2, then, the maximal braking power was applied and the braking distance was recorded. This procedure represents the worst case which can hypothetically occur on the track Each set of braking tests includes the following steps:

- Three braking tests under baseline conditions (without TORL-B) to determine the reference average braking distance under baseline conditions.
- Application of given amount of TORL-B on the top of both rails.

- Several braking tests (3–6) under TORL-B conditions in order to investigate the changes in the braking distance under TORL-B conditions.
- Determination of spreading ability of TORL-B.
- After the completion of the above described points, the off-board system was turned off and the next set of the braking tests was performed one week later.

Subsequently, the optimal quantity, in terms of braking distance, was used for the long-term experiments where sound was measured. The sound was always recorded for 10 seconds because this time approx. represents the duration of tram in the curve.

### 5.3.3 Paper C

The experiments were conducted using the MTM machine in an effort to investigate the role of the typical FM constituents in adhesion and wear at wheel-rail interface. Moreover, it should be highlighted that some experiments were conducted after the base medium evaporation of FM in order to investigate how this evaporation influences the performance of FMs. The experimental conditions of both the friction and wear test are summarized in Tab. 5.4.

**Tab. 5.4** Experimental conditions for MTM measurements – Paper C

|  | Pressure (GPa) | Speed (mm/s) | SRR (%) | Quantity (µl) | Disc material |
|---|---|---|---|---|---|
| Friction test | 0.75 | 300 | 5 | 5–1000 | AISI 52 100 |
| Wear test | 0.75 | 300 | 5 | 20 | C45 |

For friction tests, a hard contact pair (bearing steel AISI 52 100) was used. It enabled us to evaluate the "true" performance of FMs because the effect of wear debris on adhesion is insignificant. Based on input parameters, the rolling speed (300 mm/s) was chosen as suitable because it leads to the boundary lubrication. The chosen value of SRR ensured that the contact operates in the vicinity of the saturation point. To evaluate the effect of the common constituents of FMs on adhesion, film formation and wear, various complex substances were tested.

After a substance preparation and completing a run-in, the substance was applied to the contact path using a micropipette, and then the friction test started either immediately or after evaporation of water. The friction test was stopped when the adhesion coefficient reached the value of 0.4. During these experiments, the performance of substances/FMs was primarily assessed in term of the minimum adhesion necessary for a safe traction and braking (considered as 0.15). Besides that, the lasting effect of substances/FMs was monitored during these measurements.

In the case of wear tests, duration of each experiments was 60 minutes. Whenever the adhesion coefficient reached the value of 0.4, FM was reapplied. Then, the wear test was re-started. Finally, the surface damage and wear rate were evaluated.

# 6    RESULTS AND DISCUSSION

The performance of two commercial TOR lubricants (identified as *TORL-A* and *TORL-B*) with different content of PFM was investigated using the MTM device (Paper A). Regarding to the intervals listed in Tab. 5.2, four sets of friction tests with different slip values and a fixed quantity were conducted under baseline (dry – without TOR lubricants), TOR lubricants, and oil conditions. It was revealed that the lowest adhesion occurred immediately after the application of TORLs where the adhesion coefficient was lower than 0.15, representing the critical low adhesion interval. Then, a gradual increase in adhesion was observed for both tested TOR lubricants. It should be emphasized that TORL-A generally led to higher adhesion values than TORL-B for all tested slips. The reason is that the content of PFM in TORL-A was approx. 44 times higher than that of TORL-B. Despite this significantly larger content of PFM, TORL-A did not provide a shorter lasting effect, but vice versa, the lasting effect was even longer in most cases. This behaviour can be explained as follows: TORL-A has a large content of PFM which were gradually adhered to the contact surfaces. These adhered PFM form a thin friction layer providing the intermediate adhesion level. In contrast, no stable friction film, as well as no stable adhesion, was found under TORL-B conditions because the content of PFM was too low. In this case, the effect of fluid prevailed; therefore, the friction behaviour of TORL-B rather corresponded to the behaviour of castor oil where a gradual adhesion increase was observed during the entire test.
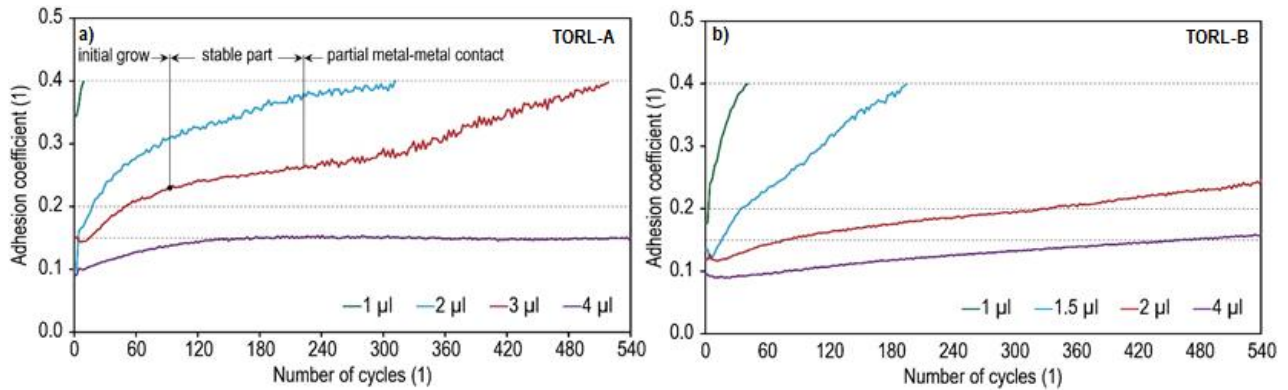


