Department of Engineering Design and Production

Wet and dry friction of passenger car tires during ABS braking

Lassi Hartikainen

Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 210/2014

Wet and dry friction of passenger car tires during ABS braking

Lassi Hartikainen

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall K216 of the school on 19th December 2014 at 12.

Aalto University
School of Engineering
Department of Engineering Design and Production
Vehicle Engineering

Supervising professor
Prof. Matti Juhala

Thesis advisor
Dr. Frank Petry, Goodyear S.A., Luxembourg

Preliminary examiners
Dr. Bo Persson, Forschungszentrum Jülich, Germany
Prof. Dr.-Ing. Matthias Kröger, Technische Universität Bergakademie Freiberg, Germany

Opponent
Dr. Malal Kane, IFSTTAR - Nantes, France

Aalto University publication series
DOCTORAL DISSERTATIONS 210/2014

ISBN 978-952-60-6023-1 (printed)
ISBN 978-952-60-6024-8 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-6024-8

Unigrafia Oy
Helsinki 2014

Finland

NORDIC ECOLABEL
441 697
Printed matter

Aalto University

Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Author
Lassi Hartikainen

Name of the doctoral dissertation
Wet and dry friction of passenger car tires during ABS braking

Publisher School of Engineering

Unit Department of Engineering Design and Production

Series Aalto University publication series DOCTORAL DISSERTATIONS 210/2014

Field of research Vehicle Engineering

Manuscript submitted 21 July 2014 **Date of the defence** 19 December 2014

Permission to publish granted (date) 21 November 2014 **Language** English

☐ **Monograph** ☒ **Article dissertation (summary + original articles)**

Abstract

This dissertation aims at improving the understanding of dry and wet friction between a tire and a road surface to improve traffic safety. The goal was reached through examination of some of the key phenomena, including tire-vehicle interaction, wet rubber friction, asphalt surface roughness, and tire deformation during aquaplaning. Test programs were carried out at various locations across Europe and new analysis techniques were developed.

It was found that changes in tire inflation pressure, ambient temperature, and tread depth affect the average slip conditions of the tire during ABS braking due to changes in the force-slip characteristics of the tire. This is because an acceleration-based brake controller adjusts the average slip operating range of the tire accordingly. However, this also leads to a change in the sliding speed at the rubber-road contact, which has an effect on the friction. Further results of the work included a new analysis method for asphalt surface roughness. A wavelength-wise correlation between asphalt surface roughness data and wet friction results of a tire was presented for the first time. Good levels of correlation were found even though only locations on the same asphalt surface type were included. In addition, the surface roughness metrics used in the study were physically meaningful and well in line with modern rubber friction theories. The developed method was also applied to dry lab friction experiments, where a good correlation between surface roughness and rubber friction was found as well. To allow detailed replication of tire-road friction in laboratory experiments, a method was developed for manufacturing durable laboratory rubber friction test countersurfaces that replicate the roughness of a target asphalt pavement. It was found, that the most suitable samples were built by using epoxy instead of bitumen as a binder for the asphalt mix, by duplicating the aggregate gradation curve of the target asphalt surface, and by initially sandblasting the surface to remove excess binder. Furthermore, the work presented in this dissertation showed that an optical tire sensor can be used for detecting partial and full aquaplaning from within a tire. This tool allows the quantification of the remaining tire footprint length in the presence of water on any given road surface.

The advancements made in the understanding of dry and wet friction of tires during ABS braking will be utilized immediately and developed further. The new methods will be put to use in the tire industry and they provide many interesting opportunities for further research.

