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Characterisation of airborne particles from rail traffic

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Characterisation of airborne particles from rail traffic

Abstract

Since the investigation of wear particles in rail transport started in late-1910s, the high mass concentration of these particles has raised worries among researchers concerned with air quality. However, effective action has yet to be taken because of lack of relevant knowledge. This thesis provides applicable information for the airborne wear particles in rail transport. Some aspects of their characteristics such as diameter size, mass concentration, number concentration, and morphology of particles were investigated in field tests and laboratory tests.

The effects on particle characterisations from different operational conditions in the field tests, and applying different braking materials, conducting tests in different applied loads or sliding velocities in the laboratory tests were studied. The main advantage of conducting laboratory tests was to focus on studying particles from one source. The possibility of repetition, using high sensitive instruments and conducting tests at low costs are the other advantages of laboratory studies.

Paper **A** describes how a pin-on-disc machine was used to reproduce similar real operational conditions during mechanical braking in a train. The results were validated by comparing the field tests results with the laboratory studies. The particles morphology and size distribution were also studied.

Paper **B** presents a summary of field tests results. The effects of curve negotiating and applying braking in different real conditions were investigated with an on-board measurement.

The element composition of the particles and their potential sources were also investigated outside of the particles morphologies.

Paper **C** presents comprehensive results from laboratory studies on airborne particles from different braking materials. The differences in the particle characteristics in similar test conditions were attributable to different material compositions and dominant wear mechanisms. A new index was introduced in this paper and is suggested to be used as a qualitative factor with regard to the airborne wear particle emission rate.

Paper **D** is a review of the recent studies of exhaust emission and non-exhaust emission from rail vehicles. A summary of results, measurements, adverse health effects, and proposed or applied solutions are reviewed in this paper.

Keywords
Airborne, railway, brake pad, brake block

Language
English

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I would like to thank my supervisors Docent Ulf Sellgren and Professor Ulf Olofsson. Many thanks also to my papers' co-authors Professor Lars Olander, Dr. Anders Jansson, Mrs. Christina Larsson, and Dr. Jens Wahlström.

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Stockholm, May 2011

Saeed Abbasi

List of appended publications

This thesis consists of a summary and the following appended papers:

Paper A

S. Abbasi, J. Wahlström, L. Olander, C. Larsson, U. Olofsson, U. Sellgren, A study of airborne wear particles generated from organic railway brake pads and brake discs, Accepted for publication in ***Wear, special issue Nordtrib 2010.***

The author performed the major part of the writing and experimental works and contributed to the planning and evaluation.

Paper B

S. Abbasi, L. Olander, C. Larsson, A. Jansson, U. Olofsson, U. Sellgren, A field test study of airborne wear particles from a running regional train, Accepted for publication in ***IMechE, Part F: Journal of Rail and Rapid Transit, 2011.***

The author performed the major part of the writing and contributed to the planning, experimental works and evaluation.

Paper C

S. Abbasi, A. Jansson, L. Olander, U. Olofsson, U. Sellgren, A pin-on-disc study of the rate of airborne wear particles emission from railway braking materials', Submitted to ***Wear, 2011.***

The author performed the major part of the writing and experimental works and contributed to the planning and evaluation.

Paper D

S. Abbasi, U. Sellgren, U. Olofsson, Particle emissions from rail vehicles (A review paper) Submitted to ***Atmospheric Environment, 2011.***

The author performed the major part of the writing and contributed to the planning and evaluation.

Abbreviation

AD: Aerodynamic diameter

AAR: The Association of American Railroads

ACGIH: American Conference of Governmental Industrial Hygienists

ASTM: The American Society for Testing and Materials

ASHREA: American Society of Heating, Refrigerating and Air-Conditioning Engineers

ATSDR: Agency for Toxic Substances and Disease Registry

BoBo: In this axle arrangement, all two-axle bogies are driving

Bo2: In this axle arrangement, one two-axle bogie is driving while the other is trailing

CEN: The European Committee for Standardization

CFCB: Compact freight cars brake

CNS: Central nervous system

DFG: Deutsche forschungsgemeinschaft

DMA: First driving motor car in an electric multiple unit

DMB: Last/second driving motor car in an electric multiple unit

DNA: Deoxyribonucleic acid

DPM: Diesel particulate matter

D_{50}: A particle diameter value in case cumulative distribution percentage reaches 50%.

EC: European commission

EDS: Energy dispersive X-ray

EDX: Energy-dispersive X-ray spectroscopy

EPA: Environmental Protection Agency

EU: European Union

EUROMOT: The European association of Internal Combustion Engines Manufacturers

FESEM: Field emission scanning electron microscope

GI: Gastrointestinal

HGVs: Heavy goods vehicles

IARC: International agency for research cancer

ICP-MS: Inductive coupled plasma mass spectrometry

IRW: Independently rotating wheels

ISO: International Organization for Standardization

LRT: Light rail transit

LGVs: Light goods vehicles

MECA: Manufacturers emissions control association

MMT: Methylcyclopentadienyl manganese tricarbonyl

MMD: Mass median diameter

MSHA: Mine Safety and Health Administration

NIOSH: The National Institute for Occupational Safety and Health

NRMM: Non-road mobile machinery

NYC: New York City

OPC: Ordinary Portland cement

PAHs: Polycyclic aromatic hydrocarbons

PM: Particulate matter

PNS: Peripheral nervous system

ppm: Parts per million

RZS: Compact brake caliper unit for wheel-mounted brake disc (from Knorr-Bremse)

SEM: Scanning electron microscope

SMPS: Scanning mobility particle sizer

TSI: The technical specification of interoperability

UFP: Ultrafine particles

UIC: International union of Railways

UNIFE: The Association of the European Rail Industry

WHO: World health organization

TABLE OF CONTENTS

1. INTRODUCTION

This chapter presents the background information to airborne particles, the terminology used, the objective and research questions, as well as briefly describing the research methodology used and outlining the structure of this thesis.

1.1 Background to airborne particles

The suspension of solid particles or liquid droplets in a gas or another liquid is referred to as particulate matter (PM). It conveys the suspension in both liquid and gas. In contrast, aerosol refers to the particles or droplets only in a gas (Hinds, W., 1999). In ISO 4225:1994, dust has been defined as “Small solid particles, conventionally taken as those particles below 75 µm in diameter, which settle out under their own weight but which may remain suspended for some time”. Particulate matter, aerosol, dust, and airborne particles are the common terms that we normally deal with in topics related to air quality.

The relation between PM and atmospheric phenomena have been proven and well-documented, for example by Cheremisinoff (2002) and Ruzer (2005). Health problems in human and animals, inverse effects on visibility, and global climate changes are the common adverse effects of particulate matter.

These relations are not new topics for humans, although they were not priorities in the past. For instance, an Assyrian king, Tukulti-Ninurta II (890-884 BC), reported a strange smell in the air during a visit to Hit, a town located west of Babylon and the centre of asphalt mining (Hopke, 2009).
One of the oldest descriptions of these relations can be found in the Hippocratic Corpus, which details that Greek and Romans were familiar with these problems in crowded cities and mines (Hippocrates, 460–377 B.C) (Sundell, 2004). In 61 AD, the Roman philosopher Seneca also reported air pollution in Rome and its adverse effects on him. However, the first serious report on air pollution and its adverse health effects was published by John Evelyn in 1661. Evelyn reported that burning wood would be less harmful than burning sea-coal to the human lungs. He also suggested to relocate London’s polluting industries such as lime-burning and brewing (Krech et al., 2003).

Ramazzini conducted investigations about people’s diseases and their occupations. He wrote *De Morbis Artificum* Diatriba’, Diseases of Workers) in 1713. Ramazzini identified airborne particles as the second factor of worker diseases after ergonomics (Schenk, 2011). In the Victorian era, six different factories were identified as “dangerous trade” and using ventilation systems became obligatory to diminish harmful air pollutant (Lee, 1973). However, only in the recent century has the mechanisms of particles effects and characteristics been identified and more active efforts are achieved (Nielsen and Ovrebø, 2008).

We refer to the suspension of solid particles or liquid droplets in the air as airborne particles. Throughout this thesis, the term “particles” refers to the airborne particles unless otherwise specified.

PM is a mass-based criterion, and many different sub classifications have been defined for PM based on the so-called aerodynamic diameter (AD). AD expresses the same gravitational settling velocity for a particle in standard air as if it were perfectly sphere with the unit density.

Some examples of PM subcategories are:

- $PM_{2.5}$ refers to particles with an AD up to 2.5 µm.
- PM_{10} refers to particles with an AD up to 10 µm.
- Ultrafine fraction ($PM_{0.1}$) refers to particle/s with an AD up to 0.1 µm.
- Fine fraction ($PM_{(2.5-0.1)}$) refers to particle/s with an AD between 0.1-2.5 µm.
- Coarse fraction ($PM_{(10-2.5)}$) refers to particle/s with an AD between 2.5-10 µm.

Figure 1 shows a rough comparison of the size of $PM_{2.5}$, PM_{10} particles, fine beach sand, and a human hair.

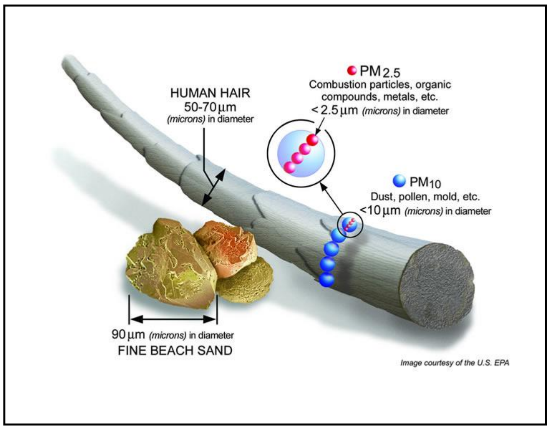


Figure 1. A comparison between the size of fine sand beach diameter, human hair diameter and PM_{10} , $PM_{2.5}$. (EPA PM Research, 2011).

1.2 Objective and research questions

The main research question for the project, of which the work presented in this thesis is the first part, within the context of rail transport is:

- How can the emission of airborne particles from a running train be efficiently controlled?

In the presented work, this main question has been broken up into the following sub-questions:

- What is the state-of-the-art knowledge of airborne particles generation mechanisms, characteristics and sources?
- What is the element composition of airborne particles generated by a running train?
- How can the composition of the airborne particles be classified with respect to their health effects?
- What are the effects of different operational conditions on airborne particle characteristics?
- Is it feasible to study the generation of airborne particles with reduced testing in a controlled laboratory environment?
- How large of a portion of the total amount of non-exhaust particles originates from wear processes?
- What is the best criterion to quantify airborne particle emission factors?

1.3 The research method

This thesis is part of the KTH Railway Group project entitled “Airborne particles in rail transport”. The aim of the project is to provide practical solutions that make it possible to control the generation of particles that are emitted from rail transport into the ambient air. In this regard, two stages are considered. The aim of the first stage is to increase the general knowledge of particle characteristics, evaluation of and distinction between different particle sources, and investigate technical specifications and operational conditions of the sources. Further, one of the objectives is to develop methods to generate particles in controlled laboratory conditions that are similar to those created in field operations. This thesis is a part of stage one of that project. The objective of the second stage will be to develop, verify and validate computerised models that can be used to predict and control the generation of airborne particles from the main wear processes. The validation should be based on a combination of experimental methods and laboratory tests.

Figure 2 shows a schematic view of the proposed method for this project.

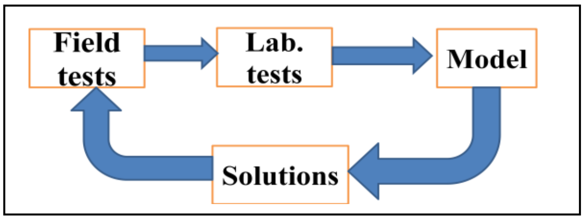


Figure 1. A schematic view of the methodology used in the current project.

1.4 Thesis outline

Chapter 1 gives a short introduction of the purpose for the thesis and the research questions. Chapter 2 reviews basic concepts of environmental engineering, railway engineering and tribology. In Chapter 3, the research methodology, that is the used methods and tools, are more thoroughly described. First, the particle instruments are described followed by the instrumented test train, and the laboratory test set-up with a modified pin-on-disc machine. Chapter 4 summarises the results from the appended papers, and in Chapter 5 these results are discussed. The answers to the stated research questions are answered in Chapter 6 and future work is proposed.

2. FRAME OF REFERENCE

This chapter provides some fundamental information about the adverse health effects of particles, particle legislations, and rail vehicle dynamic and its main systems with non-exhaust emission as the context.

