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Towards elimination of airborne particles from rail traffic

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Abstract

Since the investigation of wear particles from rail transport started in the late 1910s, the high mass concentrations of these particles have prompted concern among researchers interested in air quality. However, effective action has yet to be taken because relevant knowledge is still missing. This thesis provides knowledge of airborne wear particles originating from rail transport. Some aspects of their characteristic parameters, such as size, mass concentration, number concentration, and morphology, were investigated in the field and in laboratory tests. We also discuss means to mitigate non-exhaust emissions, as well as the advantages and disadvantages of various test set-ups in the seven appended journal papers:

Paper **A** reviews recent studies of exhaust and non-exhaust emissions from rail vehicles. The results, measurements, adverse health effects, and proposed or applied solutions presented in this literature are summarized in this paper.

Paper **B** summarizes the results of field tests we conducted. The effects of curve negotiation and braking under different real conditions were investigated in a field test in which on-board measurements were made. The elemental composition and morphology of the particles emitted and their potential sources were also investigated.

Paper **C** describes how a pin-on-disc machine can be used to reproduce real operating conditions during mechanical train braking in a controlled laboratory setting. The results were validated by comparing the field test results with the results of laboratory studies.

Paper **D** presents comprehensive results of laboratory studies of airborne particles from different braking materials. A new index is introduced in this paper, which can be used as a quantitative metric for assessing airborne wear particle emission rates.

Paper **E** describes the effects of using various friction modifiers and lubricants on the characteristics of airborne particles from wheel–rail contact under lubricated and unlubricated conditions.

Paper **F** reports work to simulate thermoelastic instability in the cast-iron braking material. We simulated the fluctuation of the flash temperature by considering the temperature dependency of the material properties and the transformation of the contact state due to thermomechanical phenomena and wear.

Paper **G** reviews new full- and sub-scale measurements of non-exhaust emissions from ground transport. The advantages and disadvantages of on-board measurements, pin-on-disc tests, dynamometer tests, and test rig studies are discussed in this paper.

Keywords
Airborne, brake block, brake pad, railway, subway,TEI, wheel–rail, wear

Language
English

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Finally, I dedicate this work to my lovely wife, Roksana, and my cute children, Tania and Adrian.

Stockholm, September 2013

Saeed Abbasi

List of appended publications:

Paper A

S. Abbasi, A. Jansson, U. Sellgren, U. Olofsson. Particle emissions from rail traffic: A literature review. Published in ***Critical Reviews in Environmental Science and Technology*, 43, No. 23 (2013), 2511–2544.**
The author performed most of the writing and contributed to the planning and evaluation.

Paper B

S. Abbasi, L. Olander, C. Larsson, U. Olofsson, A. Jansson, U. Sellgren. A field test study of airborne wear particles from a running regional train. Published in ***IMechE, Part F: Journal of Rail and Rapid Transit*, 226(2012) 95–109.**
The author performed most of the writing and contributed to the planning, experimental work, and evaluation.

Paper C

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. Published in ***Wear*, 273(2011), 93–99.**
The author performed most of the writing and experimental work and contributed to the planning and evaluation.

Paper D

S. Abbasi, A. Jansson, L. Olander, U. Olofsson, U. Sellgren. A pin-on-disc study of the rate of airborne wear particle emissions from railway braking materials. Published in ***Wear*, 284–285 (2012), 18–29.**
The author performed most of the writing and experimental work and contributed to the planning and evaluation.

Paper E

S. Abbasi, U. Olofsson, Y. Zhu, U. Sellgren. Pin-on-disc study of the effects of railway friction modifiers on airborne wear particles from wheel–rail contacts. Published in ***Tribology International*, 60 (2013), 136–139.**
The author performed most of the writing and contributed to the planning and evaluation.

Paper F

S. Abbasi, S. Teimourimanesh, T. Vernersson, U. Sellgren, U. Olofsson, R. Lundén. Temperature and thermo-elastic instability of tread braking using cast-iron friction materials. Submitted to ***Wear*, Special issue CM2012.**
The author performed most of the writing, BEM modelling, and experimental work and contributed to the planning and evaluation.

Paper G

S. Abbasi, U. Sellgren, U. Olofsson. Technical note: Experiences of studying airborne wear particles from road and rail transport. Published in ***Aerosol and Air Quality Research*, 13 (2013) 1161–1169.**
The author performed most of the writing and contributed to the planning and evaluation.

List of other publications not appended in this thesis

U. Olofsson, Y. Zhu, S. Abbasi, R. Lewis, S. Lewis. Tribology of the wheel−rail contact: Aspects of wear, particle emission and adhesion. Published in ***Vehicle System Dynamics*, 51 (2013), 1091–1120.**

R. Lewis, S. Lewis, Y. Zhu, S. Abbasi, U. Olofsson. The modification of a slip resistance meter for measurement of railhead adhesion. Published in ***IMechE Part F: J. Rail and Rapid Transit*, 227(2013), 196–200.**

S. Abbasi, B. Ekstrand-Hammarström, U. Bergström, A. Bucht, U. Olofsson, U. Sellgren, A. Jansson. Biological response in lung cells to brake dust from a novel set-up to generate one-source wear particles. ***EAC 2013,* 1–6 September 2013, Czech Republic.**

S. Janhäll, M. Gustafsson, S. Abbasi, G. Blomqvist, A. Gudmundsson, C. Johansson, M. Norman, U. Olofsson, B. Sjövall. Road tunnels: Particle properties, wet and dry conditions. ***EAC 2013,* 1–6 September 2013, Czech Republic.**

M. Gustafsson, S. Abbasi, G. Blomqvist, A. Gudmundsson, S. Janhäll, C. Johansson, M. Norman, U. Olofsson, B. Sjövall, H. Wilhelmsson. Particles in road and railroad tunnel air: Properties, sources and abatement possibilities. ***EAC 2013,* 1–6 September 2013, Czech Republic.**

T. Vernersson, R. Lundén, S. Abbasi, U. Olofsson. Wear of railway brake block materials at elevated temperatures: Pin-on-disc experiments. ***Euro Brake,* 16–18 April 2012, Germany.**

S. Abbasi, U. Olofsson, U. Sellgren. Experiences of measuring airborne wear particles from braking materials and wheel–rail contact. ***17th Nordic Seminar on Railway Technology,* 3–4 October 2012, Sweden.**