Keywords tire-road wet friction, rubber friction, traffic safety, asphalt surface roughness

ISBN (printed) 978-952-60-6023-1 **ISBN (pdf)** 978-952-60-6024-8

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2014

Pages 124 **urn** http://urn.fi/URN:ISBN:978-952-60-6024-8

A? Aalto-yliopisto

Tiivistelmä

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tekijä
Lassi Hartikainen

Väitöskirjan nimi
Henkilöauton renkaan kuiva- ja märkäkitka ABS-jarrutuksen aikana

Julkaisija Insinööritieteiden korkeakoulu

Yksikkö Koneenrakennustekniikan laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 210/2014

Tutkimusala Ajoneuvotekniikka

Käsikirjoituksen pvm 21.07.2014 **Väitöspäivä** 19.12.2014

Julkaisuluvan myöntämispäivä 21.11.2014 **Kieli** Englanti

☐ **Monografia** ☒ **Yhdistelmäväitöskirja (yhteenveto-osa + erillisartikkelit)**

Tiivistelmä

Tämän väitöskirjan tavoite on renkaan ja tien välisen märän ja kuivan kitkan ymmärryksen lisääminen liikenneturvallisuuden parantamiseksi. Tavoitteeseen päästiin tarkastelemalla tärkeitä aiheeseen liittyviä ilmiöitä, kuten renkaan ja ajoneuvon vuorovaikutusta, kumikitkaa märällä alustalla, asfaltin pinnankarheutta, sekä renkaan muodonmuutoksia vesiliirron aikana. Projektin aikana suoritettiin laajoja testiohjelmia eri puolilla Eurooppaa ja kehitettiin uusia analyysimenetelmiä.

Tulokset osoittivat kuinka rengaspaine, ulkoilman lämpötila ja renkaan urasyvyys vaikuttavat renkaan keskimääräiseen luistotilaan, johtuen renkaan voima-luisto-ominaisuuksien muuttumisesta. Ilmiö selittyy ABS-jarrujärjestelmän kulmakiihtyvyyksiin perustuvalla toimintaperiaatteella, joka muuttaa renkaan keskimääräistä luistotilaa voima-luisto-ominaisuuksien mukaisesti. Tämä kuitenkin johtaa myös liukunopeuden muuttumiseen kumi-tie kontaktissa, vaikuttaen syntyvään kitkaan. Tutkimuksen tuloksiin kuului myös uusi menetelmä asfaltin pinnankarheuden analysoimiseksi. Tuloksissa esitettiin ensi kertaa renkaan märkäkitkan ja asfaltin pinnankarheuden välinen aallonpituuksittain laskettu korrelaatio. Menetelmä tuotti vahvan korrelaation jopa vertailtaessa eri alueita samalta asfalttityypiltä. Lisäksi menetelmässä käytettävillä arvoilla on selkeä fysikaalinen merkitys ja menetelmä on linjassa modernien kitkateorioiden kanssa. Menetelmää sovellettiin myös kuivalla asfalttipinnalla tehtyihin laboratoriokitkakokeisiin, jotka tuottivat myös hyvän korrelaation. Tutkimuksessa kehitettiin myös menetelmä kestävän vastinpinnan valmistamiseksi laboratoriokitkakokeita varten siten, että laboratorionäytteen pinnankarheus vastaa annettua kohdeasfalttia. Paras tulos saavutettiin käyttämällä laboratorioasfaltin sideaineena bitumin sijaan epoksia, käyttämällä samaa rakeisuuskäyrää kuin kohdeasfaltissa, sekä hiekkapuhaltamalla näytteen pinta puhtaaksi liiasta sideaineesta. Lisäksi tutkimuksessa selvisi, että optista rengasanturia voidaan käyttää täyden tai osittaisen vesiliirron tunnistukseen renkaan sisäpuolelta. Tämä mahdollistaa renkaan jäljellä olevan kosketusalan pituuden mittaamisen millä tahansa veden peittämällä tien pinnalla.

Tutkimuksen tuloksena tehtyjä kehitysaskeleita ABS-jarrutuksen aikaisen kuivan ja märän kitkan ymmärryksessä aletaan välittömästi hyödyntämään ja niitä kehitetään edelleen. Kehitetyt menetelmät tullaan ottamaan käyttöön rengasteollisuudessa ja ne tarjoavat monia mielenkiintoisia jatkotutkimusaiheita.