2.1 Airborne particles: adverse health effects and legislation

2.1.1 Health effects

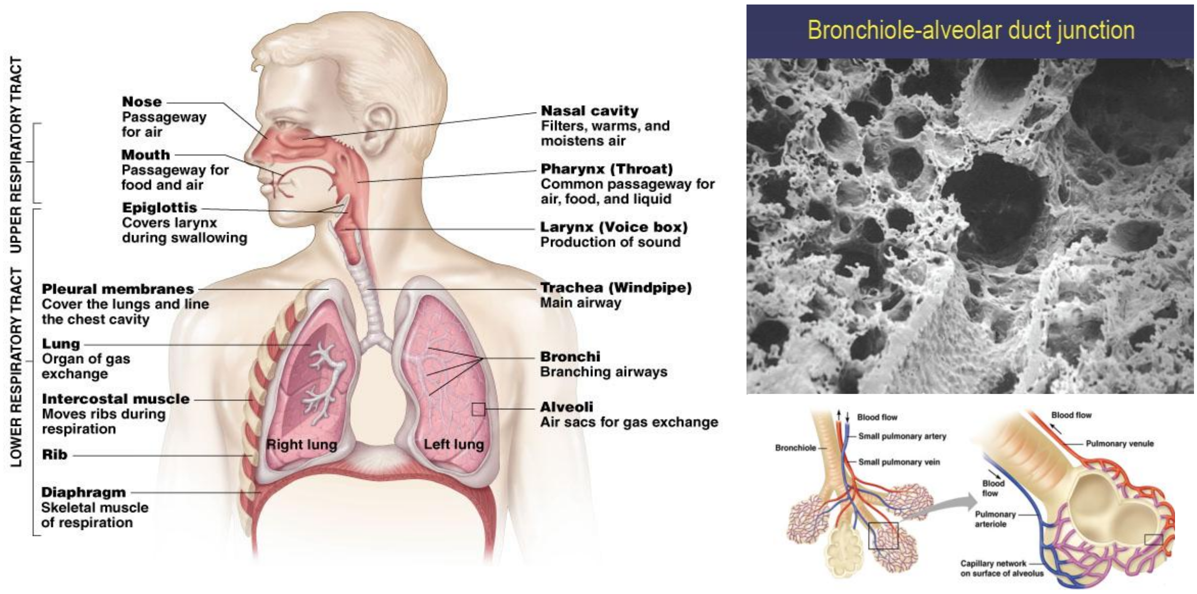
Humans are subjected to risks from particles through different routes. The routes of exposure can be classified as:
-Contact with the skin (dermal)
-Breathing (inhalation)
-Drinking or eating (ingestion or oral)
-Injection (nanoparticles for medical treatment)

Allergy/irritation of eyes and irritation or discoloring of the skin are common dermal symptoms caused by particles. Particles can come in contact with the skin and be absorbed as pre-formed solutions, or become soluble by sweat, blood or fatty acids on the skin. After solution, the penetrations process starts (Hostynek, 2004). The skin absorption and its reactivity have been well-documented in (Guy, R.H., 1999). However, there are several factors that affect skin absorption. Hostynek introduced several exogenous factors (such as size, dose, PH, protein reactivity, solubility) and endogenous factors (such as skin age, anatomical site and skin tissue section) in this regard (Hostynek, 2004).

It must be noted that the deposited particles in the skin can also be due to ingestion. Hand to mouth is one on the most common routes to ingest particles. According to Hawley (2005), an individual might ingest up to 25% of the dirt present on the fingers by hand-to-mouth contact (25% of the amount on the hands for children, 14% for adults). Recently, Xue et al. (2007) reported that hand-to-mouth behaviour among children is highly dependent on age group and location.

According to their work, the highest hand-to-mouth frequency belonged to two-year-olds during indoor activities (Xue et al., 2007).

Inhaling particles has a more intense and rapid effect, as particles can enter into the blood via the respiratory system. The surface area in the respiratory system is hundreds of times larger than the total area of the human skin. Also, the size and shape of different parts of the respiratory system are quite suitable to deposit particles. Figure 3 shows different parts of the upper respiratory and lower respiratory tracts. A real image from the bronchiole-alveolar duct is presented in the upper-right image.



Figures 3. These figures show different parts of upper and lower respiratory tracts. (By permission from Prof. K. Pinkerton.)

In the early 1990s, the ISO, ACGIH and CEN reached a general agreement to define the inhalable fraction, the thoracic fraction and the respirable fraction of particles. The inhalable fraction of airborne particles in ambient air, which can penetrate the respiratory system via the mouth or nose, was called the inhalable fraction. The inhalable fraction was defined based on D_{50} equal to 100 μm in aerodynamic diameter. The thoracic fraction refers to the fraction of inhalable particles that pass the larynx and penetrate into the conducting airways. This fraction was defined based on D_{50} equal to 10 μm in aerodynamic diameter. A portion of inhalable particles could reach the deepest part of the lungs and alveoli. This was referred to as the respirable fraction and was defined as D_{50} equal to 4 μm in aerodynamic diameter.

Particles penetrate and can deposit in different parts of the respiratory system depending on their size. Tager (2005) has summarised the particle size criteria for penetration and deposition in the respiratory system. His results are shown in Table 1.

Table 1. The respiratory tract penetration of particles in various sizes (Adopted from Tager,2005)

Paricle size range(μm)	*Level of penetration*
≥11	*Donot penetrate*
7-11	*Nasal passages*
4.7-7	*Pharynx*
3.3-4.7	*Trachea and primary bronchi (1^{st})*
2.1-3.3	*Secondary bronchi (2^{nd}- 7^{th})*
1.1-2.1	*Terminal bronchi (8^{th})*
0.65-1.1	*Bronchioles (9^{th} -23^{rd})*
<0.65	*Alveolar ducts (24^{th}-27^{th}) and alveoli*

According to Tager's work, particles with a size less than 11 µm penetrate the respiratory system and the finest ones with a size less than 0.65 µm can reach the alveolar duct and alveoli. He also mentioned that the particles deposition rate in tracheobronchial and alveolar regions is highly dependent on sex, age and respiratory diseases. It has been proven that for an equal particle size interval, the greater deposition occurs in female groups, young adults in the age span of 14-18 years, and individuals with pre-existing respiratory diseases.

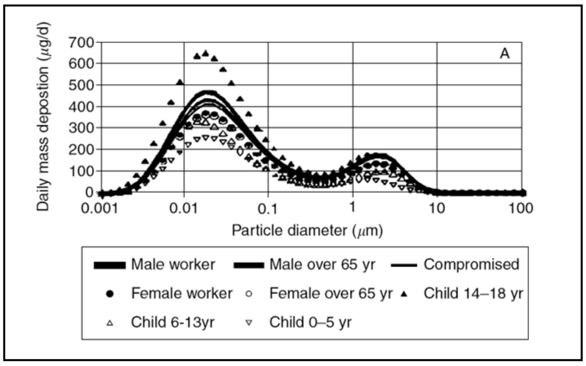


Figure 5. Daily mass particle deposition rate for 24-h exposure at 50 µg/m3 in tracheobronchial and alveolar regions. (Adopted from Tager, 2005.)

Figure 5 illustrates the variability in mass deposition (µg/d) as a function of age and sex according to these results.

It must be noted that the particle hygroscopic growth factor is another important issue in studying particle deposition rate in the respiratory system. In Li and Hopke (1993), this effect was studied in detail.

Recently, Madl and Pinkerton reported more than 30 different characteristics in particles and exposure factors that must be evaluated when studying the adverse health effects of particles in respiratory systems (Madl and Pinkerton, 2009). It has also been proven that diabetics are more susceptible to adverse health effects when inhaling particles (Golhd, D. R., 2008).

Figure 6 shows a view of how nanoparticles enter the blood through different routes. If we skip drug delivery by injection, other parts can be used and generalised for the particles' effects on humans. It also shows how particles can reach different body organs. The inputs and outputs of organs have been shown schematically. In fact, the particles' toxic effect starts when the accumulation amounts of elements exceed the certain amount, which can be tolerated by the natural metabolism in the human body.

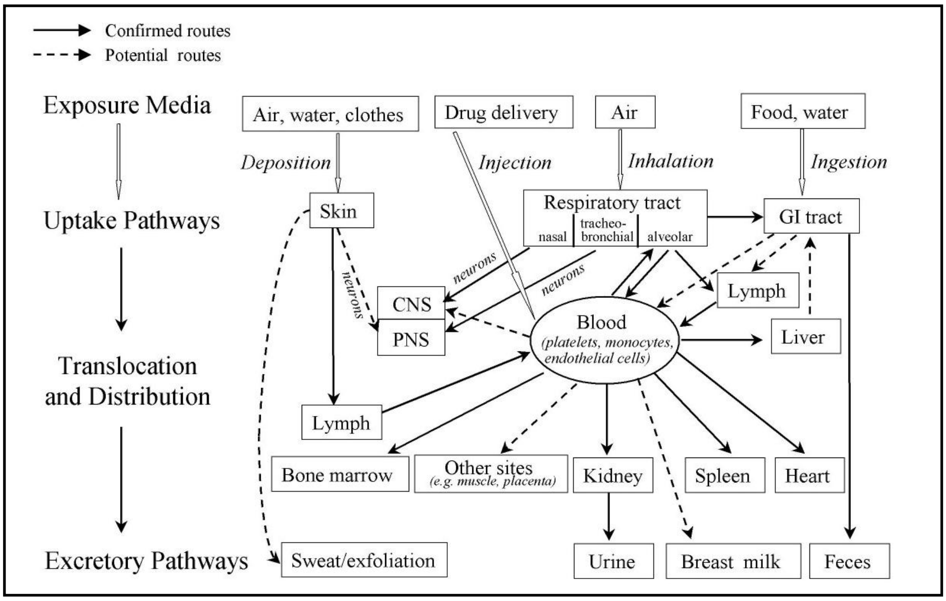


Figure 6. A schematic view of particles' exposure routes and their potential effects in different organs. (Adopted from Oberdörster et al. 2005.)

According to studies by ATSDR, such accumulations of lead, copper, zinc, nickel, aluminum, chromium, mercury, manganese, iron, and cadmium can damage human organs, including the kidney, liver, bones, lungs or GI tract. It must be noted the adverse health effects and damages caused by particles are not limited to accumulation problems in different organs. It has been proven that particles can cause some other long-term damages or short-term damages with regard to their characteristics and human exposure. Vomit, metal fever, effects on the nervous system, siderosis, oxidative stress, and cancer are reported because of exposure to these particles (ATSDR website, 2011). It must be noted that some health problems appear after a markedly long period from the first exposure. For instance, mesothelioma, a type of lung cancer caused by exposure to asbestos, has a latency period of more than 40 years, and after this period it can be diagnosed (Blanchi and Blanchi, 2007).

2.1.2 Legislations

Almost all of the present legislations have defined their criteria based on particles' mass concentration for certain materials when inhaling air, particularly for outdoor air quality. Concerning particle composition, water solubility or insolubility, inhalable fraction or respirable fraction, and the total time of measurement or exposure are other factors that they have considered been in the workplace. The effects of human gender, age, pre-existing disease (e.g., diabetes, asthma) and particles with a size less than three respirable fractions have not been defined in the legislations until now. The carcinogenicity of materials is important for particles as well. According to IARC, soot, quartz, asbestos, lead, arsenic, nickel, and chromium (VI) compounds are carcinogens. Making some limitations to apply these compounds or stop their use are other issues that are followed by national and international organisations.

In both the US and EU, legislation has determined limitations for the amount of PM_{10} ,$PM_{2.5}$, and certain metal compounds for outdoor air quality. These criteria are considered alongside the amount of nitrogen dioxide, sulphur dioxide, ozone, and carbon monoxide. Table 2 shows a comparison between some of the selected criteria from EU legislation and the US standard. (EPA NAAQS, 2011; EU Directive 2008/50/EC, 2008)

Table 2. A comparison between US and EU legislation for outdoor air quality in some of parameters.

		$PM_{2.5}$ (μg/ m³)	PM_{10} (μg/ m³)	Lead (μg/ m³)	Nickel (ng/ m³)	Arsenic (ng/ m³)	Cadmium (ng/ m³)	PAHs (ng/ m³)
US EPA NAAQS	Daily (24 h)	35	150	–	–	–	–	–
	Annual	15		0.15^{a}	–	–	–	–
EU directive 2008/50/EC	Daily (24 h)	–	50^{b}	–	–	–	–	–
	Annual	25	40	0.5	20^{c}	6^{c}	5^{c}	1^{c}

a) The rolling three-month average.
b) The limit 50 μg/ m³ must not be exceeded 35 times in a calendar year.
c) Target value enters into force 31.12.2012.

Occupational exposure limits (OELs) are defined to specify guidelines which assist protecting human's health during exposure to natural or man-made substances. Currently, several national and international organisations are actively investigating OELs. Some of those organisations claim to consider only health factors without concerning the feasibility or economical limitations. ACGIH is one of these pioneers. Recently, Schenk et al. (2008) compared exposure limit values between ACGIH and 17 well-known organisations from Europe, North America, Japan, and Australia. They reported that the highest substance coverage was offered by ACGIH. Furthermore, the offered OELs by ACGIH were usually the lowest or closer to the lowest OELs. The threshold limit values (TLVs) is one of the indices used by ACGIH, and refers to conditions under which nearly all workers may be exposed day after day without adverse health effects.