S. Abbasi, U. Olofsson, U. Sellgren. A study of friction modifiers on airborne wear particles from wheel–rail contact. ***Nordtrib 2012,* 12–15 June *2012, Norway.***

S. Abbasi, U. Olofsson, U. Sellgren. A review of particle emissions from rail vehicles. ***Railway Technology: Research, Development and Maintenance,* 18–20 April 2012, Spain.**

S. Abbasi. Non-exhaust nano-particle emission in railway industry. ***Nano Technology in Railways,* 6 January 2010, Iran.**

S. Abbasi, U. Olofsson, U. Sellgren. Lack of applicable criteria in non-exhaust emission legislation: AWPER index: A practical solution. ***KTH Transport Day,* 30 November 2011, Sweden.**

S. Abbasi, J. Wahlstrom, L. Olander, C. Larsson, U. Olofsson, U. Sellgren. A field investigation of morphology and chemical composition of airborne particles in rail transport. ***NSJ2010*****, 14–15 September 2010, Sweden.**

Abbreviations

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

ATSDR: Agency for Toxic Substances and Disease Registry

CEN: The European Committee for Standardization

CNS: Central nervous system

DFG: Deutsche Forschungsgemeinschaft

DNA: Deoxyribonucleic acid

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

EC: European Commission

EDS/X: Energy dispersive X-ray

EPA: Environmental Protection Agency

EU: European Union

EUROMOT: The European Association of Internal Combustion Engine Manufacturers

FESEM: Field emission scanning electron microscope

FM: Friction modifier

GI: Gastrointestinal

IARC: International agency for Research on Cancer

ICP-MS: Inductive coupled plasma mass spectrometry

ISO: International Organization for Standardization

LRT: Light rail transit

MSHA: Mine Safety and Health Administration

NIOSH: The National Institute for Occupational Safety and Health

OPC: Ordinary Portland cement

PAHs: Polycyclic aromatic hydrocarbons

PM: Particulate matter

PNS: Peripheral nervous system

ppm: Parts per million

SEM: Scanning electron microscope

SMPS: Scanning mobility particle sizer

TSI: The technical specification of interoperability

UFP: Ultrafine particle

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 background information on airborne particles, the terminology used, heath effects, rail vehicle definitions, particle sources in rail traffic, and the research objective and questions, as well as briefly describing the research methodology used and outlining the structure of this thesis.

1.1. Background on airborne particles

The mass concentration of suspended solid particles or liquid droplets in a gas or another liquid is referred to as *particulate matter* (*PM*), which refers to suspensions in either liquid or gas. In contrast, *aerosol* refers only to the particles or droplets suspended in a gas (Hinds, 1999). ISO 4225:1994 defines dust 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". PM, aerosol, dust, and airborne particles are the common terms that we normally deal with in topics related to air quality.

The relationships between PM and various atmospheric phenomena have well-documented, for example, by Cheremisinoff (2002) and Ruzer (2012). Health problems among humans and animals, inverse effects on visibility, and global climate change are the most common adverse effects of PM.

These relationships are not new considerations, although they were not priorities in the past. For example, an Assyrian king, Tukulti-Ninurta II (890–884 BC), reported a strange smell in the air during a visit to Hit, a town west of Babylon and the centre of asphalt mining (Hopke, 2009). These relationships are described in the Hippocratic Corpus (Hippocrates, 460–377 B.C), which indicates that Greeks and Romans were familiar with these problems in crowded cities and mines (Sundell, 2004). In 61 AD, the Roman philosopher Seneca reported air pollution in Rome and the adverse effects it had 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 to the human lungs than burning "sea coal"; he also suggested relocating London's polluting industries, such as lime-burning and brewing (Krech et al., 2003).

Ramazzini investigated the relationship between people's diseases and their occupations, writing *De Morbis Artificum Diatriba* (Diseases of workers) in 1713. Ramazzini identified airborne particles as the second most important factor, after ergonomics, causing workers' diseases (Schenk, 2011). In the Victorian era, six industries were identified as "dangerous trades", and using ventilation systems became obligatory to diminish harmful air pollutants (Lee, 1973). However, only in the past century have the mechanisms of particle effects and characteristics been identified and more active pollution abatement efforts been undertaken (Nielsen and Ovrebø, 2008).

We refer to suspended solid particles or liquid droplets in the air as airborne particles; throughout this thesis, the term "particles" refers to such matter unless otherwise specified.

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

Some examples of PM subcategories are as follows:

- $PM_{2.5}$ 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 particles with an AD up to 0.1 µm.
- Fine fraction ($PM_{(2.5\text{-}0.1)}$) refers to particles with an AD of 0.1–2.5 µm.
- Coarse fraction ($PM_{(10\text{-}2.5)}$) refers to particles with an AD of 2.5–10 µm.

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

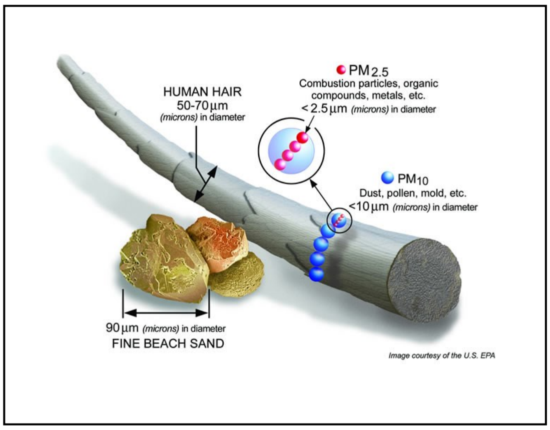

Figure 1. Comparison of the sizes of fine beach sand, human hair, and PM_{10} and $PM_{2.5}$ (EPA PM Research, 2011).

It should be noted that ISO/TC 146/SC 2/WGI N320 defines nanoparticles and ultrafine particles in similar terms. It defines a nanoparticle as "a particle with a nominal diameter smaller than about 100 nm". Nanoaerosols and nanostructured particles are also defined there. A nanoaerosol is defined as "an aerosol comprised of or consisting of nanoparticles and nanostructured particles" and a nanostructure particle as "a particle with structural feature smaller than 100 nm, which may influence its physical, chemical and/or biological properties". This definition addresses particles larger than 100 nm, since the agglomeration of particles 100 nm in diameter leads to a larger particle.