**Fig. 6.1** Effect of quantity on friction performance of TORL-A (a) and TORL-B (b).

Afterwards, the volume tests were performed to evaluate how strongly the performance of TOR lubricants is affected by the applied quantity. The obtained results are consistent with the above-mentioned friction tests because the optimal quantity of TORL-A exhibited the N-shape behaviour, see Fig. 6.1a, which was previously reported for the mixture of grease and FM [34]. This behaviour is beneficial in terms of lasting effect and wear. In the case of TORL-B, a gradual increase in adhesion was observed over time for all tested quantities but the slope of the curve was changed with regard to the applied quantity, see Fig. 6.2b. This friction behaviour was previously observed typically for water-based products

(FMs) [33],[35],[36]. In general, the results of volume tests showed that the higher was the applied quantity, the longer lasting effect was evaluated. Besides this, the lasting effect was significantly affected by the content of PFM. In terms of operating conditions, the lasting effect was significantly shortened with the increasing slip. The volume tests also gave the evidence that if the quantity is inappropriately large, then a critically low adhesion can occur. Following these findings, Stribeck tests were carried out under fully flooded conditions in order to investigate the worst case which can occur if the wheel-rail contact is overdosed with TOR lubricants. The results from Stribeck tests clearly showed that the over-application can lead to the extremely low adhesion which can cause braking and traction difficulties. For all these measurements, the adhesion coefficient was reduced to the values lower than 0.08 at low speeds where the boundary lubrication regime is generally expected, and friction was even lower than 0.04 at higher speeds. These results are in good agreement with reference [40] where TOR lubricants provided the adhesion coefficient about 0.05. Based on this, it was suggested that PFM likely cannot enter the contact under fully flooded conditions. However, this hypothesis was subsequently falsified through the additional experiments performed using a ball-on-disc optical tribometer. These measurements showed that PFM can enter the contact even under fully-flooded conditions as is evident from interferograms in Fig. 6.2. It is noteworthy that PFM enter the contact more easily in the presence of grooves and asperities on contact surfaces. Hence, it can be reasonably expected that the real contact roughness allows for the particles to pass the contact. At the end of Paper A, the ability of TOR lubricants to reduce wear and surface damage was proven. It was revealed that both tested TOR lubricants reduced wear compared to baseline conditions; however, the lowest wear rate was found, as was expected, for the specimen which was run under oil conditions. Although both TOR lubricants reduce wear, they are not able to completely avoid the formation of deep scoring marks on the surfaces which were also found for baseline conditions. A TOR lubricant with a lower content of PFM (TORL-B) led to a less substantial wear and surface damage than TORL-A.
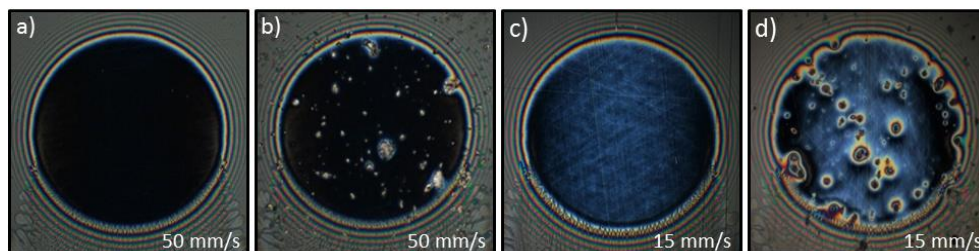


**Fig. 6.2** Examples of interferograms under pure rolling conditions: base oil of TORL-A (a), TORL-A (b), base oil of TORL-C (c), and TORL-C (d).