Table 3. A summary of selected Occupational exposure limits (OELs) from ACGIH

Substance	Chemical abstract number, (CAS)	The threshold limit values (mg/ m³), Time-weighted averages (TWA) for an 8 h day during a 40 h week
Iron	7439-89-6	5
Nickel	7440-02-0	0.2 insoluble compound 10 metal/elemental
Chromium	7440-47-3 7440-47-3 13765-19-0 7789-06-2 7758-97-6	0.5 Chromium (III) 0.05 Soluble compounds of Chromium (VI) 0.01 Insoluble compounds of Chromium (VI) unless listed below 0.001 Calcium chromate 0.0005 Strontium chromate 0.012 Lead chromate
Molybdenum	7439-98-7	10 metal/ insoluble/ inhalable fraction 3 metal/ insoluble/ respirable fraction 0.5 metal/ soluble/ respirable fraction
Manganese	7439-96-5	0.2 Inhalable fraction 0.02 Respirable fraction
Silicon	7440-21-3	5 Inhalable fraction 0.1 Respirable fraction
Cobalt	7440-48-4	0.02
Cadmium	7440-43-9	0.01 Inhalable fraction 0.002 Respirable fraction
Aluminum	7429-90-5	10 Inhalable fraction 1 Respirable fraction
Titanium	7440-32-6	10
Zinc	7440-66-6	2
Tin	7440-31-5	2
Zirconium	10101-52-7	5
Calcium	7789-78-8	10 Inhalable fraction 3 Respirable fraction
Vanadium pentoxide	1314-62-1	0.05
Barium	7440-39-3 7727-43-7	0.5 10 for Barium sulfate
Copper	7440-50-8	1 Dust 0.2 Fume (0.1 in STEL) 0.05 Respirable fraction
Lead	7439-92-1	0.05
Antimony	1345-04-6	0.5
Aresenic	7440-38-2	0.01
Carbon	7440-44-0	10 Inhalable fraction 3 Respirable fraction
DPM (soot)	58-32-2	0.02 EC fraction[1], 0.16 TC fraction[2], 0.35 EC fraction[2]
1. ACGIH withdrawed the TLV of DPM from their lists in 2003 2. These TLVs are suggested by MSHA in 2005		

Table 3 shows the TLVs of substances that are related to the topic of this thesis.

These OELs are set for time-weighted averages (TWA) and are usually set for an 8-hour day during a 40-hour week. The short-term exposure limits (STEL) are used in some rare cases and refer to 15-minute exposure. OELs are dependent on chemical composition of substances and a few particle characteristic factors such as solubility, respirable fraction and inhalable fraction.

It must be noted that when a mixture of different substances are considered, the cumulative effects must also be considered. The summation ratios of recorded concentration

the OELs must be less than unity. It can be shows as:

$$\frac{C_1}{OELs_1} + \frac{C_2}{OELs_2} + \ldots. + \frac{C_n}{OELs_n} < 1 \quad (1)$$

2.2. An overview of rail vehicles

2.2.1 Rail vehicle definition

A rail vehicle can be defined as a movable rail guided/interacted device that is used to transport objects or provide essential services to facilitate transporting objects. Rail vehicles can be classified based on their main functionalities.

a) Transportation in long distance: Rail vehicles such as passenger cars, freight cars, locomotives, multiple units, LRTs, and rail buses.

b) Transportation in short distance: Rail vehicles such as rollercoasters and carriages in cable railways or funiculars. These kinds of rail vehicles are usually used for distances less than five km.

c) Supporting machineries for transportation: Rail vehicles such as track maintenance machines (tamping machines, ballast stabilizing machines, etc.), rail snowplows and railway cranes.

Almost all of these functionalities can be achieved either when both rails interact with rail vehicle components such as conventional railways, or when only one rail exists and interacts with rail vehicle components such as monorails.

The main focus in this thesis is group (a), with exception of rail vehicles of single-based rail and rail vehicles with rubber tires. Nevertheless, some results and discussions can be extended to the other rail vehicles that were out of scope of this thesis.

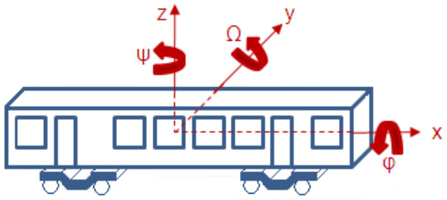
2.2.2 Main systems in rail vehicles

The main systems in a rail vehicle are carbody, running gear and brake systems.

2.2.2.1 Carbody

The main role of a carbody is to carry loads that are either passengers or goods. Carbodies must fulfill demands such as safety, comfort, aesthetic design, aerodynamic design, maintenance aspects, and economical limitations (Andersson et al., 2007) According to EU legislation for end-of-life vehicles (EU Directive 2000/53/EC , 2000), up to 95% of a vehicle’s total mass must be recovered. Therefore, the recoverability of a carbody must also be considered, as the main fraction of a rail vehicle’s mass comes from the carbody. Recycling, reusing and energy recovery of materials are factors in the recoverability rate that must be taken into account and added to the previous demands in the design of a carbody.

The carbody has six different movements and all of them are important in the study of rail vehicle dynamics. They are three translation motions and three rotational motions. The translation in the direction of travel is called longitudinal movement. The translation in the transverse direction parallel to the track plane is called lateral movement. The translation perpendicular to the track plane is called vertical movement. The rotation on longitudinal axis is called roll. The rotation on the transverse direction parallel to the track plane is called pitch. The rotation on an axis perpendicular to the track plane is called yaw. Figure 7 shows a schematic view of these six relative motions.



Relative motions	Symbol	Notation
Translation in direction of travel	x	Longitudinal
Translation in transverse direction, parallel to the track plane	y	Lateral
Translation perpendicular to the track plane	z	Vertical
Rotation on the longitudinal axis	φ	Roll, Sway
Rotation on the transverse axis, parallel to the plane	Ω	Pitch
Rotation on the axis perpendicular to the track plane	ψ	Yaw

Figure 7 A Schematic view of six possible relative motions in a carbody or a rail vehicle.

2.2.2.2 Running gear

The interaction between rails and a rail vehicle's carbody occurs in the running gear. The running gear must support the carbody, and accelerate or decelerate vehicle. Wheelsets and brake systems play crucial roles in the dynamic functionalities of the running gear.

Wheelsets are the fundamental components in all rail vehicles (Figure 8a). Wheelsets are classified as Solid wheelsets and IRW. A solid wheelset consists of an axle and a wheel on each side of axle. In IRW, however, each wheel can rotate independent of the other wheel. Railway wheel material are generally classified as medium carbon steel with a carbon (0.3%-0.6%) and manganese amount (0.6%-1.65%). Recently, a review of railway wheel material compositions and mechanical properties was completed by Clarke (2008).

Wheel profile is divided into three parts: wheel tread, wheel flange and wheel chamfer (Figure 8b, c). The lowest contact stress, lateral force and wear occur when the wheel tread is in contact with the rail profile (Tournay, 2001).

A special conical profile is designated for railway wheels (Figure 8a). This conicity facilitates the curve negotiating performance during curve negotiation. This conicity also allows for a sinusoidal motion for a wheel when it runs in a straight track. Higher conicity induces higher instability in the vehicle motion, as an increase in the conicity is associated with an increase in the frequency and acceleration in the vehicle oscillating motion. Recently, the limit value for conicity was reported in the EU directive 2008/232/CE according to the maximum operational speed of the vehicle (2008). The sinusoidal motion also causes the movement of the contact patch between wheel tread and wheel flange (Figure 8b, c). Figure 8c shows one point contact and Figure 8c shows two points of contact between the wheel and rail. In the latter, the difference between the two points' radius causes two different rolling radiuses, and consequently larger slippages can occur which lead to higher wear in the wheel. This effect is studied by Markine et al. (2007) in detail.

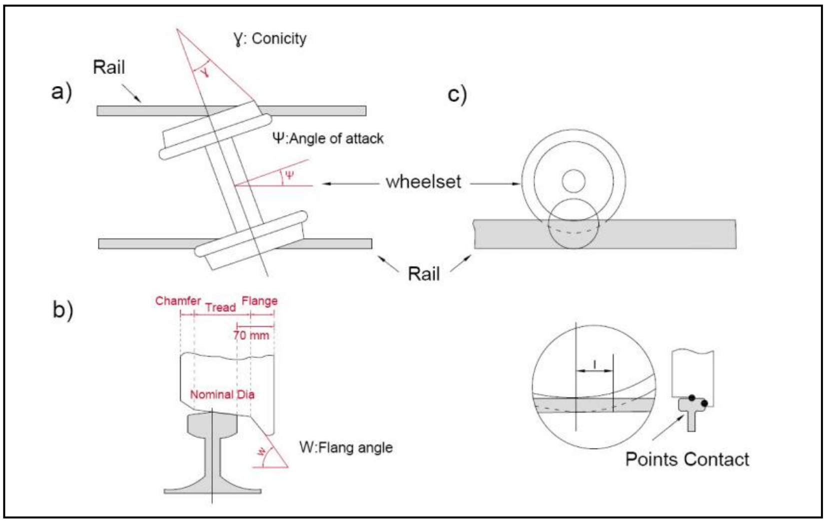


Figure 8. The schematic views of key parameters in a railway wheel profile. A wheelset view along with referring to the conicity and angle of attack (a). An one point contact view of a wheel and rail along with addressing wheel tread, wheel flange, flange angle, and nominal wheel diameter (b). An illustration of two points contact (c).

According to Nadal's equation (1986), the magnitude of the flange angle plays a crucial role in flange climbing and consequently the derailment of a rail vehicle. The angle of attack presents the yaw motion in a wheelset as it has been depicted in Figure 8. The effect of the angle of attack in wheel wear rates was confirmed by different researchers. In models presented by Heumann (1954), Marcotte (1978), Ghenonem (1978), Kalousek (1982), and Vogel (1981), the wheel wear was linearly or quadratically dependent on the angle of attack (Barghini, F. et al., 2009).

The single axle running gear is used in a "rigid-frame" vehicle. In other words, only two wheelsets exist in a rigid-frame rail vehicle. These vehicles were normally light, simple and inexpensive, but their payload capacity and curving performance were limited. Furthermore, their maximum operational speed was less than 120 km/hr because of their used suspension system, which resulted in limitations and an uncomfortable ride characteristic. In order to solve this problem, bogies were introduced. Rail vehicles with bogies are called a bogie vehicle. Distinctively, the behaviour of the wheel and its yawing motion affects the bogie performance. Figure 9 shows a typical bogie.

Several configurations can be defined to achieve different performances and functionalities. The main factors in these configurations can be summarised as:

a) The type of wheel connections to the bogie frame.

b) The dependency or independency of two wheels on one axle axis.

c) The existence and type of applied steering systems

The review of different running gears wasconducted by Wickens (2009); Goodall et al. (2006); Jönsson (2002); Hecht (2001); Hawthorne (1996); and Scales (1996).

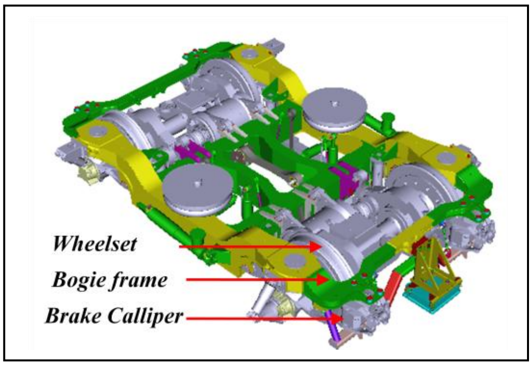
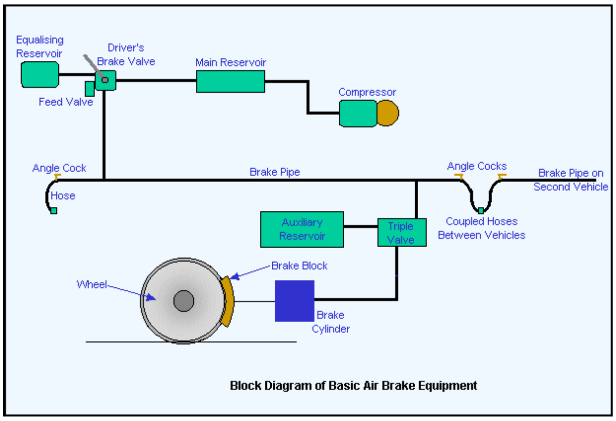


Figure 9. A typical bombardier bogie.

2.2.2.3 Brake systems

Converting kinetic energy to heat is an old system that is still in use in railway brake systems. Applying wooden blocks to the wheel treads were the oldest design of friction brake systems to stop the initial steam locomotives. It was the driver's task to actuate a lever or operate a screw to make a contact between the wooden block and running wheel to apply the brake. This kind of manual system did not match the increasing demand of a suitable brake system, and a system with higher reliability and safety was needed. In the mid-1870s, new systems were introduced replacing the old ones. Compressed air brakes in the US and vacuum brakes in the UK were introduced simultaneously (Elliot, 2006).

Figure 10 shows the block diagrams of these two systems.