Avainsanat renkaan märkäkitka, kumikitka, liikenneturvallisuus, asfaltin pinnankarheus

ISBN (painettu) 978-952-60-6023-1 **ISBN (pdf)** 978-952-60-6024-8

ISSN-L 1799-4934 **ISSN (painettu)** 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2014

Sivumäärä 124 **urn** http://urn.fi/URN:ISBN:978-952-60-6024-8

Dedicated to the loving memory of my brother, Arsi.

"Usko minua ystäväni,
meitä kaikkia kerran musta kuolo päähän koppaa.
Yksi toisensa perään hän meitä maahan nuijii."

- Aleksis Kivi-

Preface

The work presented in this dissertation was mainly conducted at the Goodyear Innovation Center Luxembourg in Colmar-Berg, Luxembourg. The analysis and writing for the article about aquaplaning **[Article IV]** was performed at the Aalto University (then TKK) Vehicle Engineering lab in Espoo, Finland. The vehicle measurements presented in the articles were performed at various proving grounds around Europe. The preparation of the asphalt samples for the article about laboratory test surface development **[Article III]** was carried out at the Highway Engineering lab at the Aalto University.

The work was supported by the European Commission under the Marie Curie Industry-Academia Partnership and Pathways (PIAP-GA-2009-251606). The article about laboratory test surface development **[Article III]** was a direct result of the researcher secondments facilitated by this funding. In addition, the Marie Curie fund allowed carrying out the coursework needed for the doctoral degree and getting immersed in the field of highway engineering.

The work was also supported by the Fonds National de la Recherche (Luxembourg) under the AFR grant number 1368189. The AFR fund was instrumental for being able to carry out such a long-term personal project in a fast-paced industrial R&D environment. The work done for **Article IV** was financially supported by the European Commission under the FP6-project FRICTION FP6-IST-2004-4-027006. All these contributions are greatly appreciated.

I would like to thank Goodyear Tire & Rubber Company for the permission to publish the results presented in this dissertation and in the corresponding articles.

I would like to thank my instructor Dr. Frank Petry for guidance and support throughout the past several years. Most of the work presented in this dissertation was done in Goodyear internal projects run by him. I would also like to thank Dr. Stephan Westermann for defining and running together with Frank the umbrella project under which this dissertation was done, as well as for advice and expertise in polymer physics, contact mechanics and rubber friction.

I would also like to thank my supervisor from the University, Prof. Matti Juhala for facilitating my doctoral studies despite my remote location, and for all the advice and discussions along the way. I would also like to thank Prof. Terhi Pellinen for facilitating my studies in the field of highway engineering and by providing invaluable advice on questions related to road surfaces and road research. I would further like to thank the rest of my co-authors Dr. Ari Tuononen and Antti Kuosmanen for their contributions in the published articles. I would like to thank them and Tuomas Alhonnoro also for their friendship throughout the years and the courage to come and spend a year in Luxembourg.

Big thanks go to my chief engineers Dave Hubbell and Matt Kaufman, Manager Edouard Michel, as well as our human resources department for making my doctoral studies possible. I would also like to thank Dr. Georges Thielen and Dr. Benoit Duez from the External Science Programs for their help in setting up the Marie Curie and AFR funding.

I would like to thank Project Managers Bruno Maitre and Peter Dahlberg, as well as Director of Global Tire Performance Prediction Laurent Colantonio for sponsoring the internal Goodyear projects under which most of the work was carried out.

I would also like to thank Thomas Müsch and Olaf Theissen for support with the lab friction tests performed for **Article III** as well as Jean-Paul Lambotte, Jacques Schouten, Sebastien Duluard and Claude Jacque for planning and organizing the extensive test program needed for **Article II**. I would also like to thank all the drivers and technicians for performing the skid trailer and British Pendulum measurements for **Article II**.

