Railway Open System Tribology

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Academic thesis, which with the approval of KTH Royal Institute of Technology, will be presented for public review in fulfilment of the requirements for a Doctor of Engineering in Machine Design. Public review: KTH Royal Institute of Technology, Brinellvägen 85, room Gladan, at 10:00 on April, 27, 2018.
To my wife, Fangfei
and my daughter, Vilja
献给方飞和橙
Preface

Open system tribology involves the physical and chemical fundamentals at the interacting surfaces in relative motion. For a long time, people used to consider friction, wear and lubrication as the major topics of tribology and neglected the interaction with the surrounding environment. Noise and particle emissions, for example, strongly affect the health of human beings and the environment, which should also be considered simultaneously in tribology research. This thesis attempts to relate friction, wear, noise and particle emissions from the railway system with the open environment.

I started my PhD study from an unfavourable beginning within a topic that I had no interest in. I had felt perplexed for months about whether to continue the PhD study. I am deeply grateful to Prof. Ulf Olofsson, for it is he who introduced the field of tribology to me at that difficult time and encouraged me to continue my study under his supervision. Many thanks are also given to my co-supervisor Dr Ellen Bergseth, for her consistent patience, encouragement and support throughout my study. I was fortunate and happy to learn a great deal from them.

I wish to give my appreciation to all of the people who helped with my PhD research and preparation of the thesis, including the co-authors of the appended papers: Assoc. Prof. Stefan Björklund (KTH), Dr Rickard Nilsson (SLL), Dr Yi Zhu (Zhejiang University), Anders Lindgren (Tyréns), Martin Höjer (Tyréns), Minghui Tu (KTH).

Thanks are extended to all of my colleagues at KTH: Assoc. Prof. Jens Wahlström, Assoc. Prof. Anders Söderberg, Mr Peter Carlsson, Mr Staffan Qvarnström, Dr Kenneth Duvefelt, Dr Mario Sosa, Dr Martin Andersson, Dr Xuan Sun, Mrs Yingying Cha and Mr Edwin Bergstedt for their advice and assistance during my studies. Many thanks are given to Prof. Martin Törngren at KTH for his valuable comments on the thesis.

In addition, I want to acknowledge all of my friends: Ye Tian, Huijun Wang, Xin Xu, Xuge Fan, Jiaqing Yin, Peng Liu, Dan Li, Linqin Wang, Zhendong Liu and Yuyi Li for being with me during these years.

Finally, the deepest thanks go to my parents, my lovely wife Fangfei and my cute daughter Vilja. Your love means everything to me.

Yezhe Lyu
Stockholm, February 2018
Abstract

Tribology in the railway system is of increasing interest in the new railway era due to the demand for higher speed and load capacity. Since railway vehicles operate in an open environment, their performance depends greatly on temperature, humidity and natural and artificial contaminants. Meanwhile, the “feedback” of railway vehicles to the surroundings, such as noise and airborne particles, is of great importance to the human health and the environment. Therefore, this thesis aims to investigate the strong interaction between railway tribology and the open environment.

The effects of temperatures from -35 °C to 20 °C, relative humidity from 40% to 85%, natural contaminants such as ice particles on friction, wear, noise and airborne particle emissions at the wheel–rail and wheel–block brake contacts have been investigated in both lab- and full-scale contexts.

Papers A and B investigated the effect of temperature, humidity and ice particles on the friction and wear at unoxidized and oxidized wheel–rail contacts. The results indicate that increasing humidity reduces the wear at unoxidized contacts. A decrease in temperature tends to intensify the wear until an ice layer has condensed on the wheel and rail surfaces at -25 °C. Ice particles encourage the generation of oxide flakes at the contacting path, largely inhibiting the wear process.

Paper C, which was a lab-scale test, studied the friction, wear and noise generation from pre-oxidized wheel–rail contact with varied surface features. Major results include that the wear regime transition from mild wear to severe wear is always accompanied by an increase in noise level of 10 dB and a broader bandwidth of noise.

Paper D was a validation of the major findings of paper C in a full-scale test, which also saw an increase in noise level as well as a broader bandwidth when the wheel–rail contact transformed from mild to severe wear.

Paper E studied the effect of humidity on the friction, wear and airborne particle emissions of three railway brake-block materials. The results show that cast iron generated the highest friction coefficient, wear and particle emission, and organic composite the lowest levels.

Paper F conducted a thorough literature review on the open system tribology at the wheel–rail contact. Commonly seen parameters such as temperature, humidity and natural and artificial contaminants on friction, wear, noise and particle emissions were investigated.

Keywords
Wheel; Rail; Brake; Environmental conditions; Tribology; Noise; Particle
Sammanfattning

Järnvägsfordonen arbetar i en öppen miljö, vars prestanda och livslängd i form av friktion och nötning beror på temperatur, luftfuktighet samt naturliga och konstgjorda föroreningar. Samtidigt är återkopplingen, som järnvägsfordon ger till omgivningen i form av buller och luftburna partiklar, av stor betydelse för människors hälsa. Därför är målsättningen med denna avhandling att undersöka den starka samverkan som finns mellan järnvägsfordon och den öppna miljön.