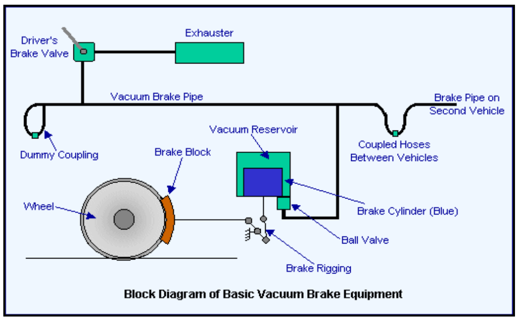


Figure 10. A block diagram of an air brake system (left hand). A block diagram of a vacuum brake system (right hand). (Adopted from a railway technical website, 2011.)

The operating principles of these two systems were fairly similar. Charging the pipe with the compressed air or with a vacuum resulted in releasing the brake. Releasing the brake was the normal situation, so making any pressure changes in the pipe resulted in applying the brake. Today, the vacuum brake system is obsolete, now outnumbered by the compressed air brake system.

Both the air brake and vacuum brake systems are friction brakes, although the latter is not popular. The principle functions of all friction brake types are quite similar even though there are many different types of friction brakes. The interaction between different mechanical parts results in controllable contacts between friction materials and rotating objects. This kind of frictional contact converts the kinetic energy into heat. The friction brake system can be classified as a tread brake, disk brake systems and hydraulic retarders.

The tread brakes are broadly used in freight cars or other rail vehicles where high speed is not the main concern. The tread brake rigging systems (conventional) are the most famous types of tread brake types.

Figure 11 shows schematic views of these systems.

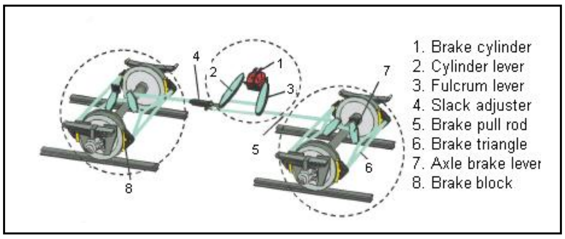


Figure 11. A simple view of the tread brake rigging system with main components. (Conventional tread brake) (Inspired by Gfatter et al., 2007.)

Figure 11 explains that when the brake cylinder is actuated, it pushes/pulls different levers until finally the brake blocks are compressed to the wheel.

Figure 12 shows a rough comparison between a conventional brake rigging system and CFCB, which are two common types of brake rigging systems. Elstorpff and Mathieu (2008) reported higher efficiency, lower noise and vibration, lower weight in the bogie total weight, and less air consumption for the CFCB in comparison to a conventional brake rigging system. They reported a lower wear rate of brake blocks in a conventional brake rigging system after running 60,000 km. They explained this phenomenon by degrading efficiency in the conventional brake rigging system.

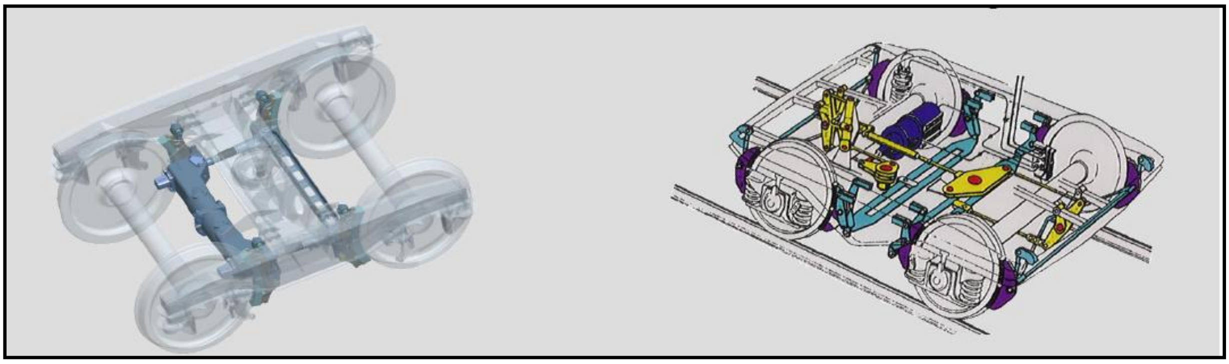


Figure 12. Two different types of brake rigging systems in a Y25 bogie. The CFCB (left) the conventional brake rigging system (right). (Adopted from Elstorpff and Mathieu, 2008.)

In the tread brake unit and CFCB, most of the mechanical parts have been combined and the same functionality is provided. The second category is disc brake systems, which are used in multiple units and passenger cars. Figure 13 shows examples of these systems. The brake discs in these systems are mounted in two different ways. If they are mounted on the wheel they are called wheel mounted (Figure 13 on the left). If they are mounted on the axle, they are called axle mounted (Figure 13 on the right).

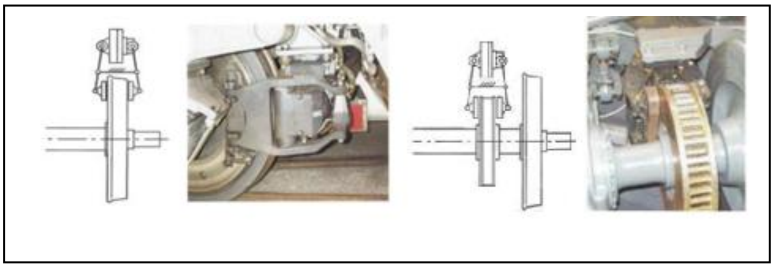


Figure 13. This figure shows a typical wheel mounted disc brake (left) and a typical axle mounted disc brake (right). (Inspired by Gfatter et al., 2007.)

Railway brake discs are usually made of cast iron (with spherical shape graphite), cast steel and ceramic matrix composite (CMC).

In tread brake systems, the brake blocks (Brake shoes) are used and in the brake disc systems the brake pads are used. The mounting arrangement of these friction materials also affects the subcategories of these brake systems. One-sided braking shoe and double-sided braking shoe are the subcategories of tread braking. The number of brake blocks in each side of a wheel and their relative rotational movement is another factor that can be used in the mounting classification. In this regard, Bg (divided), Bgu (Divided with subdivided sole) and Bdg (Double divided) are the common terms that extensively used to explain mounting of brake blocks (Gfatter et al., 2007).

Type of friction material is the key point to classify the brake blocks and brake shoes. According to (Yamaguchi, 1990) steel, brass, bronze, wood, textile were the old frictional materials that were used as frictional materials in the brake systems. Nowadays, the cast iron brake blocks, sintered brake blocks, organic brake blocks (asbestos free), sintered brake pads, and organic brake pads (asbestos free) are the common frictional materials that are used as braking materials.

Figure 14 shows typical brake pads and brake blocks. The organic brake pads are a combination of a binder, filler and other materials to stabilise mechanical properties and improve the coefficient of friction characteristics. Therefore, they are called composite brake pads in some literature.

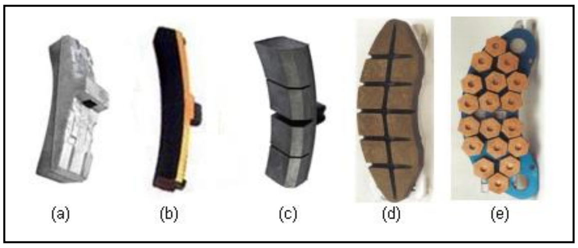


Figure 14. Different braking materials in rail traffic: (a) cast iron brake block; (b) K-type organic brake block; (c) LL-type brake bloc; (d) organic brake pad; (e) sintered brake pad.

The UIC and AAR have provided detailed standards and legislations to define frictional materials properties.

These properties and their response to the actual tests in a standard dynamometer are crucial to facilitate reliable and safe rail transport. UIC leaflets 541-3, 541-4, and UIC 832 (UIC website, 2011), and AAR standards M 926, M996 and M997 (AAR website, 2011) are typical examples of these legislations. There are three kinds of organic brake blocks with regard to their friction coefficients. The brake blocks with a high friction coefficient, low friction coefficient, and direct replacement with cast iron brake blocks are called UIC ‘K’ type or AAR ‘H’ type, UIC ‘L’ type or AAR ‘L’ type, and UIC ‘LL’ type, respectively.

The hydrulic retarder is another type of railway brake system. It works based on viscous drag force and converts kinetic energy to heat. These types of brake systems are used in diesel hydraulic (DH) locomotives or diesel hydraulic multiple units (DHMU) trains.

In Gfatter et al. (2007), other brake systems are introduced for rail traffic. One of the main ones are electrodynamic brakes. Electric motive power units usually use a rheostatic brake or a combination of regenerative (RG) and reheostatic brakes. In the rheostatic brake, the current from the traction motors is dissipated in banks of resistors. During RG braking, the kinetic energy transfers to other forms of energy, particularly the electric forms. One of the popular alternatives in railway RG brake systems is returning the current to the overhead line or third rail. The RG brake was employed only for DC systems for many years, but it can be employed for AC systems in the current decay by using microprocessors. Saving energy is another main concern when using RG brake systems, and up to 15% energy savings are reported when using RG brakes in c2c’s fleet of Bombardier Class 357 EMUs (Ford, 2007). However, less wear particles and less noise are the other motivations to implement RG brakes.

In the 1900s, the electrical control was added to the brake systems to facilitate more precise control and convenient operation. It was successfully used in the New York subway in 1909 and the London underground in 1916, and has developed since then. This new system was called electropneumatic brakes (EP) and provided enormously new features in brake systems (railway technical website). Furthermore, it eliminated the propagation time of air pressure waves in air brake systems. Nowadays, EP is widely used in locomotives, passenger cars, multiple units, and some special freight cars.

The electrodynamic brake system plays a crucial role in high-speed rail transport. Recently, Liudvinavičius and Lingaitis (2007) suggested new solutions to improve the rheostatic brake. They suggested a new system in order to achieve better control in braking.

The eddy current brake (ECB) and electromagnetic brake (EMB) are two other systems that can be used independent to adhesion between the wheel and rail. The track brakes are another name for these two systems (Gfatter et al., 2007).

The principle of these two systems is quite similar, as both work based on the effects of a magnetic field. These kinds of magnetic fields can be generated by a permanent magnet or electric systems. However, in ECB there is no contact with the rail and no wear occurs. EMBs are widely used in tramways, mine railways, and railbuses of a maximum speed of 100 km per hour. As there is no wear in eddy current brakes, it doesn't generate any noise, dust or smell that is the intrinsic outcomes of other brake systems. However, its relatively high costs and weights are the main drawbacks of this system. Knorr-Bremse research shows ECB costs two to four times higher than the EMB (Schofield, 2002). In 2008, the ECB was written about in EU directives and recommended by the TSIOF European high-speed rail system (EU Directive 2008/232/CE). Recently, using the combination of the ECB and EMB in high-speed trains has been evaluated by Podol'skii and Kitanov (2008).

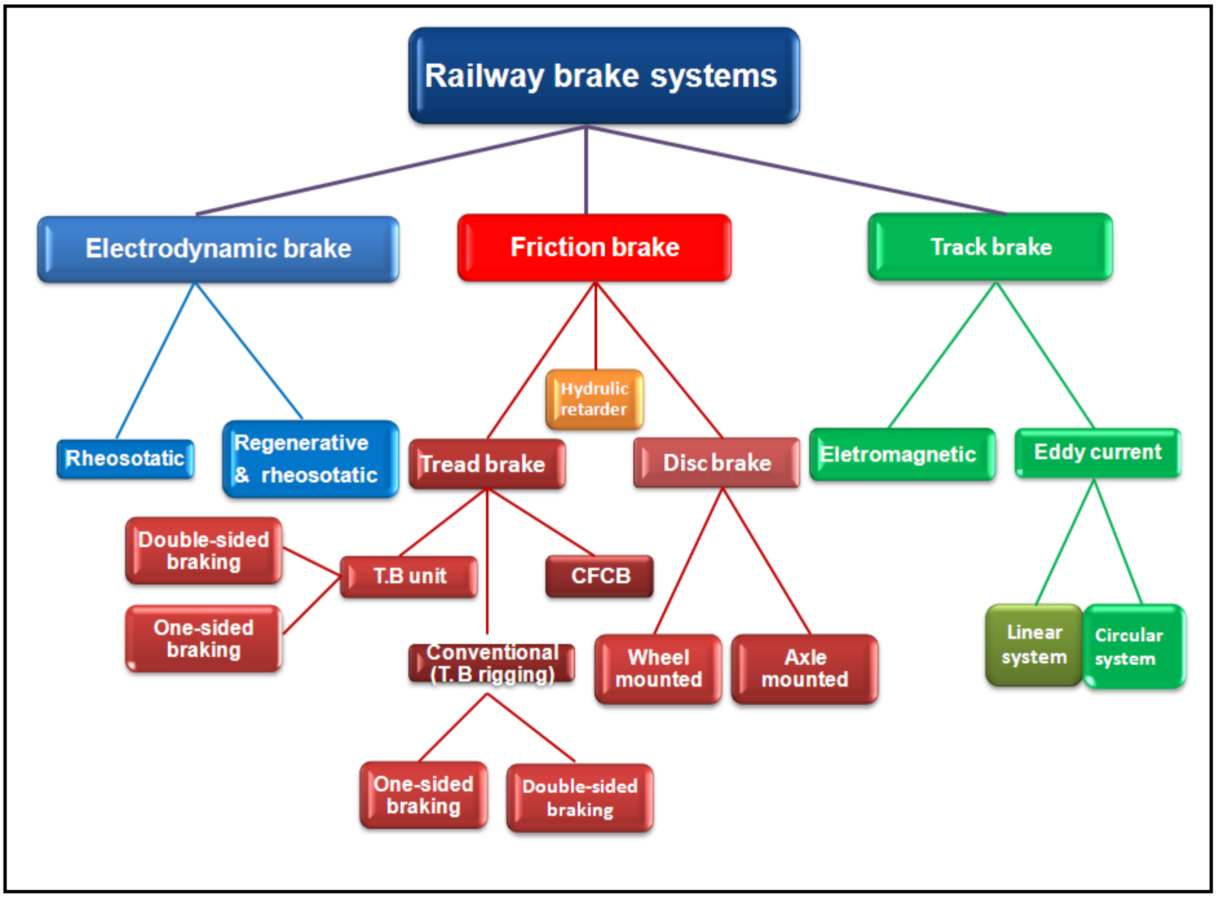


Figure 15. A summary of different railway brake systems in rail vehicles.