1.2 Health effects

Humans are subjected to risks from particles through various routes of exposure. These routes 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 the eyes and irritation or discolouring of the skin are common dermal symptoms caused by particles. Particles can come into contact with the skin and be absorbed as preformed solutions, or be dissolved by sweat, blood, or fatty acids on the skin. After the particles are dissolved, the penetration process starts (Hostynek, 2004). Skin absorption and reactivity are well documented by Guy (1999). Several factors affect skin absorption; these include exogenous factors (e.g., size, dose, pH, protein reactivity, and solubility) and endogenous factors (e.g., skin age, anatomical site, and skin tissue section) (Hostynek, 2004).

It must be noted that particles deposited on the skin can then be ingested. Hand to mouth is one on the most common particle ingestion routes. According to Hawley (2005), an individual child might ingest up to 25% of the dirt present on the fingers by hand-to-mouth contact, while the corresponding proportion for adults is 14%. Xue et al. (2007) reported that hand-to-mouth behaviour among children is highly dependent on age group and location, the highest hand-to-mouth frequency belonging to two-year-olds during indoor activities.

Inhaling particles has a more intense and rapid effect, as such particles can directly enter the bloodstream via the respiratory system, whose surface area is hundreds of times larger than the total area of the human skin. In addition, the size and shape of various parts of the respiratory system are suitable for particle deposition. Figure 2 shows various parts of the upper and lower respiratory tracts. A real image of the bronchiole–alveolar duct is presented in the upper-right image.

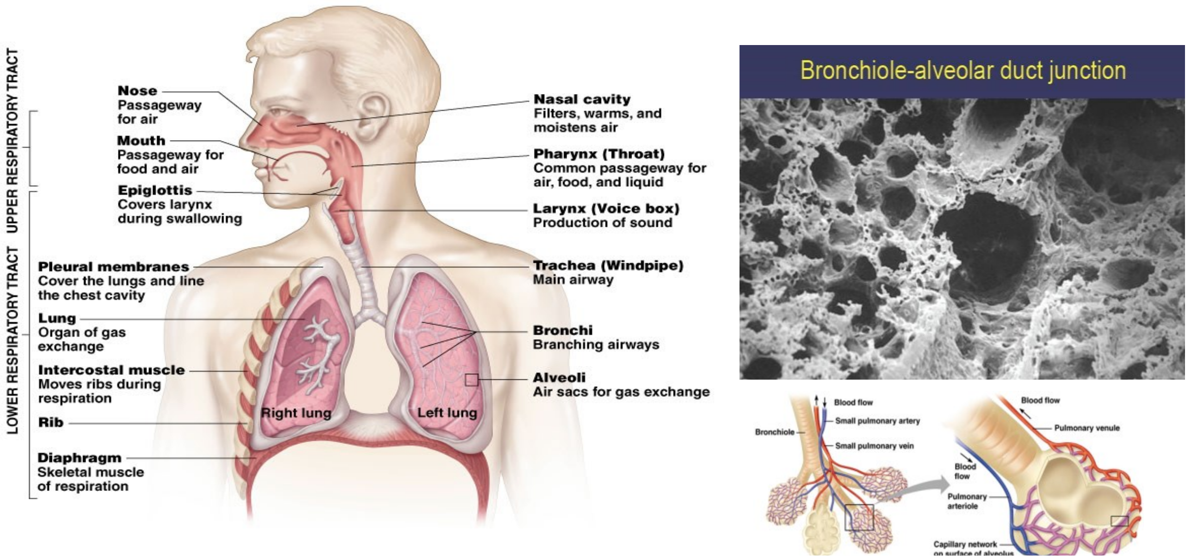

Figure 2. Various parts of upper and lower respiratory tracts (by permission of Prof. K. Pinkerton.)

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

Particles penetrate and can be deposited in different parts of the respiratory system depending on their size. Tager (2012) 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 of various sizes (from Tager, 2005)

Particle size range (µm)	*Level of penetration*
≥11	Do not 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 (2005), particles smaller than 11 µm can penetrate the respiratory system, while the finest ones, i.e., smaller than 0.65 µm, can reach the alveolar ducts and alveoli. Tager (2005) also mentioned that the particle deposition rate in the tracheobronchial and alveolar regions is highly dependent on sex, age, and respiratory disease status. It has been demonstrated that, given an equal particle size interval, greater deposition occurs in women, young adults 14–18 years old, and individuals with pre-existing respiratory diseases. Figure 3 illustrates the variability in mass deposition (µg d^{-1}) as a function of age and sex.

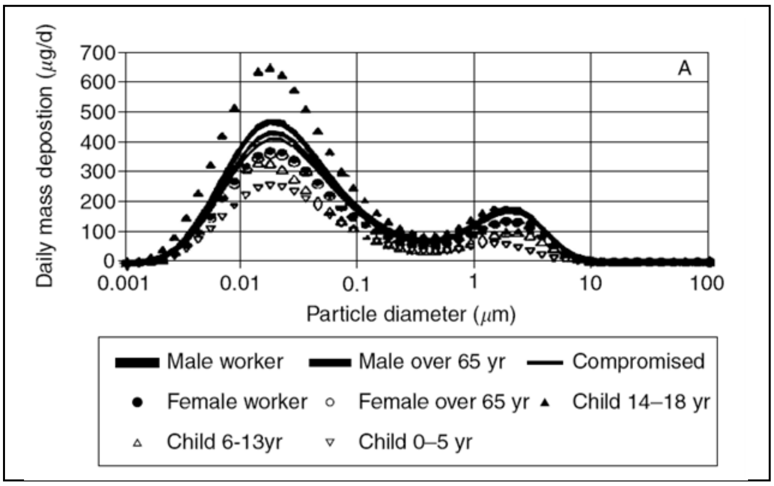

Figure 3. Daily mass particle deposition rate for 24-h exposure at 50 µg m^{-3} in the tracheobronchial and alveolar regions (from Tager, 2005).

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

Recently, Madl and Pinkerton (2009) reported more than 30 different particle characteristics and exposure factors that must be evaluated when considering the adverse health effects of particles in respiratory systems. It has also been demonstrated that diabetics are more susceptible to the adverse health effects of particle inhalation (Gold, 2008).