The first paper of this doctoral thesis revealed that TOR lubricants can be a suitable approach to control of adhesion in the wheel-rail contact where a quantity and content of PFM play a key role. However, there are some possible adhesion risks associated with an over-application. Therefore, it seems to be necessary to

verify and explain this undesirable friction behaviour of TOR lubricants using another experimental method or ideally using field experiments.

With regard to the findings from Paper A, the performance of TORL-A was investigated using a twin-disc device and also in field conditions, where the curve section of light rail system was utilized (Paper B). The aim of this paper was to confirm or falsify the statement about the possible adhesion risks when the contact is overdosed with TOR lubricant. In addition, the ability of TORL-A to reduce noise and simultaneously maintain sufficient adhesion was the subject of this study.

At first, the effect of TORL-A on noise and adhesion was studied using a twin-disc machine where AoA of 4° was set for all measurements in order to achieve typical conditions occurring in curves. These experiments showed that there is a good agreement between the twin-disc and ball-on-disc adhesion results. It was found that there is a similar adhesion-quantity dependence of TORL-A in spite of the fact that the operating conditions were not completely the same. These investigations confirmed two following statements: (1) advantageous N-shape behaviour can be also reached in curves and (2) the adhesion coefficient is critically low immediately after the application, see Fig. 6.3.
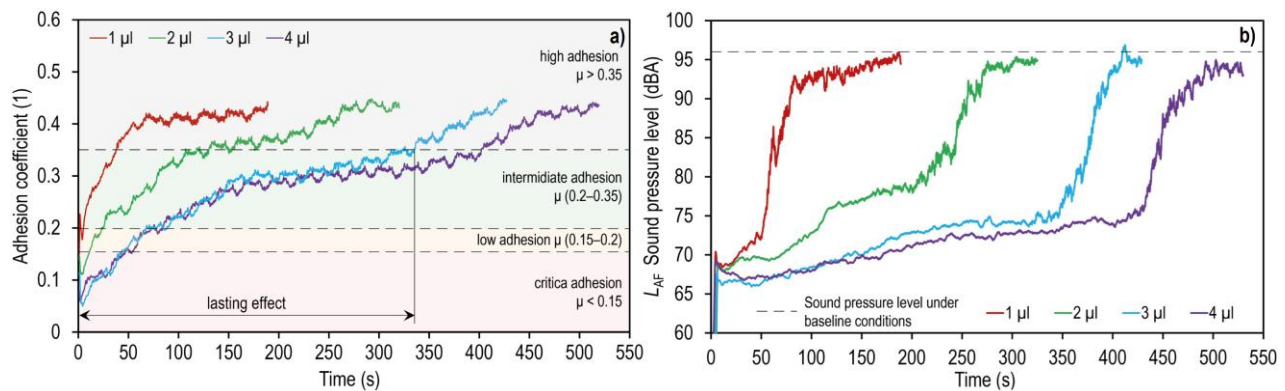


**Fig. 6.3** Effect of quantity on adhesion (a) and level of sound pressure (b).

The results of noise measurements showed that TORL-A is able to greatly reduce noise. A prompt decrease in noise, from 97 dBA (baseline) to 64-68 dBA, was detected for all the applied quantities, see Fig. 6.3b. Then, a gradual increase in noise and adhesion was observed for larger quantities, while a rapid growth of both these parameters was revealed in the case of small quantities. It means that the effect of small quantities on noise was almost negligible because noise was reduced only for a few cycles after the application of TOR lubricant. These experiments also showed that a significant rise in noise occurs when the adhesion coefficient reached 0.35. Besides a higher adhesion and noise, a more significant scatter of sound data was recorded above this value. At the end of these laboratory measurements, some additional experiments under wet conditions were conducted to evaluate how the performance of TOR product is influenced by the presence of water (these results are not included in this paper). Important and consistent results were obtained for all considered TOR lubricant quantities. It was revealed that the interaction of water

and TOR lubricant leads to a critically low adhesion (< 0.02), even with small TOR lubricant quantities. It is noteworthy that more types of TOR lubricants were tested to clarify this suggestion. The results indicate that the effect of fluid is much more significant compared to the effect of PFM which seems to be negligible. This is in good agreement with the previous results [43] where a low adhesion was revealed for the contact contaminated with a mixture of water and oil.