Figure 15 presents a summary of different types of brake systems in rail transport along with their subcategories.

In this thesis, our main focus is on friction brakes with the exception of hydraulic retarders. Here in after the friction brake system is addressed to the mechanical brake and electrodynamic brake is referred to the electrical brake.

2.3 Particle sources in rail transport

Commercialised rail transport appeared in the UK between 1804-1812. The steam locomotives were applied on cast iron rails those days to achieve this task. The London underground, the oldest subway in the world, was opened in 1863, which was 10 years before Carl Benz invented the first four-stroke cycle gasoline engine and commercialised car in road transport (Williams et al., 2000). Today, both of these transport modes have been recognised as particle emission sources. However, the numbers of researches and legislations to limit particle emission in rail transport are markedly low. It is noteworthy to mention that the particle high mass concentration in subways was raised a century ago, but few effective action plans have been achieved since that time.

Tabe 4 shows the summary of particle sources in rail transport. As it has been shown, rail vehicles, different stationary processes, air circulation, and passenger and rail staff can be taken into account as the sources of particles. Actually, most of the research is focused on particles from rail vehicles. The main focus of this thesis is non-exhaust (engine) emission from rail vehicles.

Table 4. A summary of different particles sources in rail transport.

Sources	**Sub classification**	**Examples**
Rail Vehicles	Exhaust(engine) emission	Diesel exhaust
	Non - exhaust(engine) emission	Wheel-rail contact Braking process Interaction of third rail and contact shoe Interaction of contact strip and overhead line Spraying sand to increase wheel-rail adhesion Erosion by air turbulence which is caused by a running rail vehicle (Piston effect)
Stationary process (Maintenance & construction)	Direct	Tunneling Rail cutting Rail welding Tamping process
	Indirect	Volatilization of oil and other lubricants Volatilization of cleaning material
Air circulation	Natural airflow	Moving and transferring particle emission from road transport Natural erosion of masonry structure
	Forced ventilation	Moving and transferring particle emission from road transport
Passengers and Rail staff	Human activities	Smoking in the platforms Smoking in the rail vehicle
	Others	Particle shed by passengers' clothes Degrading perishable materials and garbage

2.4 Wear and airborne particles

In tribology, wear has been defined as "Damage of a solid surface, generally progressive loss of material, due to relative motion between that surface and a contacting substance or substances" (ASTM, 2003). Tribologists are active to predict, and manage and control these kinds of issues in different applications. Generally, it is a big challenge to manage or control any physical or chemical process, but in this particular issue even predicting the amount of wear volume is also a big challenge.

In 1953, Archard introduced his model to predict the volume of removed material. He acknowledged the earlier work of Holm in 1946 and suggested that the volume of removed material per unit sliding distance is in relation to the applied normal load and hardness of material in contact:

$$Q=KW/H \qquad (2)$$

Where

Q: volume of removed material per unit sliding distance

K: wear coefficient

W: applied normal load in contact

H: hardness of the material

"K" is a dimensionless factor in the above equation and dependent on wear conditions.

The wear condition can be classified as: unlubricated sliding, lubricated sliding and wear by hard particles.

The K value can change from 10^{-6} up to 10^{-2} in unlubricated conditions, so-called dry contact. When K is lower than 10^{-4}, it is called mild wear. When it is higher than 10^{-4}, it is called severe wear.

Figure 16 shows different ranges of K in different wear conditions.

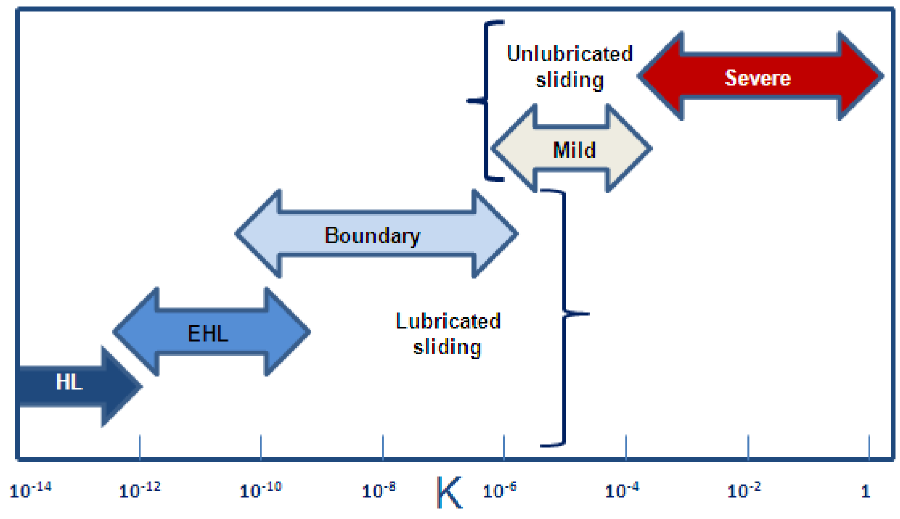


Figure 16. A rough comparison between the wear coefficient (K) in different contact conditions. (Adopted from Stachowiak, 2005)

According to Ludema, until 1994 more than 180 equations were suggested by researchers to predict wear in dry contact (Ludema, K.C.; Meng, H.C., 1995). These efforts have been in progress till this moment, but no precise and applicable equation has been provided to cover all conditions in dry contact.

In Table 5, some of the equations, which can be used to predict wear in the dry contact conditions, are presented.

Table 5. Some examples of wear models to predict wear volume.

References	Model	Parameters definitions
Archard model, 1953	$V \propto W\frac{d}{H}$ (3)	W: Applied normal load d: Sliding distance H: Hardness of softer material μ: Friction coefficient R_a: Surface roughness v: Sliding velocity e: Elongation to break S: Ultimate tensile stress a,b,c: material-dependent set parameters t: Time γ: Surface energy β: Flange angle to horizontal T_y:Longitudinal Creep force T_x:Lateral creep force γ_y:Longitudinal creepage γ_x:Lateral creepage μ_f:Adhesion at flange contact Y: Horizontal guide force μ_a: Resultant adhesion coefficient on flanging wheel ψ: Angle of attack δ: Superelevation angle
Ratner and Lancaster, 1969	$V \propto \frac{\mu W v}{HeS}$ (4)	
Rhee's model, 1973	$V \propto W^a v^b t^c$ (5)	
Kar and Bahadur, 1978	$V \propto \frac{1.5P^{1.47} d^{1.25} \gamma^{1.775}}{E^{3.225}}$ (6)	
Wang et al., 1995	$V \propto \frac{W^{1.5}\, Ra^{1.5}}{eS^{1.5}}$ (7)	
Elkins and Eickhoff, 1979	$V \propto (T_y\gamma_y + T_x\gamma_x)$ (8)	
Vogel and Kurek, 1981	$V \propto \frac{\mu_f}{\sin\beta}(Y + \mu_a W\cos\delta)\psi$ (9)	

In fact, there are physical and chemical changes in the contact surfaces during wear process. These changes are dependent on material properties, and relative speed and position of contact surfaces to each other. These conditions make it hard and quite complicated to provide a general model to cover all conditions. It is noteworthy to mention that Archard's wear equation has many limitations that cover all conditions in dry contact. Yet, it deals with some limited factors that can be measured more easily in practice. These advantages motivated researchers to use Archard's wear model over the previous seven decades.

Wear can be classified as abrasive wear, adhesive wear, fatigue wear, oxidative wear, erosive wear, and corrosive wear. We skip the last one, as the main focus of this thesis deals with unlubricated conditions. The mechanisms of different wear process, which lead to material loss, has been reviewed in Stachowiak and Batchelor (2007).

We summarised them as follows:

In abrasive wear, four mechanisms are more well-known. As Figure 17 depicts, microcutting, microfracture, fatigue by repeated ploughing, and grain poll-out are four mechanisms that can be described as abrasive wear.

The microcutting occurs when hard asperities cut the softer surface and lead to generate wear debris (Figure 17a).

The microfracture in brittle material causes wear debris. In these materials the convergence cracks cause wear debris (Figure 17b).

The fatigue wear debris are generated by the repeated deformation when a blunt grit abrades a ductile material (Figure 17c)

The grain detachment or grain pull-out occurs usually in ceramics. It happens quite fast when the inter-grain bonding is weak and the grain size is large (Figure 17d).

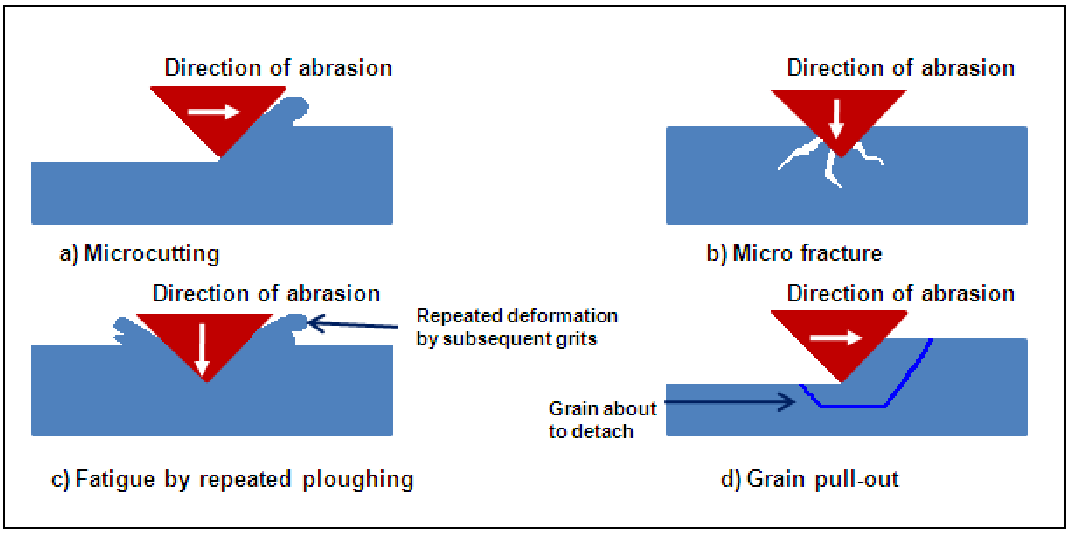


Figure 17. A schematic view of different possible mechanisms lead to abrasive wear. (Inspired by Stachowiak and Batchelor, 2007.)

The impact of particles of solid or liquid against the surface of an object causes erosive wear. The particle material, the angle of impingement, the impact velocity, and the particle size are factors that affect mechanisms involved in erosive wear.

Figure 18 shows different possible mechanisms that can occur during erosion.

When the impact angle is low, the abrasion mechanisms can be occurred (Figure 18a). By increasing the impact angle, the particle speed and substrate material interfere the process and specify the mechanisms. The fatigue mechanism occurs when the speed is still low (Figure 18b). At medium speed, plastic deformation for ductile materials or brittle fracture for brittle materials (Figure 18c) can occur. Melting would be a possible mechanism at a high speed (Figure 18d). The cones of debris can also interfere the process individually and initiate any of the above mechanisms (Figure 18e). Finally, the crystal lattice can degrade by atom (Figure 18f).