Figure 4 is a schematic of how nanoparticles enter the blood through various routes. Ignoring drug delivery by injection, the other routes shown in the figure illustrate the generalised effects of particles on humans. The figure also shows how particles can reach different body organs, whose inputs and outputs are shown schematically. In fact, the particles' toxic effects start only when the accumulation of constituent elements exceeds certain thresholds that can be tolerated by the natural metabolism of the human body.

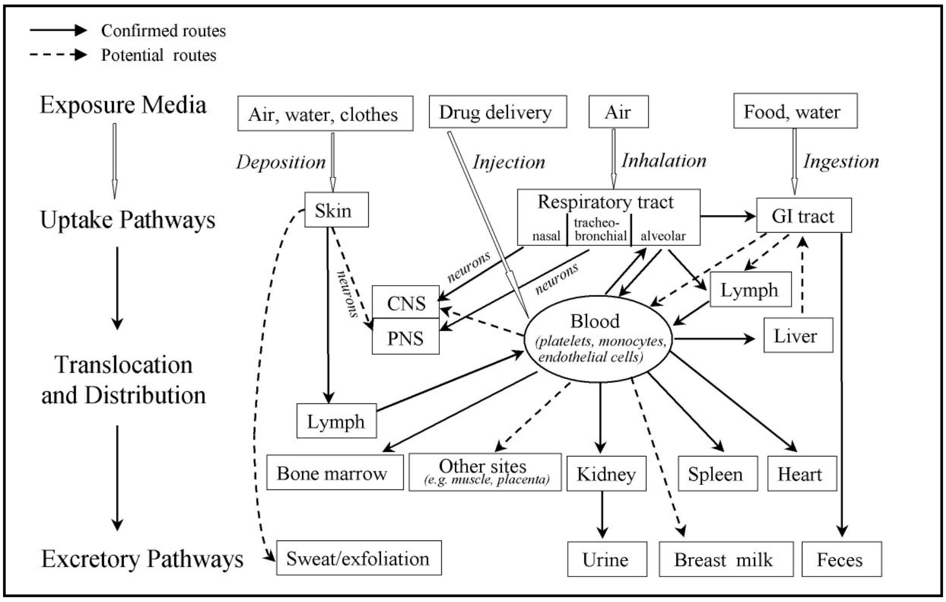

Figure 4. Schematic of particle exposure routes and their potential effects in different organs (from Fitzpatrick et al., 2005).

According to ATSDR studies, accumulations of lead, copper, zinc, nickel, aluminium, chromium, mercury, manganese, iron, and cadmium can damage human organs, including the kidneys, liver, bones, lungs, and GI tract. It must be noted the adverse health effects and damage caused by particles are not limited to accumulation problems in various organs. It has been demonstrated that particles can cause other types of long- and short-term damage depending on their characteristics and human exposure. Vomiting, metal fever, nervous system effects, siderosis, oxidative stress, and cancer are reported to occur because of exposure to particles at certain concentration levels (ATSDR website, 2011). It must be noted that some health problems appear after long after initial exposure. For example, mesothelioma, a type of lung cancer caused by exposure to asbestos, has a latency period of more than 40 years, after which it can be diagnosed (Blanchi and Blanchi, 2007).

1.3 Rail vehicle: A definition

A rail vehicle can be defined as a movable rail-guided or interactive device used to transport objects or provide essential services to facilitate the transporting of objects. Rail vehicles can be classified based on their main function:

a) long-distance transportation: rail vehicles such as passenger cars, freight cars, locomotives, multiple units, LRTs, and rail buses;

b) short-distance transportation: rail vehicles such as rollercoasters and carriages in cable railways or funiculars; such rail vehicles are usually used for distances under five km; and

c) supporting machinery for rail transportation: rail vehicles such as track maintenance machines (e.g., tamping machines and ballast stabilizing machines), rail snowploughs, and railway cranes.

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

The main focus of this thesis is category (a), with the exception of single-rail or rubber-tired rail vehicles. However, some of the present results and discussions can easily be extended to cover other types of rail vehicles beyond the scope of this thesis.

1.4 Particle sources in rail transport

Commercial rail transportation using steam locomotives running on cast-iron rails appeared in the UK between 1804 and 1812. The London underground, the oldest subway in the world, was opened in 1863, ten years before Carl Benz invented the first four-stroke cycle gasoline engine and commercialized cars for road transportation (Williams et al., 2000). Today, both these transport modes are recognized as particle emission sources. However, the amount of research into and legislation to limit particle emissions from rail transport is remarkably low. Notably, high particle mass concentrations occurring in subways evoked concern a century ago, but little effective action has been carried out since then.

Table 2 summarizes particle sources in rail transport. As shown, rail vehicles, various stationary processes, air circulation, and passenger and rail staff can all be considered particle sources, though most research has focused on particles from rail vehicles. The main focus of this thesis is non-exhaust emissions, i.e., not originating from engines, but from rail vehicles.

Table 2. Summary of various rail transport particle sources.

Sources	Sub-category	Examples
Rail vehicles	Exhaust (engine) emissions	Diesel exhaust
	Non-exhaust emissions	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 caused by a running rail vehicle (piston effect)
Stationary processes (maintenance & construction)	Direct	Tunnelling 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 emissions from road transport Natural erosion of masonry structure
	Forced ventilation	Moving and transferring particle emissions from road transport
Passengers and rail staff	Human activities	Smoking on platforms Smoking in rail vehicles
	Other	Particles shed by passengers' clothes Degraded perishable materials and garbage

1.5 Objective and research questions

The main research question of the overall research project, which has rail transport as its context and of which the work presented here is part, is:

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

In the present work, this main question has been decomposed into the following sub-questions:

- What is the state of the art of our knowledge of the generation mechanisms, characteristics, and sources of airborne particles?
- What is the elemental composition of airborne particles generated by running trains?
- How can airborne particles be classified with respect to their composition and health effects?
- How do various operating conditions affect airborne particle characteristics?
- Is it feasible to study airborne particle generation using reduced-scale testing in a controlled laboratory environment?
- What is the best criterion for quantifying airborne particle emission factors?
- To what extent can lubricants or friction modifiers affect airborne particle generation?

1.6 Thesis outline

Chapter 1 briefly introduces the purpose of the thesis and presents the research questions. Chapter 2 summarizes the results of the appended papers, and Chapter 3 discusses these results. Chapter 4 answers the stated research questions and proposes avenues for future research.