Effekten av, temperaturer från -35 °C till 20 °C, relativ fuktighet från 40 % till 85 % och naturliga föroreningar som snö, på friktion, slitage, buller och luftburna partikelutsläpp vid hjulräls- och hjulblockbromskontakter har undersökt, både i laboratorier och i full skala.

Manuskript A och B undersökte effekten av temperatur, luftfuktighet och snö på friktionen och nötning vid oxiderade och icke-oxiderade hjulrälskontakter. Resultaten visar att en ökad luftfuktighet, minskar nötningen vid icke-oxiderade kontakter. Minskning av temperaturen tenderar att intensifiera nötningen, tills is kondenseras på hjul- och rälsytorna vid -25 °C. Iskristallerna, ökar hastigheten på genereringen av oxidflingor i kontakten, och förhindrar i stor utsträckning nötningsprocessen.

Manuskript C, som är ett laboratorieprov, studerade friktionen, nötningen och ljudgenerering från föroxiderade hjulrälskontakter med varierande yttopografi. Viktiga resultat, är att övergången, från mild nötning till svår nötning, alltid åtföljs av en ökad ljudnivå och en ökning av ljudets bandbredd.

Manuskript D är en fullskalevalidering av huvudresultatet från Manuskript C, vilket också uppsvisade en ökning av ljudnivån om hjulrälskontakten gick från mild till svår nötning åtföljt av en ökning av ljudets bandbredd.

Manuskript E studerade effekten av luftfuktighet på friktion, nötning och luftburna nötningspartiklar av tre olika blockbromsmaterial. Resultaten visar att gjutjärn genererade den högsta friktionskoefficienten, nötningsnivån och halten av partikelutsläpp. Blockbromsar tillverkade av organisk komposit, uppvisade den lägsta nivån för alla tre uppmätta parametrar.

Manuskript F redovisar en litteraturgenomgång, hur det öppna systemet, påverkar tribologin i hjul-järnvägskontakten. Parametrar som temperatur, fuktighet, naturliga och konstgjorda föroreningar på friktion, slitage, buller och partikelutsläpp diskuterades i detalj.

**Nyckelord**

Hjul; Räl; Broms; Miljöförhållanden; Tribologi; Ljud; Partiklar
Appended papers and the author’s contribution

**Paper A**


Contributions: Lyu planned the experiments, did the literature survey, the major part of the experiments, the data analysis and the major part of the writing. Zhu performed part of the experiments and writing. Olofsson supervised the work and wrote part of the paper.

**Paper B**


Contributions: Lyu formulated the research questions and chose the methodology to answer them. Lyu did the literature survey, the major part of the experiments, the data analysis and the major part of the writing. Bergseth did part of the experiments. Bergseth and Olofsson both supervised the study and wrote part of the paper.

**Paper C**


Contributions: The experimental work was equally divided between Lyu, Bergseth, Olofsson, Lindgren and Höjer. Lyu and Lindgren analysed the data. All authors were involved in the writing of the text, of which Lyu did the major part.
**Paper D**


Contributions: The experimental work was equally divided between all the authors. Lyu did the literature review and analysed most of the data. All authors were involved in writing and editing the text.

**Paper E**


Contributions: Lyu formulated the research questions and chose the methodology to answer them. Lyu also did the literature survey, data analysis and the major part of the writing. Tu did part of the experiments and writing. Bergseth and Olofsson supervised the work, discussed the results and wrote part of the text.

**Paper F**


Contributions: Olofsson formulated the frame of the paper. Lyu did the major part of the literature survey. Olofsson and Lyu were equally involved in writing the paper.
Contributed papers not included in this thesis


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Appended papers

A Wear between wheel and rail: A pin-on-disc study of environmental conditions and iron oxides
B Open system tribology and influence of weather condition
C On the relationships among wheel–rail surface topography, interface noise and tribological transitions
D Development of a noise related track maintenance tool
E Effect of humidity on the tribological behaviour and airborne particle emissions of railway brake block materials
F Open system tribology in the wheel–rail contact—A literature review
1 Introduction

This thesis deals with experimental methods at lab-scale and full-scale levels for investigating the wheel–rail and wheel–block-brake contacts in the railway open system with respect to tribological phenomena. The first five appended papers address the experimental methods for measuring the friction, wear, sound and airborne particle emissions from the wheel–rail and wheel–brake contacts. The last appended paper presents a literature review of recently documented studies of the open system tribology in wheel–rail contact.

An introduction to the railway open system tribology is given in Section 1.1. Iron oxides [1], which are believed to be essential in the tribological process of wheel–rail and wheel–brake contacts, are introduced in Section 1.2. The importance of the sliding part in the wheel–rail contact is demonstrated in Section 1.3. Emission of sound and airborne particles is discussed in Section 1.4. Section 1.5 presents the objectives of this thesis. Finally, the methods used in the experimental studies involved are summarized in Section 1.6.