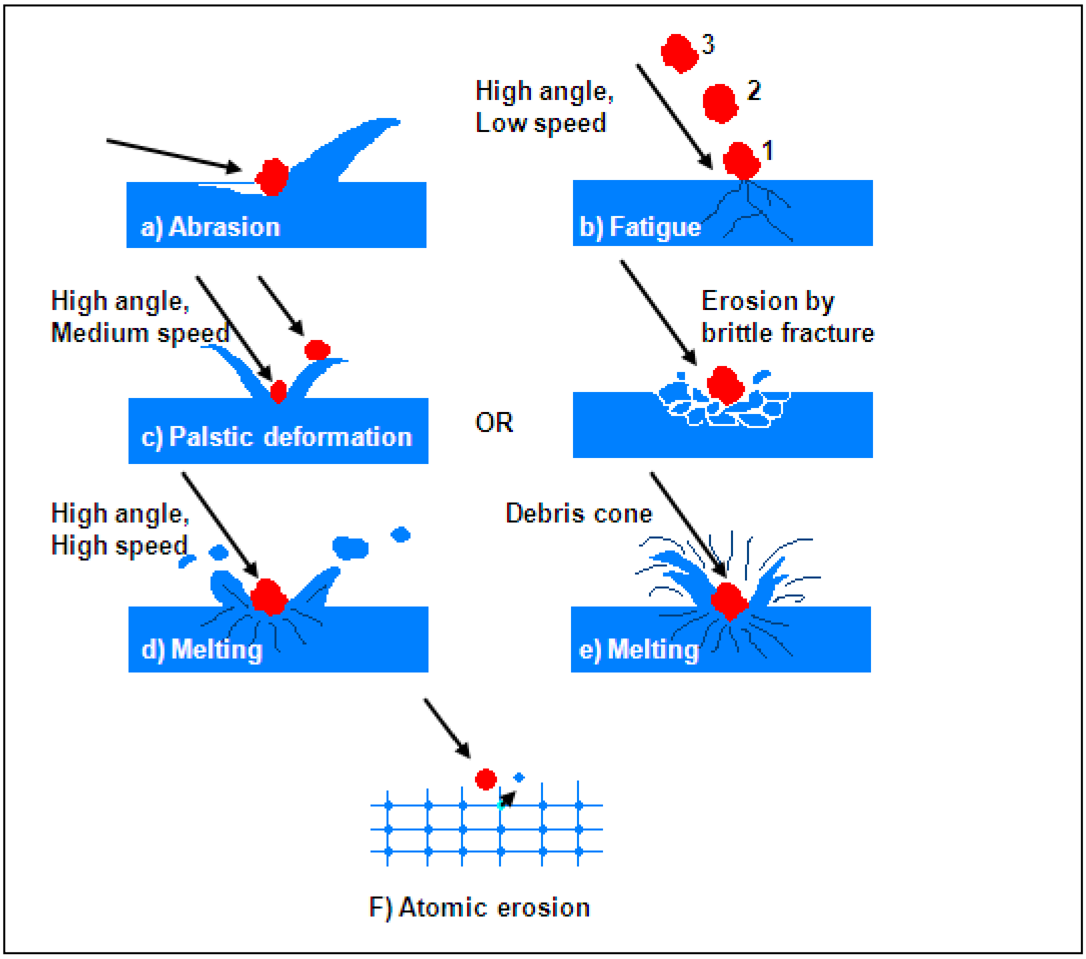


Figure 18 A schematic view of different possible routes that lead to erosive wear (Inspired by Stachowiak and Batchelor, 2007).

The simultaneous effects of the sliding motion and adhesion between asperities of contact surfaces cause a plastic deformation in asperities. This deformation can lead to the adhesion of material from one surface to another and result in adhesive wear.

Figure 19 shows a schematic view of adhesive wear. It has been proven that the low slope angle asperities are reluctant to lose material to the high slope asperities because the latter are keen to lose material. It must be noted that this kind of material loss can lead to a generation of wear debris or produce a film in a contact surface.

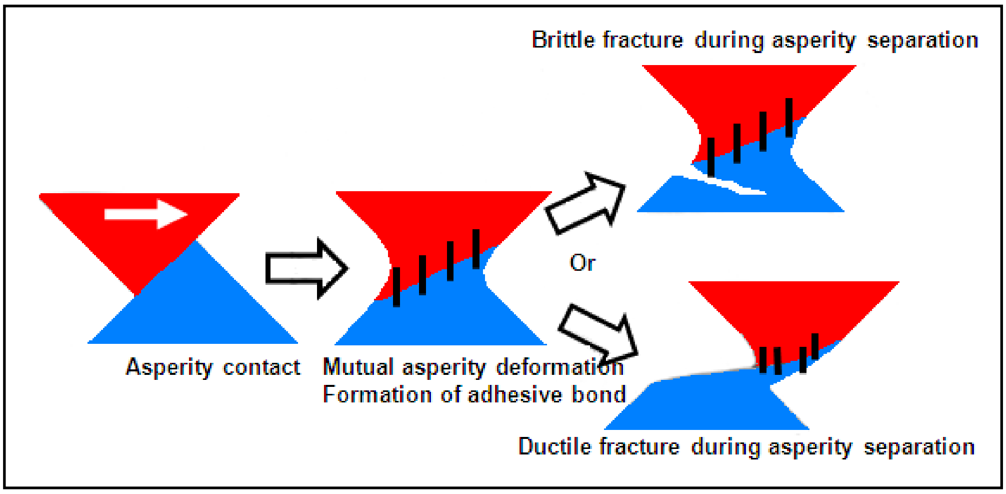


Figure 19. A schematic view of different possible mechanisms that lead to adhesive wear. (Inspired by Stachowiak and Batchelor, 2007.)

In the presence of air or oxygen, oxidative wear occurs in dry contact conditions. At low temperature or ambient temperature, the oxide layer thickness is limited to mere nanometers. This layer would be quite beneficial, as it can ban the adhesive wear. At high temperatures, the oxide layer thickness grows unlimitedly. When each oxide layer reaches critical thickness, they cannot withstand the load and they will be destroyed totally or partially. Figure 20 shows the generation of oxidative wear and consequently the wear debris from it.

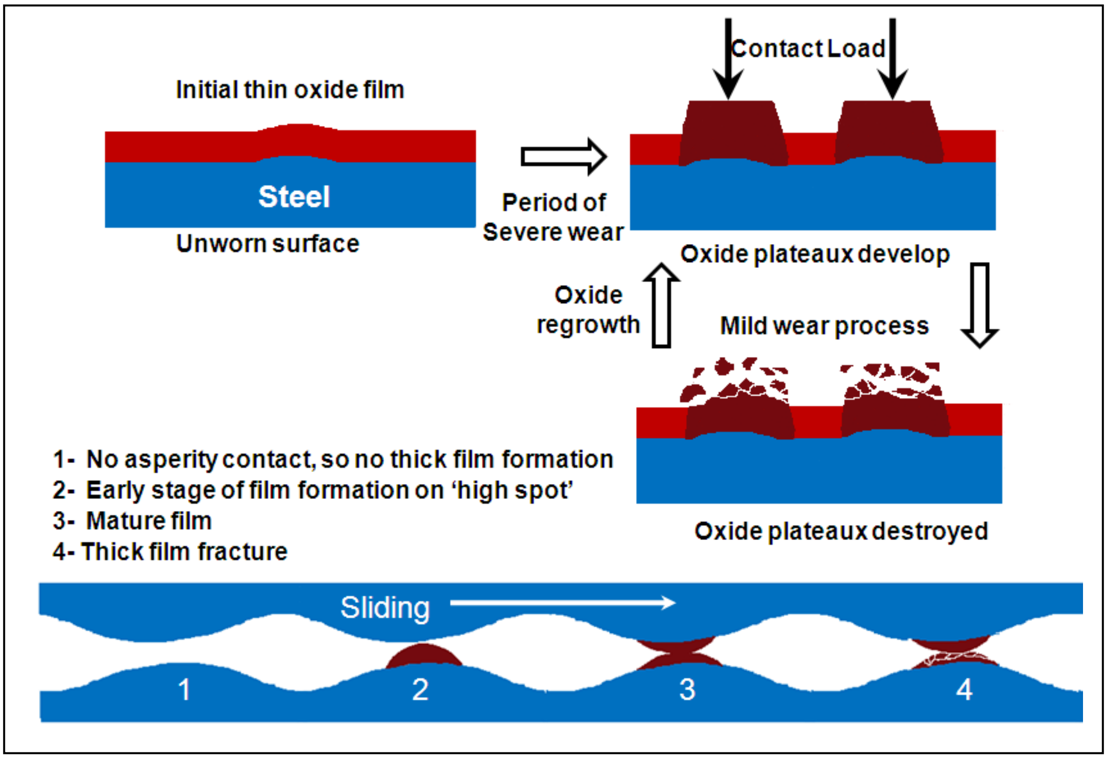


Figure 20. A schematic view of different possible mechanisms that lead to oxidative wear. (Inspired by Stachowiak and Batchelor, 2007.)

Fatigue wear occurs when contact between asperities is accompanied by a repeated number of high local stresses. The rolling contact or sliding contact initiates these kinds of stresses and propagates cracks.

Figure 21 shows how the deformation in different layers of a material happens. Repetition of these deformations can cause cracks in the weak cell boundaries, and the convergence of those cracks leads to fatigue wear.

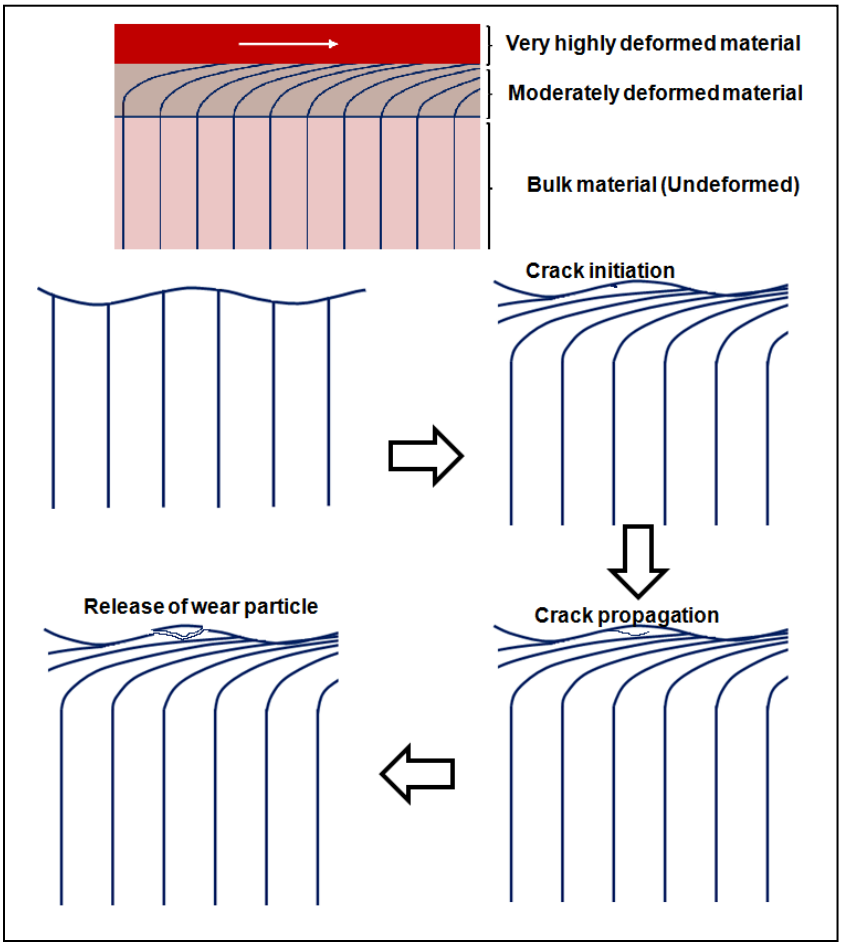


Figure 21. A schematic view of different possible mechanisms that lead to fatigue wear. (Adopted from Stachowiak and Batchelor 2007.)

There is no model to describe how and how much of wear debris can convert to airborne particles. However, there are different end results for the resulting wear debris from abrasive, erosive, fatigue, and adhesive wear:

- They can leave mating surfaces and transfer to the airborne.

- They can stick to the regions of the mating surfaces where it is not interacting with the wear process.

- They can stick to the regions of mating surfaces in the interacting wear process.

In the last case, wear debris has the potential to repeat the above scenario and contribute to the generation of particles.

Until this moment no model has been provided to consider all of the forces that may affect detached wear debris or particles. Recently, effects of Brownian diffusion, drag force, gravitational force, thermophoresis force, electrostatic drift, and turbophrosis have been studied by Sippola and Nazaroff (2002) to predict particle suspension possibilities in ducts. According to their work, other forces have negligible effects for the particle-air system. Nearly almost all of those forces can affect detached wear debris. However, the initial velocity of the detached wear debris during detachment and surface forces are other factors that exist during the wear process and must be taken into account. The overall effects of affected forces can result in fluidised particles converted into airborne particles. Therefore, we expect the particle characteristics, air properties, airflow conditions, and temperature on contacts to affect the wear debris and influence the possibility of transferring to airborne particles.

The study of airborne wear particles from road transport was seriously started during the 1970s (Subramani, 1971). This part is quite well-known in road transport and referred to as non-exhaust emission. It deals with airborne particles from tire and braking material and road surface wear. Recently, the different methods and results of emissions from these sources have been reviewed in the EEA report 2009 (EEA website, 2011). The fractions of total particles are provided in mg/km according to the defined test conditions for a specific vehicle. Table 6 shows a typical result of measurement for different vehicles in different conditions based on an average speed of 80 km/h (UK Informative Inventory Report, 2011).