I would like to thank Sebastien Duluard, Peter Lautwein and Guy Wiesen for the instrumentation of the test vehicles used in **Article I**, and Christian Franck and the other test drivers for running the tests with great accuracy. I would also like to thank Paul Joubert for the initial work regarding the vehicle instrumentation and Dr. Tibor Fülöp and all my other colleagues who have provided me with data, advice, and lively discussions over the years.

Finally, I would like to thank all my friends and my family for their support over the years. Many of my old friends in Finland have provided the motivation to pursue a doctoral degree by finishing their degrees promptly before me, or by otherwise immersing themselves in some area of science. Others have provided amazing stress relieving experiences in the fields of motorsport and aviation, to name a few. And my new friends in Luxembourg have provided like-minded company both in and outside the office, which I have very much enjoyed.

The very last, and by far the highest, praise goes to my mother Sirkku for raising her sons to be independent and to always seek for the truth.

Colmar-Berg, June 30th, 2014

Lassi Hartikainen

Contents

List of publications

This dissertation consists of a summary and the following publications, which are referred to by their Roman numerals:

Article I L. Hartikainen, F. Petry, S. Westermann. *Longitudinal wheel slip during ABS braking*. Accepted to Vehicle System Dynamics. In press. DOI: 10.1080/00423114.2014.991332

Article II L. Hartikainen, F. Petry, S. Westermann. *Frequency-wise correlation of the power spectral density of asphalt surface roughness and tire wet friction*. Wear, Vol. 317 pp. 111-119, 2014. DOI:10.1016/j.wear.2014.05.017

Article III A. Kuosmanen, T. Pellinen, L. Hartikainen, F. Petry, S. Westermann. *Durable laboratory rubber friction test countersurfaces that replicate the roughness of asphalt pavements*. Wear, Vol. 321 pp. 38-45, 2014. DOI:10.1016/j.wear.2014.09.011

Article IV A. Tuononen, L. Hartikainen. *Optical position detection sensor to measure tyre carcass deflections in aquaplaning*. Int. J. Vehicle Systems Modelling and Testing, Vol. 3, No. 3, 2008. DOI:10.1504/IJVSMT.2008.023837

Author's contribution

For **Article I**, the author contributed to the conception and test design, prepared the initial vehicle instrumentation, oversaw most of the measurements, performed the analysis, interpreted the results together with the co-authors, and prepared the manuscript.

For **Article II**, the author took part in the conception and design of the study, performed about half of the road surface scans, developed and performed the road surface analysis and the correlation analysis, and prepared the manuscript. The results were interpreted together with the co-authors.

For **Article III**, the author took part in the conception of the study and some preliminary bitumen removal experiments. The preparation of the asphalt samples, friction tests and surface scans were performed by Antti Kuosmanen. The author performed the final analysis of the friction and surface roughness results presented in the paper, while a preliminary analysis had been done before by Antti Kuosmanen. The author also performed the correlation analysis and prepared the manuscript together with Antti Kuosmanen. The results were interpreted together with the co-authors.

For **Article IV**, the author contributed to the conception, measurements, analysis, interpretation of results, and preparing the manuscript equally together with Dr. Ari Tuononen.

Summary of publications

Article I: ABS braking tests with two passenger cars were performed on different types of summer and winter road surfaces to quantify the average operating conditions of the tires in terms of wheel slip. Histograms and median values were used for the quantification. Tests were also performed at different ambient temperatures, with different tire inflation pressures, and with different tire tread depths to capture the effects of the most common variables affecting tire force-slip characteristics throughout tire life. Clear effects were observed from all studied variables. The changes in the slip operating range also modified the relative local sliding speeds, which is important for rubber friction. The results highlight the importance of the ABS controller's ability to adapt to changing force-slip characteristics of tires.