2. SUMMARY OF RESULTS OF APPENDED PAPERS

This chapter summarizes the results of the appended papers and presents the division of work for each paper.

Paper A

In this paper, we reviewed most of the recent documented studies of exhaust and non-exhaust particle emissions from rail transport. This work investigates particles in terms of adverse health effects, size, morphology, chemical composition, suggested solutions for reducing the particle number, current relevant legislation, and PM_{10} and other PM values recorded on platforms and in compartments.

Since the adverse health effects of airborne rail traffic particles are one of the most contentious issues in rail research, they were discussed in this paper. Furthermore, lung cancer, neuro–behavioural impairment, heart attack, and exacerbated respiratory disease have been recorded in people exposed to diesel exhaust. As has been discussed, new legislation in the USA and the EU is intended to tighten the limit values for exhaust emissions.

It has been claimed that non-exhaust particle emissions from rail transport are more genotoxic than are particle emissions from road transport, as the former can affect the amount of chromium, manganese, and iron in the blood of those exposed. Higher mortality rates, higher tuberculosis notification, and lower life expectancy have been recorded among those living near highly trafficked railroads. The particle-exposure biomarkers among subway drivers and subway workers were higher than among bus drivers; surprisingly, however, the incidence of heart attacks and cancer were no higher among male subway drivers than among men working in other occupations in subways. No legislation sets limit values for non-exhaust emissions, although the high mass concentrations of such particles were recognized before 1909. We summarized current legislation for outdoor and indoor air quality as well as for emissions from diesel engines in rail traffic, and also presented some current legislated exposure limits for certain materials related to rail traffic particles.

In this study, we summarized the amounts of PM_{10} and $PM_{2.5}$ associated with both ground-level and underground rail traffic. For ground-level PM, we created a sub-classification distinguishing between diesel-powered and electric-powered rail traffic.

The elemental composition of non-exhaust emission particles was discussed based on differences between the results of the reviewed studies. Iron, however, was the dominant element treated in all studies. Interestingly, in the oldest investigation, conducted in the 1910s, the amount of iron in the particles was found to be approximately 60%, a proportion that has not changed significantly over the years.

Some recent images of 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 study. The morphological differences between wear particles are likely attributable to differences in material composition and dominant wear mechanism.

Finally, we reviewed the current alternatives that affect exhaust and non-exhaust emissions. For non-exhaust emissions, we considered studies focusing on reducing wear among components usually subject to wear processes in rail traffic.

Paper B

Most existing studies of railway-related particles evaluate particle mass concentrations based on stationary measurements. As coarse particles account for most of the total particle mass, few studies present any results for submicron-sized particles. However, recent studies have demonstrated that ultrafine particles can cause more severe health effects than can coarse particles. In this paper, we accordingly investigated the characteristics of particles near their sources using on-board measurement devices.

A series of full-scale field tests was performed using the Gröna Tåget test train (Regina 250) equipped with Becorit 950-1 brake pads and steel disc brakes. Four test runs were performed on part of a Swedish intercity track at a maximum operational speed of 200 km h^{-1}. A special instrument set-up in the train was used to investigate particle generation under different operating conditions (e.g., activating/deactivating electrical brakes or curve negotiation). The main objective of the study was to investigate particle size, morphology, elemental composition, and size distribution.

Two airborne particle sampling points were designated under the frame of the train. One sampling point was near a pad-to-rotor disc brake contact, and a second, global sampling point was located under the frame, but not near a mechanical brake or the wheel–rail contact. The first sampling point was highly influenced by brake pad wear debris, and the second one was influenced by particles originating from all brake pads, wheel and rail wear debris, and particle resuspension. At each sampling point, three tubes were linked to three particle measurement devices. Two sets of P-TRAK®, DUSTTRAK®, and Grimm devices were used. The two Grimm devices were equipped with Millipore filters in their outlets to capture particles for further studies of particle morphology and elemental composition. The total number and size distribution of the particles at the two sampling points were registered and evaluated for different situations, including activating and deactivating the electrical brakes or curve negotiation.

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 the number of airborne particles.

A FESEM was used to capture images of particles as small as 50 nm collected on filters. Both EDS/X and ICP-MS methods were used to analyse these particles. According to an ICP-MS investigation of the filters, the PM was composed mainly of 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

This paper checked the validity of generating airborne wear particles in laboratory conditions by comparing the characteristics of such particles with those of particles measured in the field.

For this purpose, 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 to sample air containing only wear particles. The pins were prepared from Becorit 950-1 brake pad material and the discs were cut from railway steel brake disc material similar to the field test materials. We used the same particle measurement instruments that we used in the field tests (paper B) plus an SMPS. The latter device allowed us to measure particle size distributions for particles 10–520 nm in diameter in 110 intervals.

The FESEM and EDX were used to investigate particle morphology and elemental composition. The results recorded by the particle measurement instruments and FESEM images from both the field and laboratory tests were in agreement. Both sets of results indicate a dominant fine peak for particles approximately 350 nm in diameter, and a coarse peak for particles 3–7 µm in diameter. Furthermore, increasing the applied loads caused higher particle concentrations in both systems.

Paper D

In this paper, we investigated the characteristics of particles generated by organic brake pad–steel brake disc, sintered brake pad–steel brake disc, cast-iron brake block–railway wheel, and organic brake block–railway wheel systems in laboratory conditions. We also introduced a new index, the airborne wear particle emission rate (AWPER), and a methodology for comparing airborne particles from different materials.

For this purpose, 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 to sample air containing only wear particles. The pins were prepared from brake pads and brake blocks and the discs were prepared from steel brake discs and railway wheels.

Four different particle instruments were used to investigate particle size, particle number concentration, and particle size distributions. Two P-TRAK®, one Grimm, one DUSTTRAK®, and one SMPS devices 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 particle morphologies were investigated using FESEM and EDX.

Relationships between increased sliding velocity or contact pressure and increased particle concentration were found in the results. The numbers of fine and ultrafine particles generated by sintered brake pads were lower than those generated by organic brake pads under similar test conditions. The number of ultrafine particles from cast-iron brake blocks was higher than the number from organic brake blocks under similar test conditions.

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

We suggested that the new AWPER index introduced in this paper should be used in legislation on non-exhaust emissions.

Paper E

As discussed in paper A, lubricants and FMs are suggested means to reduce particle emission rates from the wheel–rail contact. To the best of this author's knowledge, however, the effects of such lubricants and FMs on UFP emissions are not clear.