Table 6. A typical result of PM10 per km for tire, brake and road surface wear, which resulted from different cars.

mg PM10/km		Tire	Brake	Road surface wear
Car (passenger)	Urban	8.74	11.68	7.5
	Rural	6.80	5.53	
	Motorways	5.79	1.30	
LGVs	Urban	13.80	18.22	7.5
	Rural	10.74	86.2	
	Motorways	9.15	21.2	
Rigid HGVs	Urban	20.74	51.00	38
	Rural	17.39	27.14	
	Motorways	13.98	8.44	
Artic HGVs	Urban	47.07	51.00	38
	Rural	38.24	27.14	
	Motorways	31.49	8.44	
Buses	Urban	21.18	53.60	38
	Rural	17.39	27.14	
	Motorways	13.98	8.44	
Motorcycle	Urban	3.76	5.84	3
	Rural	2.92	2.76	
	Motorways	2.49	0.68	

3. RESEARCH METHODOLOGY

A brief introduction about different particle instruments, the test train and the modified pin-on-disc laboratory tests are presented in this chapter.

3.1 Particle measurement instruments

In this thesis, four different types of particle instruments were used. The main instrument was a GRIMM 1.109 aerosol spectrometer. This instrument measured airborne particles 0.25–32 µm in diameter in 31 size intervals and at concentrations from 1 to 2 x 10^6 particles L^{-1} (Peters et al., 2006). The instrument registered number concentrations with a time resolution of 6 seconds. As GRIMM is an optical counter, its stated particle sizes are approximate and dependent on the particle shape and refractive index (Liu and Daum, 2000).

The second device was a TSI™ P-TRAK (Model 8525, referred to hereinafter as P-Trak) condensation nuclei particle counter that measured the number concentration of airborne particles of 0.02–1 µm in diameter with no size resolution (Zhu et al., 2006). Number concentrations were registered with a time resolution of 1 second.

The third instrument was a TSI™ DustTrak (Model 8520, referred to hereinafter as DustTrak) photometer that reported the mass concentration as mg m^{-3}. This is a laser photometer and measures particle concentration roughly corresponding to respirable size fractions. Thus, it registered mainly particles in the 0.1–10 µm diameter range. The instrument is factory calibrated using a test dust (with a density of 2650 kg m^{-3}), which has a size distribution, density and refractive index different from those of the particles measured here. Though the results could only be used as relative measures, they were useful in describing the changes in generated particle mass over time (Cheng, 2008).

The fourth instrument was a scanning mobility particle sizer (SMPS) combining an electrostatic classifier (TSI™ 3071) with a particle counter (TSI™ CPC 3010). The particles are charged in a controlled manner and thereafter sequentially classified according to their electrical mobility. Electrical mobility is transformed to a corresponding particle size (Fissan et al., 1983). The counter was a condensation nuclei counter that, by means of condensation, optically counted particles down to 10 nm in diameter. The size distribution was divided into 110 size classes in the 10-520 nm range. Number concentrations down to a few particles per cm^3 could be registered. The SMPS gave a particle number concentration size distribution every 5.5 min.

3.2 Instrumented test train

In Papers A and B, a series of full-scale field tests was performed using the "Gröna Tåget test train Regina 250" (Bombardier Regina) on the regular Swedish intercity tracks (grona tåget website, 2011). The train followed normal traffic operation when it was on main tracks. Parts of the test runs were conducted on a low trafficked track, where the maximum operational speed was only 90 km h^{-1} and the electrical brake was intentionally deactivated. The test train was instrumented to measure and record the speed and the total electrical and mechanical brake forces on each axle. The data acquisition frequency was 10 Hz. Two sampling points were deployed in these tests.

One sampling point was located 145 mm far from the main brake pad. During braking, it was highly exposed to the particles generated by the main brake pad. The effect of particles from the wheel and rail was also traceable in this sampling point when the train was in an accelerating condition or curve negotiating. We refer to this point as the brake pad sampling point. The other point was located in the middle of the axle. The effect of generated particles from concrete sleepers and ballast was more traceable in it. We refer to this point as the global sampling point. This study used the GRIMM 1.109, DustTrak and P-Trak on each sampling point, and the number and mass concentration of particles recorded every 6 seconds.

In this study, the two-sheet *Prescale*™ films were used to investigate mean contact pressure between brake disc and brake pad. The two-sheet films are composed of A-Film and C-Film. A-Film is coated with a microencapsulated colour-forming material, and a C-Film, which is coated with a colour-developing material (Figure 23a). The A-Film and C-Film must be positioned with the coated sides facing each other. The changes of colour density in the film are dependent on the magnitude of pressure levels in the contact and can be interpreted by manufacturers guideline (Figure 23b).

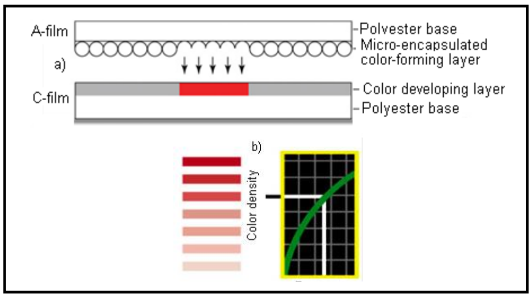


Figure 23. An illustration of how prescale films work.

3.3 Modified pin-on-disc laboratory tests

The laboratory tests were performed using a pin-on-disc machine in a sealed box with a horizontal rotating disc and a dead-weight-loaded pin (Figure 24). The sealed box allowed us to control the cleanliness of the supply air and sampling of air containing only wear particles. The machine could run under stationary conditions with constant applied normal forces of up to 100 N and at constant rotational speeds of up to 3,000 rpm.

A load cell was used to measure the tangential force acting on the pin. The feature of using a displacement sensor in order to measure wear rates of specimens during test running time or measuring the weight of samples before and after the test in order to evaluate the average wear rates of specimens was not used in the achieved tests.

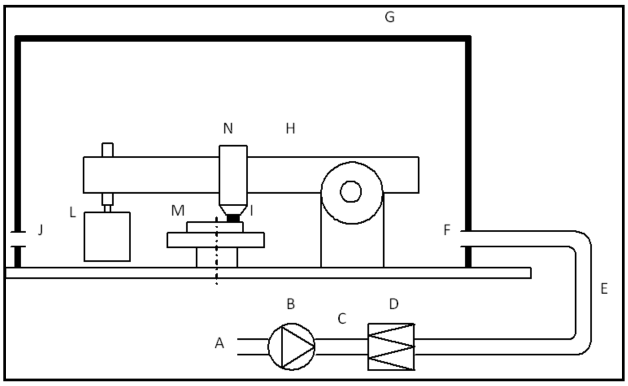


Figure 24. Schematic of the test equipment. A: Room air; B: Fan; C: Flow rate measurement; D: Filter; E: Flexible tube; F: Inlet for clean air, measurement point; G: Sealed box; H: Pin-on-disc machine; I: Pin sample; J: Air outlet, measurement points; L: Dead weight; M: Rotating disc sample, N: Air inside chamber.

The fan (B) took the air from the room (A) and passed it into the chamber (G) via a flow measurement system (C) a filter (D) and through the air inlet opening (F). The connections between the fan, measurement system, filter and chamber were flexible tubes (E). In the sealed box the air was well mixed (N) due to the complicated volume of the pin-on-disc machine (H) and the high air exchange rate. This mixing was verified by registering particle concentrations from the box. The air in the sealed box transported the generated particles to the air outlet (J), where sampling points for the particle measurement devices were situated.

The supply air was set to a flow rate of 7.7 m^3 h^{-1} (2.1 L s^{-1}). The sealed box volume was 0.135 m^3, and the volume of the pin-on-disc machine was approximately 0.035 m^3, giving an approximate air change rate of 77 h^{-1} corresponding to a time constant of 47 s. The measured flow rate varied somewhat during the tests, from 7.7 to 9.2 m^3 h^{-1}. The flow rate measurement system consisted of a straight calibrated tube with separate connections for total and static pressure, measured using an ordinary U-tube manometer. The system was calibrated in the flow interval 2–50 m^3 h^{-1}. The filter used to ascertain a particle-free inlet air was of class H13 (according to the EN 1822 standard) with a certified collection efficiency of 99.95% at maximum penetrating particle size (MPPS).

All of the particle instruments' pipes were mounted in point (J). Another P-Trak device was used in the inlet point and its pipe was inserted into the flexible tubes near the inlet opening point (F) in order to measure the cleanliness of inlet air and control the functionality of filter during test running time.

The laboratory simulation in the modified pin-on-disc used the GRIMM 1.109, DustTrak, P-Trak, and SMPS. The number and mass concentration of particles were recorded in the minimum available time of each instrument.

4. SUMMARY OF RESULTS AND APPENDED PAPERS

This chapter summarises the results from the appended papers and the division of works for each paper is presented.

4.1 Summary of appended papers

Paper A
This paper attempted to check the validity of generating airborne wear particles in a laboratory condition with their characteristics in real conditions.

In this regard, we conducted field tests with a running train, instrumented with two sets of P-trak, DustTrak and Grimm devices connected with the two sampling points. The P-Trak® 8525 is an optical particle measurement device that can measure particle diameter in the size interval of 20 nm up to 1 micrometer. The DustTrak® was used to measure particle mass concentration. The Grimm 1.109 is an aerosol spectrometer that counts number of particles from 0.25 micrometer to 32 micrometer in 31 intervals. The Millipore filters were mounted in the Grimm outlets to capture particles for further studies on morphology and matter of particles.

That train was equipped with Becorit 950-1 brake pads and steel disc brakes. The effects of different brake levels on a running train with the speed of 70 km/h in particles size distribution and number concentration were recorded. The particles were collected in the Millipore filters of Grimm device. Furthermore, the activating and deactivating electrical brake on particles characteristics were investigated.

The laboratory simulation used a pin-on-disc machine in a sealed box with a horizontal rotating disc and a dead-weight-loaded pin. The sealed box allowed us to control the cleanliness of the supply air and sampling of air containing only wear particles. The pins were prepared from Becorit 950-1 brake pad and discs were cut from railway steel brake disc similar to field test materials. We used the same particle instruments as a scanning mobility particle sizer (SMPS) in laboratory simulations. This device allowed us to measure particle size distribution for particles with the size 10-520 nm in diameter in 110 intervals.

The SEM and EDX were used to investigate particles morphologies and element composition. The recorded results from particle instruments and SEM images from both tests were in agreement. Both results show a dominant fine peak for particles with a size of around 350 nm in diameter, and a coarse peak with a size of 3-7 μm in diameter. Furthermore, the effects of increasing applied loads in both systems resulted in higher particle concentration in both systems. However, the particle size distribution was independent of the applied loads.

Paper B

Most of the existing railway particle studies were mainly on the stationary measurement, evaluating the particle mass concentration. As the coarse particles have the main contribution in the total particles mass, a few information was documented for the submicron-sized particles. However, new studies show ultrafine particles can cause more severe health effects. In this paper, we investigated particle characteristics near their sources with an on-board measurement.

A series of full-scale field tests was performed using the “Gröna Tåget test train Regina 250”. Four test runs on a part of a Swedish intercity track were performed, where the maximum operational speed was 200 km/h. We considered a special set-up in that train to investigate particle generation in different operational conditions (e.g., activating/deactivating electrical brakes or negotiating curves). Investigating particles sizes, morphology, element composition, and particle size distributions were the main objective of that study.

We designated two airborne particle sampling points: one near a pad–rotor disc brake contact and a second under the frame, but not near a mechanical brake or the wheel–rail contact. The numbers and size distributions of the particles detected were registered.

Two sampling points for airborne particles were designated in the train under the frame. One of the sampling points was near a pad to rotor disc brake contact, and a second global sampling point was chosen under the frame, but not near a mechanical brake or the wheel-rail contact. The first one was highly influenced by brake pad wear debris and the other one was influenced by all of the brake pads, wheel and rail wear debris, as well as re-suspension. In each sampling point, three tubes were linked to three particle measurement devices. Two sets of P-TRAK®, DustTrak® and Grimm devices were used. The P-TRAK® 8525 is an optical particle measurement device that can measure particle diameter in the size interval of 20 nm up to 1 micrometer. The DustTrak® was used to measure particle mass concentration. The Grimm 1.109 is an aerosol spectrometer which counted number of particles from 0.25 micrometer to 32 micrometer in 31 intervals. These two Grimm devices were equipped with Millipore filters in the devices’ outlets to capture particles for further studies on morphology and matter of particles.

The total number and size distribution of the particles for these two sampling points were registered and evaluated in different situations, including activating and deactivating the electrical brake or train curve negotiating.

During braking, three speed/temperature-dependent particle peaks were identified in the fine region, representing particles 280 nm, 350 nm, and 600 nm in diameter. In the coarse region, a peak was discerned for particles 3–6 µm in diameter. Effects of brake pad temperature on particle size distribution were also investigated. Results indicate that the 280 nm peak increased with increasing temperature, and that electrical braking significantly reduced airborne particle numbers.

A FESEM was used to capture the images from collected particles on filters. Its images captured particles sizing down to 50 nm. Both EDS and ICP-MS methods were used. According to ICP-MS investigation of the filters, the particulate matter mainly comprised Fe, Si, Al, Ca, Cu, and Zn. The higher amounts of some elements—such as Ca, Si, Na, and Al—in the global sampling point filters indicated that ballast and concrete sleepers were the main sources of these particles, although some originated from rails, wheels, brake discs, and brake pads.