1.1 Railway open system tribology

Tribology, the science of interacting surfaces in contact, is an interdisciplinary subject that can be addressed from several different viewpoints [2]. The interacting surfaces deliver different characteristics in terms of friction and wear due to the surface topography, hardness, plastic deformation, etc. These parameters are often set in the manufacturing processes and in the material selection of the surfaces and bulk material. One possible division of tribological systems is
by open and closed system tribology. If the system is sealed away from the external environment, like bearings and seals, one can call it a closed system; this enables a better control of the friction, wear and applied lubrication due to the isolation of external contaminants. In addition, such a system partly or totally obstructs the emission of sound and particulates. In contrast, an open system like tyre–road contact is exposed to the external environment where artificial and natural contaminants will exert an influence on friction and wear. Sound and airborne particles from the friction and wear process have no shield and will be emitted to the surrounding air [3].

Railway vehicles contain several typical open tribology systems – like wheel–rail contact and block brake–wheel tread contact – that are exposed to natural contaminants such as high humidity, rain, snow, sand and leaves. Meanwhile, the radiated noise from the railway vehicles may disturb passengers when a railway vehicle traverses sharp curves. Particulates will also be generated from the wear process at the wheel–rail contact and block brake–wheel tread contact during acceleration and deceleration/braking of the railway vehicles. Airborne particles can easily drift for hundreds of metres in the open environment [4], which may exert both short- and long-term adverse effects on lung function [5].

In railway operations, a friction coefficient at a proper level is demanded. Too high or too low a friction coefficient at the wheel–rail contact will result in a series of adverse consequences as shown in Figure 1. Too low a level leads to a schedule delay due to poor traction and brake coefficients [6]. A conspicuous trend of prolonged braking distances was
recorded during the very rainy days in the railway traffic statistics of the UK and Sweden [7]. Meanwhile, too high a value causes rapid exhaustion of materials because of high wear damage.

Temperature and humidity are among the most erratic environmental parameters and have been found to affect the friction and wear damage and friction coefficient at clean and oxidized wheel–rail contact (Figure 2). If the temperature dropped off to -15 °C, the wheel–rail contact yielded a wear rate ten times higher compared with the one measured at 10 °C. If a further reduction in temperature to -35 °C was seen, the wear rate at the wheel–rail contact fell off to the same level as the one at 10 °C (Figure 3). This change is associated with both physics and chemistry, in that at -15 °C the ductility of wheel and rail steel largely decreases and thick oxide layers that protect the materials flourish at -35 °C.

![Figure 1. Typical friction coefficient levels at the wheel–rail contact and their consequences [3].](image-url)
Other parameters exist in the railway open system including natural (water, leaves, etc.) and artificial (friction modifiers and lubricants) contaminants. A large number of studies have seen the decrease of friction and wear when water is present at wheel–rail and brake–wheel contacts [10–18]. Snow (water in solid form) has been proved to strongly affect the friction coefficient at the wheel–rail contact under different contact pressures (Figure 3). Although the mechanism of reducing the friction coefficient using water presence is still debated, most believe that water encourages the generation of iron oxides at the contact, inhibiting...
friction [14, 19]. Further, water was found to have a better lubrication effect than oil on extremely smooth surfaces Ra (centreline average roughness) of 0.1 μm, showing a great potential as an environmentally friendly lubricant [20]. Fallen leaves represent another commonly seen natural contaminant for railway traffic. Once the leaves are dragged into the wheel–rail and wheel–brake contacts, they will chemically react with the steel materials and generate a coherent black layer on the steel surfaces, reducing the friction coefficient [21, 22].

Figure 3. Friction coefficient as a function of temperature, which declined with snow (water in solid form) presenting at the wheel–rail contact [19].
Due to the complexity of the railway system, some artificial contaminants are frequently added into the wheel–rail contact to maintain a proper friction level. These include positive friction modifiers that enhance the friction and lubricants that reduce the friction. Positive friction modifiers can be solid or liquid, and most are confidential commercial products. They are usually added into the wheel head–rail tread contact for maintaining the friction coefficient at a proper level (normally 0.2–0.4) to eliminate noise and rail corrugation [23–25]. A significant side effect of the positive friction modifiers is that they introduce wheel–rail contact insulation, resulting in signal interruption [26, 27]. Conversely, lubricants are usually applied to the wheel flange–rail gauge contact on curving tracks to relieve the wear and noise problem. A vast number of studies with varied types of instruments have found that oil-based and grease-based lubricants significantly downgrade the friction coefficient at the wheel–rail contact [28–35]. Meanwhile, it is important to appropriately manage lubrication at the rail gauge. Over-dosed lubricants are apt to move to the rail head, causing a loss of friction.