In this paper, we investigated the effects of biodegradable rail grease, water-based FM, and oil-based FM on the particles generated from wheel–rail contacts in laboratory conditions.

According to this study, use of all three types of rail grease and FMs significantly reduces the number concentration of coarse particles; however, use of the water-based FM can result in the generation of UFPs.

In this respect, we made a general awareness of using water-based FMs. We accordingly suggested that water-based FMs should only be used after considering factors leading to high contact temperature in the wheel–rail contact (e.g., high rails, tight curves, high axle loads, and hot weather). These factors can increase the UFP concentration, which entails risk in an enclosed system and can necessitate the increased replacement of water-based FM.

Paper F

In papers A–E, temperature was recognized as a factor affecting the generation of airborne particles.

In this paper, we focused on frictional heating and thermoelastic instability (TEI) phenomena at the interfacing surfaces. We used a pin-on-disc machine equipped with railway braking materials. An inductive heater was used to reproduce the thermal effects of sudden temperature increase in the interfaces. An infrared camera, an inductive displacement sensor, and a laser displacement sensor were used to monitor temperature increase and the displacement of both the pin and the disc. This set-up and the results are presented in detail by Vernersson et al. (2012); some of these results, i.e., those concerning cast-iron brake block material, were used in paper F.

We used two approaches in this paper. In the first approach, we considered wear and attempted to simulate the fluctuating behaviour of flash temperature leading to hot spots. In the second approach, we neglected the wear and focused on the average temperature of the pin and disc. Both approaches showed good agreement with the experimental results.

Paper G

This paper is a short review of some published research into non-exhaust emissions in ground transportation. As there are some similarities between the characteristics of particles emitted in road and rail transportation, we considered both cases simultaneously.

In this paper, we reviewed the set-ups, results, and limitations of new research, excluding stationary measurements. The advantages and disadvantages of full-scale field studies with on-board measurements and of sub-scale studies by means of pin-on-disc machines, dynamometers, and test rigs were discussed.

3. DISCUSSION

The results are discussed in this chapter.

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

Some results of this thesis pertain to the particle size. Three size regions were identified and dominant peaks were distinguished for each region. According to the results, a similar dominant peak at approximately 280–350 nm was recognized in all test conditions. We separated peaks for 280 nm and 350 nm when we conducted our tests with organic brake pad and steel disc brake materials at a sliding velocity of 12.4 m s^{-1}. In other cases, there was no peak at a particle size of 280 nm. However, one peak in that region was quite obvious. It must be noted that two different devices with two different measurement principles gave the same results. Moreover, these results were in agreement with those of similar studies by other researchers. These similarities detected are thus independent of the measurement techniques and particle sampling instruments used.

Our particle instruments had some limitations that influenced our results. One particle instrument used to investigate the size distribution had a six-second time resolution and a lower limit of 250 nm, which was close to the detected peak. Another particle instrument had a lower limit of 10 nm but evaluated the size distribution with a 5.5-minute resolution. In the future, we plan to use particle instruments with higher time resolutions in order to check factors that may influence the size distribution. Studying changes in particle morphology is another approach that may shed light on this matter; furthermore, we plan to measure particle shape factors (i.e., sphericity, convexity, and elongation) at the same time. In addition, we explored the elemental composition of airborne particles off line by collecting them on filters and investigating them using ICP-MS or EDS/X. Recently Morawska (2009) reviewed some of the available techniques that can be used to investigate the elemental composition of particles in situ. We believe that the on-line investigation of the elemental composition of particles sheds more light on the transient behaviour of the wear process and the subsequent generation of airborne particles. It is hoped that simultaneously measuring wear rate, particle morphology, and particle size distributions using a high-time-resolution instrument along with the on-line measurement of the elemental composition of airborne particles will help us grasp as yet unclear characteristics of airborne particles.

One fact emphasized in paper G was the increasing proportion of wear-based particles from ground transport, particularly in the coarse fraction. Figure 5 shows the PM level trend in EU rail transportation. As shown, the $PM_{2.5}$ and PM_{10} levels are decreasing, but the proportion of coarse particles (PM_{10}–$PM_{2.5}$) is increasing.

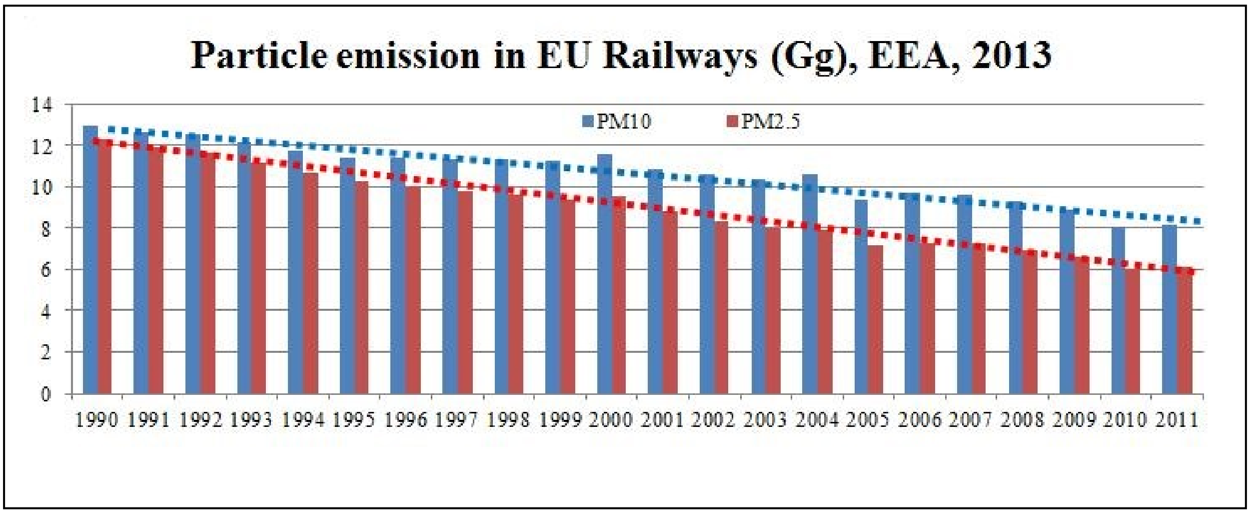

Figure 5. PM10 and PM2.5 emissions from EU railways over the last 20 years, Gg (EEA, 2013).