Article II: To increase the understanding of road surface roughness analysis methods with regard to modern rubber friction theories, the surface topographies of different asphalt surfaces were measured. The surface topographies were analyzed using a top-cutting technique and by calculating the power spectral densities of the resulting data. The power spectral density at each evaluated spatial frequency was then correlated individually to wet tire friction results from the corresponding locations using linear regression. The results showed the highest correlations at the highest evaluated frequencies, as limited by the spatial resolution of the measurement. With the addition of road surface temperature information, the correlation was further improved.

Article III: The article presented the development of a durable pavement sample for laboratory rubber friction testing that has the surface roughness characteristics of a predefined road surface. The study included four types of asphalt, including samples bound with bitumen, concrete, and epoxy. The best one to both replicate the surface characteristics of the target surface and to produce a durable surface in terms of surface topography and friction results was the one using epoxy resin as a binder. A reasonable correlation between the surface roughness power spectrums and the friction results was also found.

Article IV: Aquaplaning tests were performed using a tire equipped with an optical sensor tracking the movements of the tire inner liner with reference to the wheel. It was found that partial and full aquaplaning can be detected using the sensor. The method also provides a tool for measuring the length of the remaining contact patch and for deepening the understanding of the aquaplaning phenomenon.

Scientific contribution

The research presented in this dissertation has extended the state-of-the-art of vehicle braking performance by providing a toolkit for the quantification of tire operating conditions during ABS braking on dry and wet asphalt surfaces. The results include the following specific advancements:

1. The effects of ambient temperature, road surface type, tire inflation pressure, and tire tread depth on the average slip and relative sliding speed of a tire during ABS braking were quantified experimentally.
2. Asphalt surface roughness and tire wet friction were correlated as a function of the roughness wavelength.
3. The effect of road surface roughness evaluation depth on the correlations between the surface roughness power spectrums and tire wet friction was quantified. A clear optimum was found for the studied surfaces.
4. A good correlation was found between tire wet friction and the combination of surface micro- and macro roughness metrics and surface temperature. The result was attained despite small differences between the studied asphalt surface formulations and while maintaining physically meaningful surface roughness metrics.
5. A contribution was made to the development of a method for manufacturing durable asphalt samples for lab friction testing that replicate the roughness of a given road section.
6. A large contribution was made toward showing the feasibility of using an optical location tracking tire sensor to detect and quantify partial and full aquaplaning of a tire and to estimate the length of the remaining contact patch.

List of abbreviations

2D	Two-dimensional
3D	Three-dimensional
ABS	Anti-Blockier System, Anti-lock Brake System
ACC	Adaptive Cruise Control
AD	Analog-to-Digital converter
ADAS	Advanced Driver Assistance System
ASR	Anti-Slip Regulation (traction control system)
BPN	British Pendulum Number
CFD	Computational Fluid Dynamics
ESC	Electronic Stability Control
FEA	Finite Element Analysis
FEM	Finite Element Method
FL	Front Left wheel
FR	Front Right wheel
FVM	Finite Volume Method
IR-LED	Infrared Light Emitting Diode
LED	Light Emitting Diode
PSD	Position Sensitive Device (with reference to tire sensors)
RL	Rear Left wheel
RMS	Root Mean Square roughness
RMSE	Root Mean Square Error
RR	Rear Right wheel
UHP	Ultra-High Performance tire
YLL	Years of Life Lost