1.2 Oxide formation

This section introduces the iron oxides that are generated at the wheel–rail contact and wheel–brake contact and discusses the contribution of iron oxides to friction and wear. Although the mechanisms of friction and wear at the wheel–rail contact and wheel–brake contact are of great complexity, the generation of iron oxide layers on material surfaces is suggested to be responsible for the friction and wear process. Mølgaard and Srivastava stated that oxidation clearly leads to
the wear of dry surfaces of ferrous materials at moderate and high sliding speeds, because the wear debris generated under such conditions is mostly composed of oxides [36].

There are in total fifteen types of iron oxides, which are different in chemical composition and crystal structure, but only five kinds are usually found in the context of railway traffic under different environmental conditions. Suzumura et al. applied a portable X-ray diffractometer equipped with X-ray fluorescence in situ and identified the iron oxides as follows: hematite (Fe$_2$O$_3$) and magnetite (Fe$_3$O$_4$), which are anhydrous, and goethite (α-Fe$_2$O$_3$·H$_2$O), akaganeite (β-Fe$_2$O$_3$·H$_2$O) and lepidocrocite (γ–Fe$_2$O$_3$·H$_2$O), which are hydrated (also called rust) and only differ in crystalline system and colour [37]. Iron oxides can naturally form on the surfaces of wheel, rail and brake in an atmospheric environment, but will generate more promptly during sliding at the wheel–rail contact and wheel–brake contact where temperature is high.

In an atmospheric environment, iron oxides will slowly form through electrochemical corrosion, which involves the oxidation of wheel and rail steels by oxygen as the oxidizing agent [38]. This reaction usually occurs in wet weather (high relative humidity), where the aqueous layer covering the wheel and rail surfaces will act as an electrolyte (as shown in Eq. 1). Under such conditions, the oxidation rate is controlled by the amount of electrolyte (available water) and the products are usually hydrated.

$$4Fe(s) + 3O_2(g) \rightarrow 2Fe_2O_3 \cdot xH_2O$$ (1)
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When the weather is dry (low relative humidity), electrochemical oxidation is unlikely to happen, or the rate of reaction becomes quite low. However, oxidation of steel would still happen through a thermal corrosion process. Under such conditions, the water layer is not necessary and the temperature becomes the controlling factor. With increasing temperature, the diffusion of iron ions and oxygen is expedited, speeding up the oxidation reaction. At room temperature, the oxide layer is very thin, about several nm, while a thick and coherent oxide layer will form at elevated temperatures. Transformations between different types of oxides may happen under alternating dry and wet cyclic weather conditions. Generally, rusts (hydrated oxides) tend to transform to anhydrous oxides under dry conditions and the other way around under wet conditions [39]. The dominating mechanism of the transformation is “topotaxy”, which includes all chemical solid state reactions where one crystal orientation changes to another crystal orientation [40].

If the surface of the metal is smooth enough, a homogeneous oxidation will occur, where a coherent and compacted oxide layer will form on the surface. But this is usually not the case for the wheel and rail surface. Since the wheel and rail surfaces constantly experience rolling-sliding contact, plastic deformation and tiny defects will occur on the surfaces, encouraging pitting and localized corrosion. The oxide will first form as a spot. If this spot has enough binding force with the metal, it will stay and become an oxide layer (oxide island), preventing the metals from experiencing severe wear. On the contrary, if the binding force between the oxide spot and the surface is too weak, it will be sheared off.
by the rolling-sliding contact and pulverized into tiny particles, accelerating the abrasive wear as third bodies [41].

Great efforts have been made to study the influence of oxides on the friction at the wheel–rail contact and wheel–brake contact. A large drop of friction and wear was found at the wheel–rail contact where an intact oxide layer formed and thoroughly covered the surface [42, 43]. Iwabuchi et al. demonstrated that the friction coefficient declines as the oxide thickness increases, based on their own research in combination with the work of Kragel’skiĭ [44, 45]. Beagley found that the friction coefficient becomes extremely low when a paste containing iron oxide and a small amount of water is formed [43]. An increase in the coverage of the oxide layer leads to a decline in the wear coefficient [46]. The oxide layers formed also contribute to a decrease in wear rate. Zhu and Olofsson conducted a pin-on-disc study and found that the oxidized samples at high humidity yielded a lower wear rate compared with the unoxidized samples [47]. Stott revealed that oxidation is beneficial for reducing wear during sliding of metals by preventing metal–metal contact. Thermal corrosion can be easily induced by frictional heat [1].

1.3 The sliding part of the wheel–rail contact

Unlike the pure sliding wheel–brake contact, wheel–rail contact can be divided into two types – the contact between wheel tread and rail head, and the contact between wheel flange and rail gauge (Figure 4). The wheel tread–rail head contact is usually seen on straight tracks and wheel flange–rail gauge contact always occurs on sharp curves. As with the
wheel–brake contact, the wheel flange–wheel gauge contact is also a pure sliding contact accompanied by very high contact pressure and large plastic deformation. The wheel flange–rail gauge contact usually experiences wear transition from severe to catastrophic and wheel tread–rail head contact from mild to severe [48]. The wheel tread–rail head contact is a rolling-sliding contact that contains stick (no-slip) and slip regions [49].