In the case of field experiments conducted in Paper B, the impact of various quantities of TORL-A on braking capabilities was initially studied in order to establish the optimal quantity ensuring a sufficient braking performance. As was mentioned in the previous chapter, TOR lubricants were applied on the top of both rails using a wayside lubrication system. A detailed experimental procedure of braking tests is described in subchapter 5.3.2. These results gave the evidence that if the applied quantity is inappropriately high, then a considerable extension of braking distance can be expected. Beside this extension, braking was accompanied by the wheels slide (complete wheels slip) resulting in the formation of the so-called flat spots on wheels leading to an increase in rolling noise and discomfort of passengers. Two of three tested quantities caused a significant extension of braking distance accompanied by wheels slide. The best results, in terms of braking distance, were achieved when the smallest tested quantity of TORL-A (1 g/rail) was applied. In this case, good braking capabilities were ensured for all tram passes. Hence, this amount was chosen for long-term experiments where noise was monitored. At the end of the above-mentioned braking tests, the carry distance of 100 m was determined with naked-eye. The observed value was significantly lower compared to the values reported in literature [44] where the carry distance was in orders of kilometres without causing any negative impact on a braking performance. However, in that case, a heavy haul train was utilized. It probably means that light rail systems are more prone to a wheel slide, causing an extension of braking distance. Note that a shorter carry distance may not be perceived as a disadvantage in the case of tram because such distance should avoid braking or traction difficulties near the next tram station.

It should be pointed out that the longest braking distance was always observed in the second and third tram pass after the application, while the closest braking distance to baseline conditions was found in the first tram pass (immediately after the application). It leads to the conclusion that a redistribution mechanism of TOR product in the real wheel-rail contact differs considerably compared to the laboratory case where the lowest adhesion was usually observed during the first cycles after the application. The main difference can be that the TOR product mainly remains on the wheelset rather than being continually transferred between both bodies [2], while in the case of laboratory devices, both bodies are covered with a uniform layer of TOR product. In spite of this discrepancy, laboratory measurements provide useful qualitative data which revealed that TOR lubricants can cause insufficient braking and traction capabilities. These findings are in good agreement with literature [18],[19],[40] where the effect of TOR lubricants on adhesion was evaluated.

The results of noise measurements showed that the positive effect of TORL-A on noise reduction was negligible despite the fact that the TOR lubricant was visible on both rails. Although other authors reported a considerable noise reduction for both FMs [10],[12] and TOR lubricants [40], the impact on traction or braking performance was not discussed in these articles, except for [40] where low adhesion conditions were found after the application of TOR lubricant. Regarding these facts and results of laboratory and field measurements, it seems to be difficult to achieve a reduction of noise without extension of braking distance for TOR lubricants.

Two above-mentioned papers of this doctoral thesis were focused on the performance of two TOR lubricants with different content of PFM. It should be highlighted that a special attention was devoted to possible adhesion risks associated with the application of TOR lubricant. Besides TOR lubricants, FMs represent another type of TOR products which is also a widely used approach to friction modification at the wheel-rail interface. Hence, the third paper (Paper C) dealt with the influence of chemical composition and the applied amount of water-based substances/FMs on adhesion and wear. For this purpose, the performance of various complex water-based substances was studied using the MTM device. It should be pointed out that the performance of some substances was evaluated in both liquid and dried form in order to evaluate how much the drying effect influences the adhesion in the contact. At first, the effect of individual constituents of FMs (without the base medium) was investigated because the application of single particles represents a possible method how to manage adhesion at the wheel-rail interface. These findings showed that both considered PFM (talc and zinc oxide particles) are able to provide an intermediate and relatively stable level of adhesion without adhesion drops as was previously found for alumina particles [39].

Subsequently, the performance of two component substances was investigated for various applied quantities, even under fully flooded conditions, to determine the worst possible scenario which can occur in the contact. The following types of two-component substances were examined: substances containing water and a binding agent and substances containing water and PFM. For both of them, it was observed that even two-component substances can offer a beneficial friction behaviour (see Fig. 6.4), even under fully flooded conditions. However, some adhesion risks were identified for substances containing water and a high content of mineral PFM (talc particles). It was established that an inappropriately high content of PFM can cause a formation of a sufficiently viscous paste between the surfaces. This paste resulted in low adhesion values; moreover, the electric insulation of contact surfaces can cause a failure of vehicle detection system. In contrast, no adhesion risks were surprisingly identified for the substances free of PFM, even if the contact was overdosed. In this case, the performance of substances is significantly affected by the content of binding agent which influences the apparent viscosity of substance. Based on the experiments with two-component substances, it was concluded that the lasting effect of substances can be mainly controlled by the applied quantity, whereas the shape of friction curve (average adhesion) is mainly