Paper C
In this paper, we investigated the particle characteristics generated by organic brake pad-steel brake discs, sintered brake pad-steel brake discs, cast iron brake block-railway wheels, and organic brake block-railway wheels in laboratory conditions. We also attempted to introduce a new index and methodology to compare airborne particles from different material.

In this regard, we used a pin-on-disc machine in a sealed box with a horizontal rotating disc and a dead-weight-loaded pin. The sealed box allowed us to control the cleanliness of the supply air and sampling of air containing only wear particles. The pins were prepared from brake pads, and brake blocks and discs were prepared from steel brake discs and railway wheels, respectively.

The mean contact pressures and sliding velocities were similar to the real operational conditions. Four different types of particle instruments were used, and particle size, particle number concentration, and particle size distributions were investigated. Two P-Trak® devices, one Grimm, one DustTrak® and one SMPS, were employed in a particular set-up. A manual pump was also used to collect particles on Nuclepore® polycarbonate filters. The changes of volume size distributions over time were also investigated. The morphologies of particles were investigated by FESEM and EDX.

According to the results, the relationships between increase of sliding velocity or contact pressure, and the increase of particles concentration, were detected. The number of fine and ultrafine particles generated from sintered brake pads was lower than those for organic brake pads in a similar test condition. The number of ultrafine particles from cast iron brake blocks was higher than those for organic brake blocks in a similar test condition.

In the ultrafine particle region, we recorded a peak at around 70-120 nm in diameter. In the fine particle region, we recorded two peaks at 300-400 nm and at 500-600 nm in diameter. And in the coarse particle region, we recorded a peak at around 3-6 µm in diameter. The fraction of this peak is highly dependent on material composition and test conditions. The effect of material composition on the particle morphologies were also discussed

The new index, AWPER, was introduced in this paper, which was suggested to be used in legislations for the non-exhaust emissions.

Paper D
In this paper, we reviewed most of the recent documented studies about exhaust-emission and non-exhaust emission in rail transport. This work consists of studying adverse health effects, particles size, morphology, chemical compositions, suggested solutions to reduce particles, current legislations, and recorded PM_{10} and other PM values on platforms and compartments.
Since the adverse health effects from rail traffic particles are one of the most questionable issues, it was discussed in this work. Furthermore, lung cancer, neurobehavioural impairment, heart attacks, and exacerbated respiratory diseases were recorded for exposure to the diesel exhaust. As it has been discussed, the new legislations in the US and EU were aiming to tighten the limit values for exhaust emissions. A summary of these legislations has been provided.

It has been recorded that the particles from non-exhaust emission are more genotoxic than road particles, as they can affect the amount of chromium, manganese and iron in the commuters' blood. The higher rates of mortality, higher tuberculosis notification, and lower life expectancy have been recorded for the residents near high-trafficked railroads. The biomarkers among subway drivers and subway workers were higher than bus drivers. But surprisingly, the incident of heart attacks or cancer was not higher among male subway drivers in comparison to other occupations among men working in subways. For the non-exhaust emission, there is no legislation, although the high mass concentrations of these kinds of particles were recognised before 1909. In this regard, we provided new legislations for outdoor air quality in the US and EU, and also presented a part of the current legislations for the exposure limits for some of materials related to the rail traffic particles.

In this study, we summarised the amount of PM_{10} and $PM_{2.5}$ for both above ground and underground rail traffics. For the above grounds, we made a subclassification for rail traffic with diesel locomotives.

The element compositions of the non-exhaust emission particles were also discussed based on the differences in the results. However, iron was the dominant one among all of the studies. It was interesting that in the oldest investigation, which was conducted during 1910s, the amount of iron in the particles was around 60%, and over these years no significant differences occurred for this fraction.

Some of the recent images from diesel particles and wear particles from railway wheels, organic brake pads, sintered brake pads, organic brake blocks, and cast iron brake blocks are presented in the current study. The differences between wear particle morphologies were more likely attributable to the difference in material compositions and the dominant wear mechanisms.

Finally, we reviewed the current alternatives that impact the exhaust emission and non-exhaust emissions. For the non-exhaust emission, we considered those papers that aimed to reduce wear among components, which are usually subjected to a wear process in rail traffic.

5. DISCUSSION

The results are discussed in this chapter.

In this thesis, we investigated some aspects of airborne particle characteristics from rail traffic. We checked the feasibility of reproducing operational real situations in laboratory conditions and validated our results. Particle characterisation (i.e., size in diameter, mass concentration, number concentration, and morphologies) were investigated for different brakes against steel brake discs and different brake blocks against railway wheels. The particle mass concentration from the sintered brake pads was lower than organic brake blocks, whereas the particle mass concentration from organic brake blocks was higher than cast iron brake blocks. These differences were attributed to different material compositions in these components. The differences in abrasivity and wear mechanisms were investigated in the particle morphologies.

A part of the results in this thesis was investigating the particle sizes. The three size regions were identified and dominant peaks were distinguished respectively. According to the results, a similar dominant peak around 280-350 nm was recognised for all test conditions. We separated peaks for 280 nm and 350 nm when we conducted our tests with organic brake pads and steel disc brakes in the sliding velocity 12.4 m/s. In other cases, there was no peak in the 280 nm. However, one peak in that region was quite obvious. It must be noted that when we used two different devices with the two different measurement principles, we received the same results. Meanwhile, those results were in agreement with similar studies by other researchers. Thus, these similarities are independent to measurement techniques or particle instruments.

However, there were some limitations in our particle instruments, which influenced our results. One of particle instruments that was used to investigate size distribution had a 6 s time resolution, and the lower limit of that device was 250 nm, which was close to the detected peak. In another particle instrument, the lower limit was 10 nm but the size distribution evaluated every 5.5 min. Currently, there is no explanation for these similarities in the results. We plan to apply particle instruments with higher time resolutions in the future in order to check factors that can result in this phenomenon. Studying the changes of particle morphology is another technique that may shed more light on this issue. Furthermore, we plan to measure particles' shape factors (i.e., sphericity, convexity and elongation) at the same time. Hopefully, the simultaneous measurements of wear rate, particle morphology and particle size distributions in a low time resolution assist us in understanding the unclear characteristics of airborne particles.

In the field of non-exhaust emission (non-combustion or non-tailpipe emission), a few studies have been conducted and consequently some limited legislations can be addressed. However, this part is quite well-known in road transport, and it deals with airborne particles from tires, braking material and roads. One of the existing legislations prohibits or limits the use of studded tires. The adverse health effects of using studded tires and their effects on PM10 are documented in Dahl et al. (2006), Lindbom et al. (2007) and Gustafsson et al. (2009). These kinds of results are motivations to ban or limit using studded tires. The use of studded tires is prohibited in the UK, Germany and 10 states in the US (Götzfried, F., 2008). There are seasonal restrictions for using them in Austria, Switzerland, Sweden, Norway, and most states in the US.

There is lack of similar methodology for non-exhaust emission in rail transport. The suggested airborne wear emission rate (AWPER) in this thesis is suggested to be used as an applicable index in this context. It can be used by clients to rank their sub-contractors during outsourcing products. Also, It can be used in legislation to force different manufacturers to optimise their products by considering the AWPER indices in their products. Furthermore, it can be used as a factor to evaluate emission tax for non-exhaust sources in rail traffic. In that case, the train operators and wagon owners will be willing to retrofit their systems (e.g., applying braking materials with lower particle emission rates) or even use bogies with higher steering performance. All of these efforts will result in lower airborne particles emission in rail transport.

As it was mentioned in Paper C, our results were based on the used set-up and the first 600 s of the sliding time. It is also suggested to control the effects of different particle density in the calibration of the measurement. One applicable solution is to use five or six different calibrations to avoid any biased results or conclusions. The particle instrument can be calibrated for different pair materials such as: organic brake pad-steel disc brakes, sintered brake pad-steel disc brakes, wheel-rails, organic brake block-railway wheels, and cast iron brake block-railway wheels. These kinds of calibrations help us obtain more reliable values for AWPERs.

Studying the adverse health effect of airborne particles was not the objective of this thesis. Yet, we have commented about the prioritisation in concerning iron in the studies. In fact, iron is the main dominant element in our study and the studies of other researchers. However, if we compare the $\frac{Mn}{Fe}$ or $\frac{Cu}{Fe}$, $\frac{Cr}{Fe}$ and the cumulative concentration of copper, iron, manganese, silicon, and chromium to the proposed OELs for these materials, we will understand the risk of those non-ferrous compound are higher.

6. CONCLUSIONS AND FUTURE WORK

This chapter presents answers to the research questions and future work is suggested.

6.1 Answers to the research questions

- *What is the state-of-the-art knowledge of airborne particles generation mechanisms, characteristics and sources?*

  We created an information survey and reviewed almost all of the documented research and studies. A part of that review is presented in Chapter 2.3. We classified the main particle sources to the exhaust emission and non-exhaust emission (Table 4). That review is summarised in paper D.

  These data were the backbone for further studies. Almost all of the documented studies were achieved based on stationary measurements by focusing on PM values and tracing some limited elements. We conducted field tests to distinguish particle sources and obtained some information about particle morphology and their sizes (Paper A and B).

  The generation mechanism for airborne particles is partly described in Chapter 2.4. We also suggested a schematic model in Paper A, which shows the interactions between different affective factors leading to airborne particles. However, this information is the first step towards a robust model. We suggest some future work (Chapter 6.2) with the aim of helping us understand the causes for the observed phenomena and results.

- *What is the element composition of airborne particles generated by a running train?*

  We investigated 32 elements during our field tests. We applied two sampling points during field tests and attempted to recognise the more likely sources of those elements. The detailed information of those results is presented in Paper B.

- *How can the composition of airborne particles be classified with respect to their health effects?*

  We presented some fundamental information about adverse health effects of airborne particles in Chapter 2.1. We also discussed the adverse health effects from exhaust emission and non-exhaust emission in Paper D. In that paper, we made critical comments on the single focus on iron in many research papers. It seems that the high amount of iron has fascinated many researchers and made them skip materials such as manganese, copper, nickel and chromium. The cumulative effects of particles and their adverse health effect on more sensitive people, such as children and people with pre-existing health problems, must be studied deeply. Future work in that area is suggested in Section 6.2.

- *What are the effects of different operational conditions on the airborne particles characteristics?*

  The effects of curve negotiating, accelerating, decelerating, activating, and deactivating electrical brakes were studied and reported on in Paper B.

- *Is it feasible to study the generation of airborne particles with reduced testing in a controlled laboratory environment?*

  In Paper A, we checked the feasibility to generate airborne wear particles in laboratory conditions. Those laboratory tests were limited to representing the condition of sliding contacts. In Chapter 6.2, we suggest further work to investigate the effect of rolling contact fatigue by using proper laboratory test benches.

- *How large a portion of the total amount of non-exhaust particles originates from wear processes?*

  As it was described in Chapter 2.4, there are numerous parameters that influence both the wear process and the conversion process, where wear debris are converted to airborne particles. According to Table 4, there are also a number of factors, besides wear, that affect the non-exhaust emission rate. The maintenance level, the operational condition, the applied technology in rail vehicles and infrastructures, the commuter cultural levels, and the traditional habits are all factors that affect the non-exhaust emission rate.

- *What is the best criterion to quantify airborne particle emission factors?*

  In Paper C, we introduced the airborne wear particle emission rate (AWPER) and described the set-up to measure and calculate this factor. This factor can, for example, be used in legislations as a measure for evaluating and controlling the amount of airborne particles generated by wear.

  And finally the main question:

- *How can the emission of airborne particles from a running train be efficiently controlled?*

  This question was the main objective of the entire project, and it is only partly addressed by this thesis. In Paper D, we reviewed the different suggested solutions to reduce the particle emission in rail transport. We have also emphasised the lack of legislations in this issue. In Section 6.2, we suggested future work with two approaches. In one approach, we propose to investigate other angles of particle generation mechanisms and attempt to simulate these mechanisms. In the other approach, our efforts would be focused on how to affect the number and size of the generated particles.

6.2 Future work

Almost all of the research about the changes in the contact surfaces are limited to studying the differences between specimen before and after testing. We are attempting to create knowledge on particle characteristics and to relate that to wear regimes and mechanisms in order to develop methods and tools to control the effect of these causes.

This thesis does not consider the following items and subjects that are proposed for future work:

- Particle emission from rolling contact of wheel and rails.

- Particle emission from wheel and switches (tongue blade).

- Particle emission from overhead line or third rail with electric collectors.

- Particle emission by erosion caused by piston effect, spraying sand or wind.

- The effect of electrical discharge from third rail or overhead lines in the characteristics of generated particles.

- Computer simulations to predict temperature, pressure, wear, and airborne particles generation from the non-exhaust sources, particularly wheel-rail contact and braking materials.

- Investigation of tribochemical films during contact of braking materials against brake discs or railway wheels.

- Creating innovative devices that collect airborne wear particles.

- Investigation on fluidising particles during the wear process.

- Investigation of the morphology of wear particles and its relation to transitions from one wear regime to another.

- Investigating disc radial groove effects on the particle characteristics from brake discs and brake pads.

- Investigating the relation between wear coefficients, friction coefficients, particles shape factors, flash temperatures, particle size distributions, and AWPERs for different materials.

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