Figure 4. Schematic of two typical types of wheel–rail contact: a) wheel tread–rail head contact and b) wheel flange–rail gauge contact.

Zhu has described the stick-slip contact condition between the wheel tread and rail head [50]. Briefly, there should be a proper ratio between the rolling (stick) part and sliding (slip) part at the wheel tread–rail head contact. The sliding (slip) part always exists and results in the frictional heating of both the wheel and rail [51]. As a consequence of occasionally excessive temperature, phase transformation and materials softening will happen, resulting in some troublesome damage such as melting and cracks on the wheels and rails [52]. Besides, the slip (sliding) part dominates the friction
coefficient at the wheel–rail contact, restricting the load capacity, traction and brake coefficient. Therefore, the sliding part of the wheel tread–rail head contact deserves detailed investigation and a large number of studies have focused on this topic [53–59].

1.4 Noise and airborne particle emissions

The railway system strongly interacts with the surroundings, and is not only susceptible to environmental conditions but also releases feedback such as noise and airborne particles. The emission of noise and airborne particles works against the promotion of the new era of the railway system with higher speeds and loading capacities, and thus draws considerable attention from railway engineers [60].

Noise from the railway system can be generated both on straight tracks and curves. Rolling noise and impact noise are usually heard on straight tracks and stem essentially from the imperfect surface conditions of the wheels and rails. The continuous noise caused by regular surface roughness is the rolling noise and the intermittent noise due to imperfect rail joints, wheel flats, switch and crossing gaps is called impact noise [61]. Rolling noise is thought to be the main source of noise from the railway system and can be reduced through measures such as smoothing wheel and rail surfaces and shielding bogies and rails [61, 62]. The same countermeasures also work efficiently for impact noise.

Squeal noise is believed to be generated through a stick-slip mechanism. When traversing a curve, the traction force makes the wheel slip whilst the static friction makes the wheel stick. These two forces alternatively dominate and
motivate the resonance of the wheels (vibration around the natural frequency) [63]. Squeal noise is much more inadvertent than rolling noise and impact noise, which is thought to be easier to eliminate. Since static friction is one important parameter that activates squeal noise, friction management at the wheel–rail contact becomes important for its control, and will involve all parameters affecting the friction coefficient at the wheel–rail contact, such as surface finishing [64], friction modifiers [65], temperature, humidity [66] and water presence [67]. The brake contact also radiates squeal noise, though current research mainly focuses on the automotive context [68–72]. Possible measures to reduce the squeal noise from automotive brake systems include modifications to the structure of the brake parts and materials. Currently there is a knowledge gap on the effect of environmental conditions on squeal noise.

Like noise, airborne particles will be emitted from both wheel–rail contact and wheel–brake contact. The inhalable particles are thought to be one of the most worrying environmental problems, raising a series of public health issues. Most studies on airborne particle emissions from the railway system were conducted in the field, where the contributions of wheel–rail contact and wheel–brake contact are hard to distinguish [61]. Most of the emitted particles are found to be deposited near railway tracks, but still some 25% will drift for over 100 metres [61]. Figure 5 shows the deposition of particles that originated from the railway system on railway tracks. Nieuwenhuijsen et al. made a comparison study of the abundant published measurements of airborne particles from railway transport and saw a clear indication that underground systems generate a higher
concentration compared with above-ground environments [73]. The composition of the emitted particles is complex. More than fifteen elements were detected from the particles collected from around the tracks [74, 75], among which Fe, Cu, Zn and Mn are dominant [76]. One lab-scale test dedicated to airborne particles from the wheel–rail contact witnessed a vast number of nano-sized particles at elevated temperatures, which usually results from high contact pressure and sliding speed [55]. The only study found on the effect of environmental conditions on particle emissions from wheel–rail contact indicated that grease-lubricated wheel–rail contact generated fewer particles than dry, water- and oil-lubricated ones [77]. Investigations into the effect of open systems on the particle emissions from railway brake systems are also rare, and the only one found was conducted by Olofsson [4]. Since the brake contacts should always be kept clean to avoid losing braking efficiency, further research is encouraged on environmental conditions (such as temperature and humidity) rather than the additives that are commonly found at wheel–rail contact.

Figure 5. Worn particles deposited at the rail foot during a field test at Högdalen test depot, highlighted with arrows.
1.5 Objectives

The open system tribology of the railway system is an open field and one which is not studied sufficiently, especially the area of wheel–block brake contact. The purpose of this thesis is to enhance the scientific knowledge about the effect of open environmental conditions on the friction, wear, noise and particle emissions from wheel–rail contact and wheel–block brake contact. This purpose is achieved by fulfilling the following objectives:

- Develop experimental methods in terms of a test stand for measuring the friction and wear from both the wheel–rail contact and wheel–block brake contact under commonly seen and well-controlled environmental conditions, e.g. temperature above 0 °C and relative humidity.