affected by the chemical composition. The lasting effect seems to be insensitive to the changes in chemical composition.
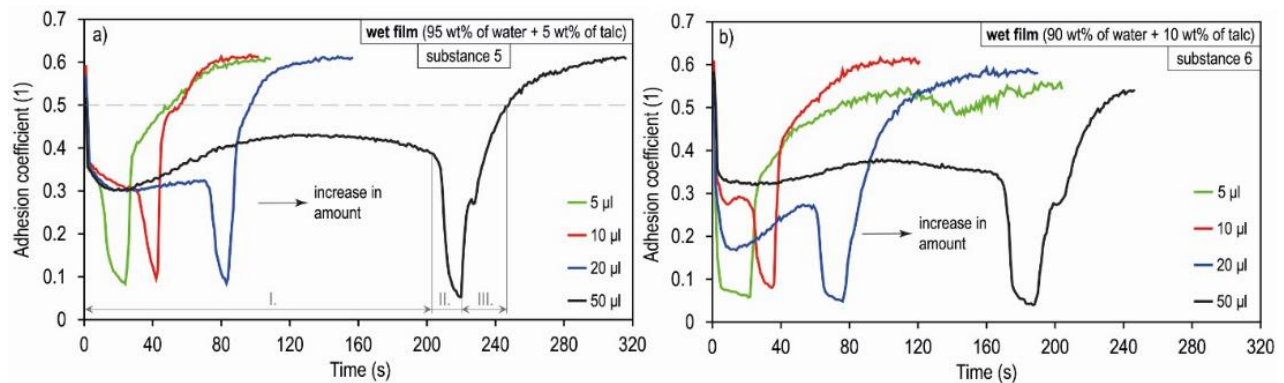


**Fig. 6.4** Effect of substance quantity and content of talc particles on adhesion

When complex substances containing water, binding agent, and PFM were tested, it was surprisingly revealed that the performance of these substances is mainly given by the effect of water and binding agent, while the effect of PFM, when the mineral PFM were used, was negligible or rather negative for all tested contents of PFM, as is depicted in Fig. 6.5a. In this case, a critically low adhesion was observed immediately after the application as a result of presence of PFM. After that, the friction behaviour corresponded to the behaviour of substances containing water and a binding agent. Note that a similar trend of friction curve, where the gradual increase in adhesion was found over the time, was previously identified for complex FMs [35]. A different friction behaviour was found for complex substances where zinc oxide particles were used as PFM. In this case, PFM can advantageously control the lasting effect without adhesion drops. The higher was the content of oxide particles (PFM), the shorter was the lasting effect, see Fig. 6.5b. This different behaviour of substances with different types of PFM can be attributed to a different Mohs hardness of mineral and oxide particles. Note that the Mohs hardness of zinc oxide particles is five time higher compared to talc (mineral particles). It indicates that while softer mineral particles are quickly crushed in the contact and create a thin friction film, the effect of harder oxide particles is rather abrasive.
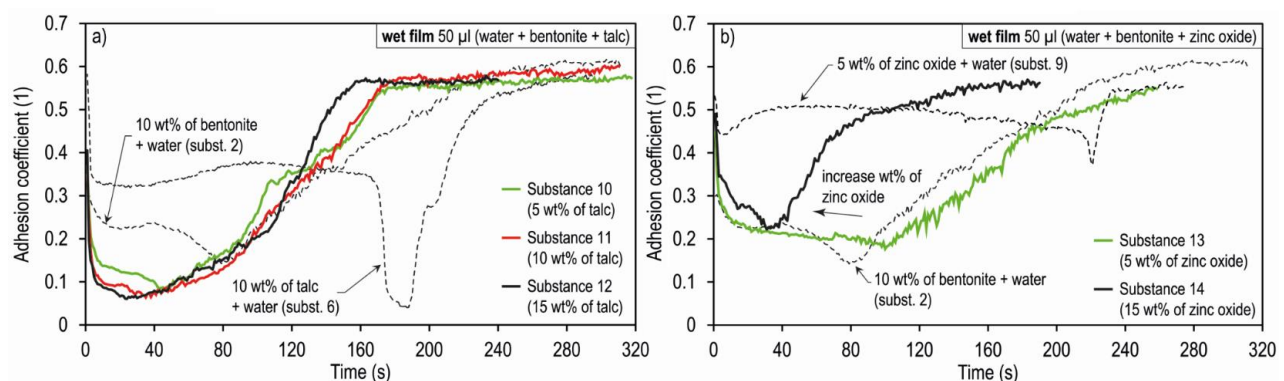


**Fig. 6.5** Complex substances with mineral particles (a) and with zinc oxide particles (b).

Afterwards, a solid lubricant (graphite or molyka) was added into the above-mentioned complex substances and their performance was investigated in both liquid (the so-called wet film) and dried form (the so-called dry film). These results indicate that the presence of solid lubricant in complex substances is beneficial only for dry films where molyka seems to be a more appropriate lubricant for top-of-rail friction modification in comparison with graphite leading to poor adhesion conditions. In the case of wet films, a critical low adhesion occurred for all the tested substances and quantities. On the contrary, a very appropriate friction behaviour was achieved for dry films, especially when PFM are mineral particles. It should be also noted that the performance of these substances was not significantly influenced by the quantity because a stable and constant adhesion (approx. 0.2) was found for all tested quantities. These findings gave the evidence that evaporation of base medium significantly changed the performance of water-based substances/FMs. It can also be concluded that the substances with zinc oxide as PFM are more beneficial in the case of wet film, while mineral particles as PFM provide better friction properties after evaporation.