List of symbols

$C(q)$	Surface roughness power spectrum
$E(\omega)$	Complex viscoelastic modulus of rubber
F_x	Longitudinal force acting on a tire or a wheel
F_z	Vertical force acting on a tire or a wheel
h	Height of a surface asperity
M_y	Torque acting on the rotational axis of the wheel
$P(q)$	Magnification function for rubber-road contact
q	Surface roughness wave vector
q_L	Lower limit spatial frequency for surface roughness
q_1	Upper limit spatial frequency for surface roughness
R^2	Coefficient of determination of linear regression
r_{eff}	Effective rolling radius of a tire
s	Longitudinal wheel slip
s_{max}	Wheel slip value at which the maximum friction coefficient is achieved on a *μ-slip* curve
v	Sliding velocity
w	Wheel rolling speed
x	Two-dimensional distance vector in the mean plane of the surface
α	Wheel angular acceleration
μ	Friction coefficient F_x/F_y
$\mu_{normalized}$	Normalized friction coefficient
μ_{peak}	Maximum value of the friction coefficient
ν	Poisson ratio of rubber
σ_0	Mean perpendicular pressure in rubber-road contact
ϕ	Direction of a wave vector in relation to sliding
ω	Rubber excitation frequency

1 Introduction

It is estimated that over a million people die in road accidents globally every year, which makes it the 8th most common cause of death when measured with *Years of Life Lost*, or YLL [Murray, 2012]. Furthermore, when considering for example only men in the age group of 15-24 years in the EU and EFTA countries, it is the most common cause of death in terms of YLL [Murray, 2012]. Road accidents are, of course, accompanied with significant material damages as well.

Improvements in traffic safety have therefore been an important topic in both public and private research, especially with regard to road building and maintenance, as well as in research and development carried out in the automotive field. Most forces guiding, accelerating and slowing down a vehicle are transferred through the contact between the tire and the road. While not all road accidents are affected by the available road forces, there is clear evidence that road sections that provide on average lower friction levels are associated with higher accident densities, as shown in [Giles, 1965], [Hemdorff, 1989], and [Schulze, 1977]. For accident types that involve emergency braking or avoidance maneuvers, the available road forces are of paramount importance. If higher braking and cornering forces could be generated, these types of accidents could either be avoided, or at least the impact velocities could be reduced, lowering the risk of injuries for the occupants. The effect of the impact velocity on the injury risk has been assessed for example in [TRL, 2009] and [TRL, 2010]. It is well known that on typical asphalt pavements the friction levels are lower when the road is wet compared to when it's dry. This is why improving wet friction is a consistent focus area for tire manufacturers. The effect of the friction level on the impact velocity is discussed for example in [TNO, 2014].

Thanks to the large effort spent in this area in the past, significant improvements have already been made over the years. However, to continue the improvements in the future, the understanding of the underlying physics must also get continuously deeper. Filling the knowledge gaps needed for the necessary characterization of tire operating conditions during ABS braking was the main goal of this dissertation. The goal was achieved through detailed examinations of some of the key phenomena surrounding the forces transmitted between a tire and a road surface. The areas covered were tire-vehicle interaction, tire-road wet friction with relation to asphalt surface topography, and aquaplaning.

Specific research questions were defined for each of the studied areas:

1. In the area of tire-vehicle interaction the research questions were:
    a. What are the most critical parameters in terms of tire operating conditions from the point-of-view of ABS braking performance?
    b. How can these parameters be quantified?
    c. How do the most common environmental variables affect these parameters?
2. For tire-road friction and asphalt surface topography, the main research questions were:
    a. Which components of road roughness affect wet rubber friction the most?
    b. How should the surface topography data be treated to extract the most relevant information in terms of wet rubber friction?
3. For aquaplaning the questions were:
    a. Can tire footprint length be estimated during partial aquaplaning using a tire-based sensor?
    b. Can full or partial aquaplaning be detected using a tire-based sensor to allow measurements on any road surface?

2 Background and methodology

Several research fields needed to be included in the study to allow for a complete understanding of the braking performance of a tire. These fields included vehicle dynamics and brake controllers, tire carcass dynamics, tire tread and contact mechanics, rubber friction and the effect of water on the friction, as well as asphalt surface characterization. The necessary background for each of the associated fields is given in this chapter.