- Apply the above test design to investigate the effect of relative humidity and different contact pairs on the friction, wear and airborne particle emissions from wheel–brake contacts.

- Update and use the above test stand in more hostile environments and investigate the effect of sub-zero temperatures on the tribology at the wheel–rail contact.

- Investigate the relationships among rail surface grinding features, generated noise and wear behaviours at the wheel–rail contact in a lab-scale test. If they are related, verify the validity in full-scale tests.

- Implement a thorough literature review of open system tribology at the wheel–rail contact, summarize the archived studies and suggest future work.
1.6 Summary of the methods

This thesis comprises five different experimental studies and one literature review on railway open system tribology. In the appended papers, varied test methods are used based on two different pin-on-disc tribometers (pin-on-disc I and pin-on-disc II) and one full-scale equipped metro. In Table 1 the test apparatus, testing conditions and responses in all appended papers are summarized.

### Table 1. Summary of the test methods in the appended papers.

<table>
<thead>
<tr>
<th>Appended papers</th>
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<th>B</th>
<th>C</th>
<th>D</th>
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<tr>
<td>Pin-on-Disc II</td>
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2 Summary of appended papers

This thesis comprises six appended papers (Appendices A to F) that fulfilled the objectives of the thesis work. A summary of the six appended papers is presented below.

Papers A and B describe a test stand for measuring the friction and wear at the wheel–rail contact during varied temperature and humidity levels. This test stand was put in a well-controlled climate chamber isolated from its surroundings. Paper C applied a professional acoustic measuring technique in this climate chamber for excluding background sound from the surroundings. Paper D complemented this technique and reformulated it for a running metro train so a full-scale field test could be conducted. Paper E improved the test stand described in Papers A and B and used it to measure the particle emissions from wheel tread–brake block contact. Paper F conducted a literature review of recently published studies on open system tribology at the wheel–rail contact and suggested possible directions for future research.

Paper A presents a study on the effect of commonly seen environmental conditions (temperature and humidity) and pre-treated oxide layers on the wear of wheel–rail contact. Commercial railway wheels and rails are used as testing materials in this pin-on-disc study. The results indicate that wear mechanisms at the wheel–rail contact can be affected by various environmental conditions and the presence of oxide layers. Unoxidized wheel–rail contact in dry air was dominated by adhesive wear. With a decrease in temperature, abrasion was aggravated and increased the wear rate. In humid air, wheel–rail contact underwent both
adhesive and oxidative wear and the self-generated oxide layers prevented the materials from severe wear. Oxidized wheel–rail contact is mainly subjected to abrasive wear.

Paper B applied the same test stand as used in Paper A, which extended the testing temperature down to -35 °C and added snow instead of humid air. The added snow particles were found to melt into liquid-like layers due to pressure melting, encouraging the formation of oxide flakes at the contact path. With snow presence, the wear at the wheel–rail contact is insensitive to change of temperature. When snow was absent, the wheel–rail contact experienced extremely high friction and wear around -15 °C, owing to the high brittleness at this temperature. When the temperature decreased further to -25 °C, a condensed ice layer at the wheel–rail contact was prone to develop, which acted similarly to the added snow particles, promoting the flake-like oxide layers and relieving the wear process.

Paper C added professional acoustic measurement instruments into similar test stands as used in Papers A and B, but focused on noise generation. Five different surface finishing features were tested against their influence on friction, wear and sound generation. Surface features perpendicular to the sliding direction generated the lowest noise level for the whole duration of the test, and a smooth surface emitted the highest noise level. Meanwhile, an increase in noise level of 10 dB was always seen when the wear transitioned from mild wear to severe wear and from severe wear to catastrophic wear. A broader bandwidth of sound amplitude was also accompanied with the wear transition.
SUMMARY OF PAPERS

Paper D reformulated the test stand used in Paper C to be used for the wheel–rail contact of a metro train. This equipped train was run repeatedly in a 200 m radius test depot to aggravate the wear transition from mild wear to severe wear. The results presented similar trends to seen in the previous lab-scale test (Paper C) in that mild to severe transition always takes place, with an increase in sound pressure and broadening of the sound pressure amplitude distribution.

Paper E employed a pin-on-disc machine placed in a one-way ventilated chamber to study the friction, wear and airborne particle emission from three commercial railway brake block materials within different levels of relative humidity. The results suggested that cast iron yielded the highest level of friction, wear and particle concentration, and organic composite the lowest. Relative humidity also had a notable effect on the friction, wear and particle emission of a specific brake-block material.