Finally, the ability of complex water-based substances to reduce wear and surface damage was investigated for both dry and wet films. These experiments showed that all the tested substances are able to substantially reduce the wear rate, particularly in the range from 66–87%. Apart from wear rate, roughness and surface damage were considerably reduced compared to baseline conditions where deep scoring marks were identified on the disc surface. Unexpectedly, the substances that used mineral particles as PFM caused more than a double wear rate in comparison with substances containing zinc oxide particles in spite of the fact that the average adhesion during the experiment was almost the same. These results correspond to the study [39] where mineral (quartz) and metal (alumina) particles were used for top-of-rail friction modification. This study [39] revealed that softer quart particles caused a higher mass loss than harder alumina particles. It can be explained by the differences in the shape and sharpness of the used particles. Besides this, it was also revealed that dry films (substances) caused a lower wear rate compared to wet films. The possible explanation is that the dry films are able to form a more durable friction layer (compared to the layer with water); this reduces or even avoids the contacts of surface asperities during experiments. The result is that this dry layer provides an intermediate level of friction. When this layer becomes too weak to withstand the shear stress, it is quickly removed from the contact surfaces and then the substance is re-applied. It means that there is only a very short time period when the partial or complete metal-to-metal contact occurs. In contrast, a gradual increase in adhesion was observed for wet films. In this case, there was a relatively long-time period when the contact of surfaces asperities occurred; therefore, a higher wear rate was evaluated in this case. It should be emphasized that wet substances resulted in a longer lasting effect.

# 7 CONCLUSIONS

The present doctoral thesis deals with the performance of TOR products which are used in rail transportation as a part of the so-called friction management methods. This new approach to top-of-rail friction management is primarily used to reduce noise, wear, and rail head corrugations. In the last 20 years, many scientific investigations have been aimed at verifying the benefits of TOR products (FMs and TOR lubricants) using both laboratory and field experiments. Although the so-far published articles proved the ability of TOR products to provide the above-mentioned benefits, it should be noted that research was almost entirely carried out with one commercial water-based product (FM). It means that only a little is known about the friction behaviour of other TOR products, especially the abilities of TOR lubricants have not been examined in detail yet. Moreover, the so-far published articles have not usually dealt with the influence of applied quantity in spite of the fact that it may be one of the most important factors influencing adhesion in the wheel-rail contact. With respect to the critical analysis of the current state of the art, the main goal of this doctoral thesis was to clarify the friction behaviour of TOR products (FMs and TOR lubricants) in terms of adhesion, wear, and noise reduction, while the main attention was paid to low adhesion issues related to the application of these substances.

The original results of this doctoral thesis are published in three scientific papers. The aim of the first paper was to investigate if TOR lubricants are able to provide the same benefits as FMs (the intermediate level of friction, positive traction curve, and wear reduction). For these purposes, two commercial TOR lubricants with different content of PFM were used in order to investigate how significantly the performance of TOR lubricants varies with regard to a different content of PFM. Apart from this, the influence of TOR lubricant quantity on adhesion was studied to reveal if TOR lubricants can cause traction and braking difficulties. Note that besides the reasonably small quantities, the experiments under fully-flooded conditions were conducted to evaluate the possible worst case when the wheel-rail contact is overdosed with TOR lubricant. At the end of this study, wear and surface damage of specimens were analysed and compared with the results obtained under dry and oil conditions. The most important conclusion was that the over-application can lead to extremely low adhesion values compromising traction and braking performance. Following these findings, the goal of the second paper was to verify the results obtained in the first paper using another experimental device (a twin-disc machine) and field measurements (a light rail system). Furthermore, the ability of TOR lubricant to reduce noise was investigated both under laboratory and field conditions. The last paper was focused on the friction behaviour of FMs with various complexities in order to describe the effect of individual constituents of FMs on adhesion and film formation. As in the case of the first paper, the performance of substances was evaluated for various applied quantities. Moreover, some of these experiments were performed in both liquid and dry form (after base medium

evaporation) in order to investigate how the drying effect affects their performance. At the end of this study, the effect of these water-based substances on wear and surface damage was determined.