Few studies have been conducted in the field of non-exhaust emissions (i.e., non-combustion or non-tailpipe emissions), so there is only limited relevant legislation that can be compared with legislation on exhaust emissions. Non-exhaust emissions are fairly well known in road transportation, where they comprise airborne particles from tires, braking material, and roads. One of the existing pieces of legislation on non-exhaust emissions prohibits or limits the use of studded tires. The adverse health effects of using studded tires and their effects on PM_{10} are documented by Dahl et al. (2006), Lindbom et al. (2007), and Gustafsson et al. (2009), whose findings justify banning or limiting the use of studded tires. Studded tires are prohibited in the UK, Germany, and ten states in the USA (Götzfried, F., 2008). As well, there are seasonal restrictions on using them in Austria, Switzerland, Sweden, Norway, and most states in the USA. Legislative progress, toxicity studies, or even mitigation alternatives in road transport can be used as a basis for future studies of non-exhaust emissions. This issue should be considered in the context of enclosed rail traffic systems, as such particles are more genotoxic than are road particles (Karlsson et al., 2005).

Another interesting idea that can be transferred from road transport is defining non-exhaust emission rates for different types of trains according to their configuration, operating conditions, and technical specifications. Currently, similar rates have been defined in road transport and are widely used in modelling. There is lack of a similar methodology for non-exhaust emissions from rail transport. The airborne wear emission rate (AWPER) proposed here could be applicable in this context. It could be used by clients to rank their sub-contractors when outsourcing products. It could also be used in legislation to force different manufacturers to optimize their products by considering the AWPER indices in their development process. Furthermore, it can be used as a factor for taxing emissions from non-exhaust sources in rail traffic. In that case, train operators and wagon owners must be willing to retrofit their systems (e.g., using braking materials with lower particle emission rates) or even use bogies with higher steering performance. All of these efforts will potentially lower the airborne particle emissions from rail transport.

As mentioned in paper D, our results are based on the particular set-up used and the first 600 seconds of sliding time. We also suggested controlling the effects of different particle densities when calibrating the measurements. One applicable solution is to use five or six different calibrations to avoid any biased results or conclusions. The particle measurement instrument can be calibrated for different pairs of materials, such as organic brake pad–steel disc brake, sintered brake pad–steel disc brake, wheel–rail, organic brake block–railway wheel, and cast-iron brake block–railway wheel materials. This kind of calibration would help us obtain more reliable AWPER values.

Studying the adverse health effects of airborne particles was not the objective of this thesis. Even so, we have commented on the prioritization of iron in the reviewed studies. In fact, iron is the dominant element treated in our research and in that of other researchers. As the iron concentration is reportedly less than the applicable occupational exposure level (OEL), some researchers have concluded that PM levels in tunnels and subway stations could not be problematic. In reaching this conclusion, however, some important facts are being neglected. First, rail transport and traffic are growing quickly and the frequencies of passing trains are increasing on almost all routes. On the other hand, OELs are not static values but are becoming more stringent over time (Schenk, 2011). Therefore, the amount of iron and other substances may eventually reach or even exceed the OELs as rail traffic and consequently related PM levels increase, while OELs have become more stringent in recent years and will continue to do so in the near future. Second, the negative synergies between various substances and their cumulative adverse health effects are unclear. As addressed in papers A, B, and G, the elemental composition of airborne particles from rail traffic includes soot, chromium, nickel, copper, aluminium, zinc, magnesium, manganese, and silicon.

4. CONCLUSIONS AND FUTURE WORK

This chapter presents answers to the research questions and suggests avenues for future research.

4.1 Answers to the research questions

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

We created an informative survey and reviewed almost all available documented research. The data acquired from this review constituted the backbone of further research, as this literature review raised some questions that called for further work. Almost all of the documented studies were based on stationary measurements, focusing on PM values and tracing certain limited elements. In response, we conducted field tests to distinguish particle sources and obtained needed information on particle morphology and size (papers B and C). In papers B–E, we noted that the high flash temperature at the asperities and the high surface-to-volume ratio of spherical shapes could cause the submicron particles detached from the bulk material to become spherical or semi-spherical in shape.

Figure 6 shows examples of particles from a cast-iron brake block–railway wheel contact in which the flash temperature was high. We also demonstrated that the particle size distribution is time dependent, and that the dominant peak of the distribution is dependent on the contact conditions. Material properties, contact pressure, and sliding velocity all affect the wear process and consequently the generation of airborne particles.

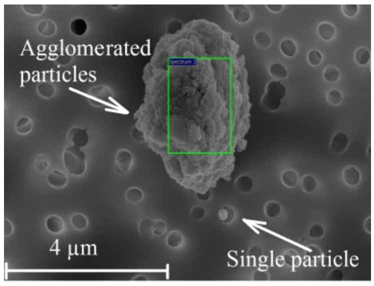

Figure 6. Morphology of a particle of cast iron brake block and railway wheel from a field test.

In paper F, we started to simulate the contact temperature and reproduce the fluctuating flash temperature. This work was the first step in linking TEI and material loss from the contact interface. Table 2 in section 1.3 and paper A are the main results of our literature survey. We reviewed hundreds of documents, which raised several questions. As was addressed in paper A, some of our other papers (B–E) are cited in this literature survey.

The mechanism for generating airborne particles is partly described in the previous work by this author (Abbasi et al., 2011). We also suggested a schematic model in paper C, which shows the interactions between various factors affecting the generation of airborne particles. This schematic model is just the first step towards formulating a robust model; we suggest some future work (section 4.2) that may help us understand the causes of the observed phenomena and results.

- *What is the elemental composition of airborne particles generated by running trains?*

We investigated 32 elements during our field tests. We used two sampling points during the field tests and identified the most likely sources of those elements. The details of these results are presented in paper B.

Figure 7 shows the Gröna Tåget train (“Green train”) used in our field test. This investigation found that the emitted particles mainly comprised Al, Ca, Cu, Fe, Si, and Zn, bearing in mind the limitations of ICP-MS. We also suggested that the main sources of Al, Ca, Na, and Si were the ballast, concrete sleepers, and masonry infrastructure of the rail lines.

Figure 7. Instrumented train used in our field test.