Paper F reviewed most documented studies of open system tribology at the wheel–rail contact, covering four important tribological parameters in the railway system: friction, wear and sound and particle emissions. In the friction part, environmental conditions such as temperature, humidity, natural and artificial contaminants are discussed, while different wear mechanisms lead the wear part. Promising trends for future research are suggested to investigate friction, wear and sound and particle emissions simultaneously, instead of separately, which is the case in most studies.
3 Discussion

3.1 Discussion on appended papers

This thesis aimed to investigate tribological performance at the wheel–rail contact and wheel–brake contact and reveal the physical and chemical fundamentals responsible. Further, the importance of the open system on investigations of tribology was highlighted, something that is usually neglected in most cases. In the thesis work, a well-controlled test stand was designed and implemented for testing the friction and wear at the wheel–rail contact and wheel–brake contact, which was also updated for measuring noise and particle emissions. In this section, the main results achieved from the thesis work will be discussed according to the sequence of the appended papers.

Papers A and B investigated the strong influence of temperature, relative humidity and water on the wear rate of oxidized and unoxidized wheel–rail contact. One of the key findings is that an unoxidized wheel–rail contact in a dry environment largely depends on the temperature, due to the dominant adhesive wear mechanism. According to the SEM observations, the adhesive characteristics become more serious due to ductile-brittle transition in decreasing temperatures from 20 °C to -15 °C, where micro adhesion joints deteriorated to large area delamination (spalling of bulk scraps). However, the condensed ice layer at temperatures below -15 °C prevented further increase of the wear rate due to the pressure melting phenomenon [78]. The possibility of ice condensation at the wheel–rail contact was confirmed by calculating the saturation vapour pressure at
low temperatures, which suggested high potential for an ice condensation layer to form at temperatures below -15 °C [79]. The condensed ice layer encouraged the formation of a flake-like oxide layer, protecting the surfaces from severe wear [80]. When the wheel–rail contact is in a damp environment or water droplets are present, a flake-like oxide layer also forms in a similar way and prevents severe wear. The pre-oxidized wheel–rail contact is found to be mainly dominated by abrasive wear, where the oxide islands sheared off the surface and then pulverized into tiny pieces of debris, aggravating the wear process.

In paper C, two rail surface grinding features (perpendicular and parallel to sliding direction) with two surface roughness values (rough 0.9 μm Ra and medium 0.4 μm Ra) were compared with a polished surface 0.04 μm Ra, with regards to the friction, wear and noise generation. This test design was inspired by a previous study suggesting that different surface manufacturing has an influence on rolling noise [81]. Since the surfaces were pre-oxidized, as in the real cases of operating tracks, the “initial stage”, where the pre-oxidized layer was not worn off, was likely to be controlled by ploughing and the featured surfaces (perpendicular and parallel to sliding direction) yielded a higher friction coefficient than the polished contact. After the pre-oxidized layer was worn off, the polished surface started to lead the friction and wear owing to the high level of adhesion, a result that conforms to previous studies [82, 83]. Another phenomenon observed in this study is the wear regime transitions from mild to severe and from severe to catastrophic were always accompanied by a sound level increase of 10 dB and a broadening of sound amplitude.
probability distribution. This test method was verified by using two different test systems, and the achieved results from each conformed to each other. Paper D complemented the measuring technique described in paper C by applying it to a metro train, which was run in a 200 m radius test curve to provoke wear and noise generation. Similar results to paper C were seen, in that the wear regime transition went along with the increase of sound pressure, encouraging a further validation of this sound-based technique for wear conditions of wheel–rail contact in real railway traffic systems.

Paper E studied the friction, wear and particle emissions from three commercial railway brake-block materials under different relative humidity levels, among which cast iron is dominantly applied. Since the water vapour in the air also can be detected by the particle counter, only an optical particle sizer with a relatively large measuring range (0.3–10 μm) was used in this study. Cast iron suggested the highest friction coefficient, wear rate and particle concentration at all three relative humidity levels (25%, 50% and 75%), while organic composite suggested the lowest. Vernersson et al. also found that cast iron brake blocks yielded a wear rate ten times higher than that of composite and sintered materials [84]. A higher particle emission rate for cast iron compared to composite brake block was observed in [4]. The high content of Fe (96 wt. %) in cast iron is responsible for the highest friction, wear loss and particle concentration due to the high adhesion with its counterpart, the railway steel wheel. The organic composite brake block is composed of some 20 ingredients whose properties largely differ from each other. Some ingredients are prone to adsorb moisture,
leading to a decline of friction, wear and particle emission. A very low friction coefficient (less than 0.4) was observed on organic composite brake block in humid air (50% and 75% relative humidity), making it an unreliable material for the complex working conditions of railway brake blocks. It should also be noted that the current study used a relatively low contact pressure and sliding speed, which is a reason for the low particle emissions of organic composite material. Further study with more hostile conditions is suggested to check the performance of organic composite at evaluated temperatures.

A comprehensive literature review on the topic of open system tribology in the wheel–rail contact was carried out in Paper F. No similar survey of the state-of-the-art on this topic was found in the subject documentation. Commonly seen environmental conditions, e.g. temperature, humidity, natural and artificial contaminants were discussed in relation to the friction, wear and sound and particle emissions at the wheel–rail contact. Since Paper F is a review paper, more detailed discussion can be found in the paper and will not be repeated here.