The current thesis contains the original results extending the knowledge in the area of friction modification within the wheel-rail contact. The results are confronted with the previous studies. A further step should be to expand the knowledge about the interaction of TOR products with common railhead contaminants under various atmospheric conditions. Besides this, the future work should be focused on the differences between the formation of friction layer in the laboratory and real conditions. Based on this, a redistribution model of TOR product could be developed; thus, a better transferability of laboratory results to the real wheel-rail contact can be achieved. The main contribution of the thesis can be summarized as follows:

- The influence of applied quantity was revealed for both TOR lubricants and FMs with various complexity where even the experiments under fully-flooded conditions were carried out in order to evaluate the worst possible scenario (over-application).

- The ability of TOR lubricants to provide the required adhesion level, wear and noise reduction was investigated and verified using both laboratory and field approaches.

- For the first time, the effect of composition of FMs on adhesion and wear was studied for both liquid and dried form of FMs in order to describe the role of particular constituents of FMs and to evaluate how much the drying effect influences adhesion.

Regarding the scientific questions, the obtained knowledge can be summarized in the following concluding remarks:

- Experiments conducted using both a ball-on-disc tribometer and a twin-disc machine proved that the larger is the applied quantity, the longer is the lasting effect of TOR products (**hypothesis H1 was confirmed**).

- Whereas the shape of friction curve can be advantageously controlled by the applied quantity in the case of TOR lubricants, almost no changes in the shape of friction curve were observed for water-based substances (FMs) with increasing applied quantity (**hypothesis H2 was falsified**).

- Regarding both the laboratory and field measurements, it seems to be difficult to achieve a significant reduction of noise without the impact on traction and braking capabilities. Even if the beneficial N-shape behaviour of TOR lubricant was identified, some adhesion losses were identified during the first cycles of measurements after the application (**hypothesis H3 was falsified**).

- The over-application of wheel-rail contact by TOR lubricants caused the critically low adhesion in spite of the fact that PFM enter the contact. These results were subsequently verified by field experiments where the over-

application led to the significant extension of braking distance accompanied by complete wheels slide. It means that over-application can lead to braking and traction issues. Some adhesion risks were also identified for FMs with solid lubricant or with a high content of mineral particles as PFM (**hypothesis H4 was falsified).**

- The field experiments revealed that the most significant extension of braking distance occurred during the second or the third pass after the application of TOR lubricants, while the braking distance closest to baseline conditions was found for the first pass after the application (**hypothesis H5 was falsified**).

- In the case of complex FMs, zinc oxide particles used as PFM had the dominant effect on friction behaviour of FMs. However, the opposite effect was found for mineral particles as PFM where the friction behaviour was mainly given by the effect of water and binding agent. In this case, the effect of PFM was even rather negative (**hypothesis H6 was falsified**).

- TOR lubricant with higher content of PFM generally provided the longer or the same lasting effect as TOR lubricant with lower content of PFM. In the case of complex FMs, the different dependencies were identified with respect to type of PFM. When oxide particles were used as PFM, then the lasting effect was shortened with the increasing content of PFM. In contrast, the lasting effect was almost insensitive to the changes in the content of PFM when mineral particles were used (**hypothesis H7 was falsified**).

- It was found that substances free of PFM can be used as TOR product because they were able to provide beneficial friction behaviour (**hypothesis H8 was falsified**).

- When the performance of FMs was evaluated in both liquid and dried form, it was revealed that dry substances provided the shorter lasting effect; however, lower wear rate was achieved for these dry substances (**hypothesis H9 was falsified**).

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2.  SVOBODA, P., D. KOŠŤÁL, R. GALAS, I. KRUPKA and M. HARTL. Tribological behaviour of ultra-dispersed diamond- graphite in liquid lubricants. *Journal of the Balkan Tribological Association,* 2016, 22(4A), 4994-5009. **(Journal impact factor = 0.737)**

3.  GALAS, R., D. KVARDA, M. OMASTA, I. KRUPKA and M. HARTL. The role of constituents contained in water-based friction modifiers for top-of-rail application. *Tribology International*, 2018, 117C, 87-97.
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4.  SPERKA, P., R. GALAS, M. OMASTA, I. KRUPKA and M. HARTL. Particle tracking in the central zone of an elastohydrodynamic contact. *Tribology International*, 2017.
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2.  GALAS, R. and M. OMASTA. The Effect of Friction Modifier on the Wheel- Rail Contact. In The Latest Methods of Construction Design. *Springer International Publishing*, 2016, 133-138.

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3. GALAS, R., M. OMASTA, I. KRUPKA and M. HARTL. The "low adhesion" problem – the influence of friction modifier composition on adhesion and film formation in wheel-rail contact. *First International Conference on Rail Transportation*, 2017, Chengdu, China.