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

We presented fundamental information about the adverse health effects of airborne particles in section 1.2. We also discussed the adverse health effects of exhaust and non-exhaust emissions in paper A. In that paper, we criticized the single-minded focus on iron particles in many research papers. It seems that the high amount of iron has captured the attention of many researchers, causing them to neglect elements such as manganese, copper, nickel, and chromium. The cumulative effects of particles and their adverse health effects on more sensitive people, such as children and those with pre-existing health problems, must be studied further and more deeply. It should be noted that the adverse health effects do not depend only the particle composition; as discussed in paper B, more than 30 factors should be considered when evaluating the health effects of airborne particles. Future work in that area is suggested in section 4.2.

- *How do various operating conditions affect airborne particle characteristics?*

The effects of curve negotiating, accelerating, decelerating, and activating and deactivating electrical brakes were studied and reported in paper B. Those factors were demonstrated to affect the wear processes in the wheel–rail contact, braking materials, and overhead lines, and they all contribute to the generation of airborne particles from running trains. As discussed, deactivating electrical brakes significantly increased the generation of airborne particles. In addition, increased particle emissions were recorded during curve negotiation. We observed that the amount of Cu-based particles was considerably higher in rainy weather, which was a strong indication of higher wear between contact strips and overhead lines under high humidity conditions.

- *Is it feasible to study airborne particle generation using reduced-scale testing in a controlled laboratory environment?*

In Paper C, we examined the feasibility of generating airborne wear particles in laboratory conditions. We demonstrated that by using the same contact pressure and sliding velocity as in the field test, we could obtain the same size distribution and morphology from the laboratory pin-on-disc tests as in the full-scale field tests. However, some factors, such as the scaling effect, are still not completely understood.

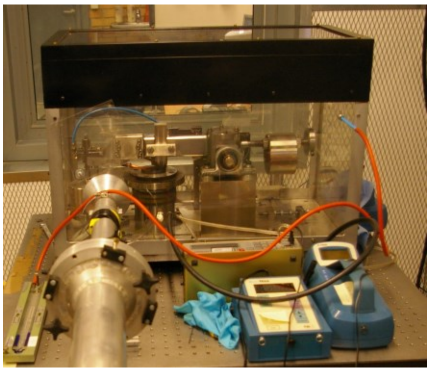

Figure 8. Pin-on-disc machine set-up with instrument (Abbasi et al., 2013).

In paper G, we discussed the different set-ups that can be used in sub-scale tests. We reviewed some of the published work considering pin-on-disc machines, dynamometers, and test rigs and evaluated the advantages and disadvantages of each type. We have also made some suggestions for improving sub-scale testing in future.

- *What is the best criterion for quantifying airborne particle emission factors?*

In paper C, we introduced the airborne wear particle emission rate (AWPER) and described the set-up used to measure and calculate this index. This index can, for example, be used in legislation as a metric for evaluating and controlling the amount of airborne particles generated by wear. We believe that it is still too early to regard it as the best criterion; however, as the index fulfils some essential requirements for such a criterion, it is a suitable candidate for further improvement.

- *To what extent can lubricants or friction modifiers affect airborne particle generation?*

In paper E, we investigated this issue in laboratory conditions. Biodegradable rail grease, water-based lubricant, and vegetable oil-based friction modifier were used; all of them reduced the number concentration of coarse particles, but the water-based friction modifier increased the number concentration of UFPs. It was concluded that water-based lubricants are more susceptible to the flash temperature, which reportedly can exceed 500°C in real wheel–rail contact conditions.

And finally the main question:

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

This question was the main objective of the entire project, and we did our best to answer it. In paper A, we reviewed the various suggested solutions for reducing particle emissions from rail traffic. Various alternatives were introduced that can be used in the near and distant future; in particular, measures for reducing exhaust emissions have been successfully applied in recent years. These alternatives can be used and implemented during railway design, manufacturing, retrofitting and upgrading, and operation. We emphasized the lack of legislation governing non-exhaust emissions and introduced an index that can be used as a metric in legislation. We lack sufficient information on the characteristics of particles from rail traffic. Such data could be used to implement brake dust collectors on vehicles or even in enclosed systems. In papers B–E, we tried to shed more light on this issue and started gathering data on the characteristics of particles from rail traffic. The main results of these papers were also addressed in paper A.

Another important result of this research is that particle concentrations and particle size distributions are highly dependent on contact conditions. Using proper materials, managing temperature, or even using proper lubricants or friction modifiers are other solutions that we investigated in a limited way.

As that research was a basic and essential step towards eliminating airborne particles from rail traffic, we interpreted our results from another perspective. We discussed the opportunities for improvement in the tests reported in paper G. In section 4.2, we suggested two approaches to future research. In one approach, we proposed investigating other particle generation mechanisms and attempting to simulate these mechanisms. In the other approach, we proposed focusing on how to affect the number and size of the generated particles.

4.2 Future work

Almost all research into changes in the contact surfaces has been limited to studying the differences between specimens before and after testing. We are attempting to create knowledge of particle characteristics and to relate these characteristics to wear regimes and mechanisms in order to develop methods and tools for controlling their effects.

This thesis does not consider the following matters, which would be productive areas for future research:

- particle emissions from rolling contact between wheels and rails

- particle emissions from wheels and switches (tongue blade)

- particle emissions from overhead lines or third rails with electricity collectors

- particle emissions from erosion caused by the piston effect, sprayed sand, or wind

- the effects of electrical discharge from third rails or overhead lines on the characteristics of generated particles

- developing a computer model to link TEI and AWPER for different braking materials

- investigating the behaviour of tribochemical films formed during contact between braking materials and brake discs or railway wheels

- creating innovative devices that collect airborne wear particles

- investigating the effects of cant efficiency and curve radius on the characteristics of particles from the wheel–rail contact of a running train

- investigating the fluidization of particles formed during the wear process leading to non-exhaust emissions

- investigating wear particle morphology and its relationship to transitions from one wear regime to another

- investigating disc radial groove effects on the characteristics of particles from brake discs and brake pads

- investigating the relationship between wear coefficients, flash temperatures, and AWPER for different materials at different temperatures

- investigating the density, refractive index, and shape factors of particles (in different size intervals) from individual sources in rail traffic

- defining and investigating cyclic tests to reproduce real braking conditions in laboratory systems

- implementing online investigation of the elemental composition of airborne particles during full- and sub-scale tests

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