3.2 Discussion on the validity of the results

This thesis comprises four lab-scale experimental studies and one full-scale experimental study. Some of the observed results in these studies are validated by reported phenomena in the railway system. For example, paper B has found that the wear rate at the wheel–rail contact generally increased with a decreasing temperature from 3 to -15 °C; this is confirmed by Green Cargo® (Swedish rail logistic operator),
who report that the wheel experiences a wear rate that is ten times higher in winter in the north Sweden area compared with that in summer. Bombardier® (a train manufacturer) also report similar phenomena in their servicing of heavy haul locomotives. Another finding in paper B is that at -35 °C, an ice condensation layer is prone to form on wheel and rail surfaces, which decreases the friction and wear. In a meeting with the Swedish Welding Commission AG 60 Rail welding, the members confirmed the observation that a thin ice condensation layer often appears on the rail surface during winter at temperatures below -15°C.

Paper D is a full-scale experiment for validating the findings in paper C. In the paper, a wear transition from mild to severe wear, and from severe to catastrophic wear, always goes with an increase of generated sound pressure of 10 dB and a broadening of the sound amplitude probability distribution. This sound-based detecting technique shows great potential for monitoring the mild to severe wear transition in railway traffic and is now used in the Stockholm metro system (on six trains) to determine maintenance actions.

3.3 Contribution and impact of the thesis

In the past, people used to study the tribology at the wheel–rail contact and wheel tread–brake block contact in an ambient environment but the influences of temperature and relative humidity were neglected. The research work contained in this thesis found that different environmental conditions (e.g. temperature, relative humidity, snow particles) had a strong influence on the tribology at the
DISCUSSION

wheel–rail contact and wheel tread–brake block contact, indicating that open system tribological contacts should be tested in the conditions in which they are used.

Papers A and B have found that temperature and relative humidity have a strong influence on the tribology at the wheel-rail contact. This is of great importance to the railway industry, which can choose suitable wheel grades for operation in different seasons to reduce operation costs. Papers C and D examined the sound generated and the wear regime at the wheel–rail contact. A sound-based wear detection technique has been developed and is now used on six trains in the Stockholm metro system to determine maintenance actions. Paper E has demonstrated a high level of airborne particle emission from cast iron brake blocks, indicating a need to develop alternative materials. Although these findings are achieved in KTH and based on the railway operation in Sweden, they can be beneficial to railway operators in other areas where railway vehicles are working in an open system. This thesis is strongly related to the environment and one of its main focuses is airborne particle emission. Therefore, it can bring some underlying research projects from international, national or local foundations whose aims include environmentally friendly development.
4 Conclusions

This thesis uses experimental methods to investigate two common open system tribological contacts in the railway system with regards to friction, wear and sound and particle emissions, both in lab- and full-scale environments. A thorough literature review has been carried out on the state of the art of open system tribology at wheel–rail contact. Main conclusions have been drawn, as follows:

- The pin-on-disc test stand placed in a well-controlled climate chamber is a reliable and efficient method to study the tribology of varied materials within different environmental conditions. With this method, not only the temperature and relative humidity can be controlled, but also plenty of contaminants such as snow, water and friction additives can be applied.

- Temperature and humidity are proven to strongly influence the friction and wear at wheel–rail contact, by generating different forms of oxide layers.

- If this test stand is improved with professional acoustic measuring equipment, it can be used to study the sound generation from different tribological contacts.

- Surface finishing features on the rail surface are found to affect the sound level emitted from the wheel–rail contact; a surface feature perpendicular to the sliding direction generated less noise than a parallel feature and smooth surface.

- Both lab- and full-scale tests demonstrated that a wear transition from mild to severe wear is always accompanied by an increase in noise level and a broadening of noise amplitude distribution.

- Promising research within open system tribology in the future should take all tribological parameters (friction, wear, sound and particle emissions) into account simultaneously. Environmentally friendly additives should also be encouraged.
5 Future work

This thesis focused on the commonly seen environmental parameters (namely temperature, humidity, water) on the tribology at the wheel–rail and wheel–brake contacts with regards to friction, wear and noise and airborne particle emissions. The railway system operates in a complex environment where some other questions are still open. Therefore, some suggestions for future research are given by the author:

- One imperative trend for future study is to take all tribological parameters (friction, wear, lubrication, sound and particle emissions) into account simultaneously, rather than independently, as is currently the case.

- Environmentally friendly lubricants (e.g. those that are water-based) should be investigated more, instead of traditional oil- and grease-based ones.

- More reliable and complete models for the open system tribology at the wheel–rail and wheel–brake contacts should be built to adapt to the complicated working environment of the railway system.

- Most documented studies on open system tribology are at lab scale for accurately controlling environmental conditions. More full-scale tests are suggested for validating the findings from lab-scale studies.

- This thesis only considered the micro-sized airborne particles from wheel–brake contact. However, nano-sized particles are of great interest as they have been found to form at higher contact temperatures and adversely affect the health of human beings, so more exhaustive research on this topic is encouraged.
6 References

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