2.1 ABS brakes

Modern passenger cars are equipped with Anti-lock Braking Systems (ABS). The system prevents the wheels from locking during braking and therefore keeps the vehicle steerable throughout the braking event [Bosch, 2006]. The system also attempts to keep the wheel slip at a range where maximum braking force can be generated, thereby optimizing braking performance [Bosch, 2006]. For the purposes of this dissertation, the wheel slip is defined as:

$$s = \frac{v - w \cdot r_{eff}}{v},$$

where v is the vehicle speed, w is the wheel rolling speed, and r_{eff} is the effective rolling radius of the tire.

Ideally, the wheel slip at which the maximum longitudinal force is generated, denoted here as s_{max}, would be known in advance, and the controller would simply try to adjust the wheel rolling speed to maintain the slip close to s_{max}. However, in real vehicle applications there are several limitations to this approach. First, controlling the wheel rolling speed and slip has typically been difficult due to the on/off nature of the hydraulically actuated brake systems [Savaresi, 2010] as well as vibrations in the tire-suspension system. Secondly, the s_{max} value is usually not known in advance by the controller because it depends on several variables connected to the tire, the road, and the prevailing conditions [Gent, 2005], which are not necessarily captured by the system. This variation in the s_{max}, along with the dynamics of the hydraulically actuated brake system is why an approach combining slip control with wheel angular acceleration control is widely used [Savaresi, 2010]. Such a system is described for example in [Bosch, 2006]. In the wheel acceleration approach, the brake pressure is gradually increased, until a large drop in the wheel rolling speed is observed, which triggers a drop in the brake pressure, as shown in Figure 1 at 2.86s.

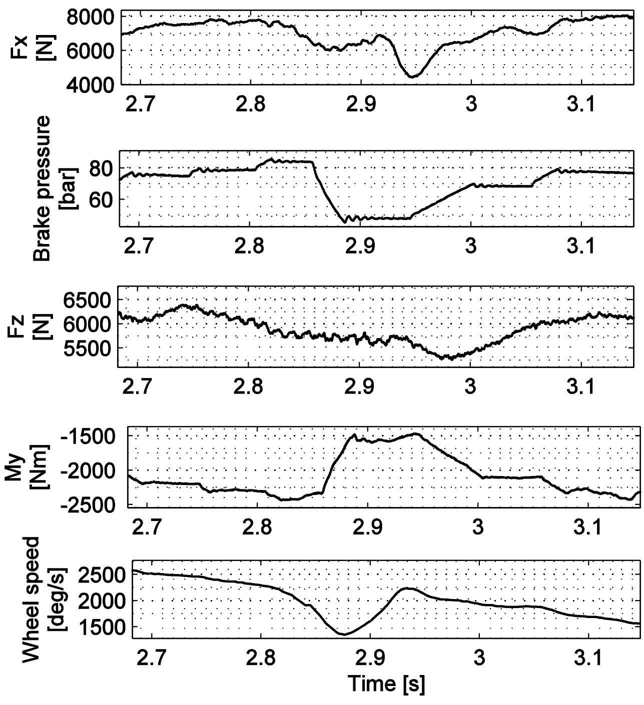

Figure 1. Time response of the F_x, brake pressure, F_z, M_y, and wheel rolling speed signals during ABS braking showing brake pressure drop, hold and rise cycles. Reprinted from [Tuononen, 2012].

The drop in the wheel rolling speed is an indication that the force generated at the tire-road contact counteracting the braking torque has started to decrease. In other words, the wheel slip has exceeded the s_{max} value and the tire is operating on the downward slope of the μ-slip curve (see Figure 2). The brake pressure is then dropped to allow for the tire to reaccelerate, bringing the wheel slip back below the s_{max} value. After this, a new pressure increase cycle is started. Cycling through these control loops leads to the fact that instead of one fixed operating point in terms of wheel slip the tire operates within a wide range of slip values. These ranges were measured as a part of this dissertation to quantify the typical tire operating conditions during ABS braking.