# CURRICULUM VITAE

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## Education

- **2013 – 2017** Doctoral study at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology. Topic of the dissertation thesis: *Friction modification with wheel-rail contact*.

- **2011 – 2013** Master study at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology. Topic of the diploma thesis: *Design of experimental stand for the study of railway vehicles sanding*.

- **2008 – 2011** Bachelor study at Faculty of Mechanical Engineering, Brno University of Technology. Topic of the bachelor thesis: *Stroke mechanism of crane trolley*.

- **2004 – 2008** Secondary Industrial School and Business Academy, Uničov. Branch: Mechanical Engineering. Passed with distinction.

## Awards

- 2013 – Dean´s award for the excellent diploma thesis
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## Teaching activities – seminars:

- CAD (3CD)
- Machine design and Machine Elements (CKP)
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## Participations in scientific projects

- 2017 – 2019: Study of the influence of lubricants rheology in elastohydrodynamic lubricated contacts (FSI-S-17-4415).

- 2016 – 2020: RISEN - Railway Infrastructure System Engineering Network (H2020-MCSA-RISE-Hartl)

- 2014 – 2017: Research and Development of System for Top-of-Rail Friction Management in Rail Transport (TA04030528).

- 2014 – 2016: Through-thickness fluid flow measurement in concentrated contacts (GP14-31139P).
- 2014 – 2016: Study of friction, wear, and lubrication of hip replacements (FSI-S-14-2336).

**Internships**

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- Tribology of wheel-rail contact
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## ABSTRACT

This dissertation thesis deals with an experimental study of top-of-rail products, specifically top-of-rail lubricants and friction modifiers, which are applied into the wheel-rail contact to optimize adhesion and reduce noise. The main goal of this thesis was to clarify the effect of the applied quantity and chemical composition of top-of-rail products on adhesion. The main attention was paid to low adhesion issues, associated with the application of these products, because low adhesion can result in traction and braking difficulties. This experimental study was conducted in both the laboratory and real conditions where a light rail system was utilized. In the case of laboratory investigations, a commercial tribometer and a twin-disc machine, enabling to achieve typical curve conditions, were employed. Apart from adhesion, wear and noise were analysed during the experiments. The obtained results showed that top-of-rail lubricants are able to provide a beneficial friction behaviour but their performance is strongly affected by the applied quantity. When the contact was overdosed with a top-of-rail lubricant, then a critically low adhesion resulting in a significant extension of braking distance was observed. In the case of friction modifiers, it was revealed that evaporation of base medium considerably changed a friction behaviour of these substances. Besides this, it was investigated that a high content of particles for friction modification can cause low adhesion issues. In general, it was observed that both types of top-of-rail products are able to significantly reduce wear and surface damage, while it seems to be difficult to achieve a significant reduction of noise without the impact on traction and braking capabilities. At the end of the present thesis, some future research steps in this area are recommended.

## ABSTRAKT

Předložená dizertační práce se zabývá experimentálním studiem modifikátorů tření a maziv pro temeno kolejnice, které jsou aplikovány do kontaktu kola a kolejnice za účelem optimalizace adheze a redukce hluku. Hlavním cílem práce bylo objasnit vliv aplikovaného množství a složení těchto látek na adhezi v kontaktu. Hlavní pozornost byla věnována zejména potencionálním hrozbám souvisejících s kriticky nízkou adhezí, která může nastat po aplikaci těchto látek. Experimentální studium probíhalo v laboratorních i reálných podmínkách, konkrétně v tramvajovém provozu. V případě laboratorních experimentů byl využit komerční tribometr a dvoudiskové zařízení umožňující simulovat průjezd vozidla traťovým obloukem. Kromě samotné adheze bylo při experimentech sledováno také opotřebení a míra hluku. Výsledky ukázaly, že maziva pro temeno kolejnice jsou schopna poskytovat požadované třecí vlastnosti, nicméně jejich chování je silně závislé na aplikovaném množství. V případě předávkování kontaktu dochází ke kriticky nízkým hodnotám adheze, které vedou k výraznému prodloužení brzdné dráhy. V případě modifikátorů tření bylo ukázáno, že chování těchto látek je výrazně ovlivněno odpařováním základního média. Výsledky také ukázaly, že nadměrné množství částic pro modifikaci tření může způsobit kriticky nízké hodnoty adheze. U obou výše zmíněných typů produktů byl prokázán pozitivní vliv na míru opotřebení a míru poškození povrchu, zatímco významná redukce hluku byla dosažena pouze v případech, kdy došlo ke značnému poklesu adheze. V závěru této práce jsou uvedena doporučení pro další výzkumné aktivity v této oblasti.