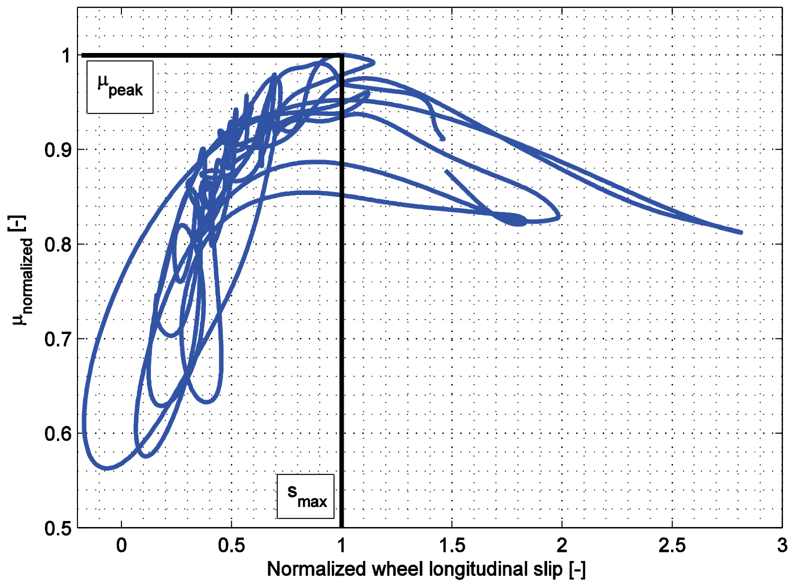

Figure 2. Normalized μ-slip curve during vehicle ABS braking. The curve varies within a large range of slip and μ values. Oscillations along the slip axis are largely a result of the phase difference between the wheel and the tire belt. [Article I]

2.2 Tire force transfer and modeling

An accurate representation of tire force generation during ABS braking requires an adequate tire model [Zanten, 1989]. In vehicle simulations, a common approach is the empirical Magic Formula tire model [Pacejka, 1991]. However, the Magic Formula model does not in itself capture tire dynamics, which are of importance for many vehicle simulation scenarios. This is why the Magic

Formula model is typically extended with a longitudinal relaxation length, such as in [Jaiswal, 2010]. However, the relaxation length model cannot capture tire vibration modes, which might be of importance in ABS braking. Modeling the tire vibrations during ABS braking is discussed for example in [Zegelaar, 1998], [Gong, 1993], [Adcox, 2011], [Jansen, 1999], and [Persson, 2011]. The significance of this topic is growing in importance because the use of electrical motors as a part of passenger car powertrain is growing. Electrical motors have the potential for providing higher controllability of both drive and brake torque. Some of the possibilities are discussed for example in [Rosenberger, 2012]. Depending on the specific setup, the masses and inertias of the electrical motors can also change the vibrational properties of the tire-vehicle system.

The vibration modes of the tire that are relevant for ABS braking can be described for example with a computationally efficient rigid ring model [Zegelaar, 1998] [Schmeitz, 2007]. However, rigid ring models neglect flexible belt modes, which are captured only by more complex models, such as the ones developed in [Kindt, 2009] and [Alujević, 2014]. The rigid ring approach can be also extended to capture combined slip conditions [Maurice, 1998] and arbitrarily uneven road surfaces [Schmeitz, 2004]. The drawback of the rigid ring model compared to the longitudinal relaxation length approach is that an additional set of parameters is needed. Moreover, these parameters often depend on operating conditions such as velocity, load and force excitation [Zegelaar, 1998] [Pauwelussen, 2003]. This makes the full parameterization of the model, including velocity and amplitude dependencies of the sidewall stiffness, time consuming and expensive.

As a part of the research project leading to this dissertation, the author, together with co-authors, carried out a study where the rigid ring model parameters were for the first time identified from standard vehicle measurements with typical instrumentation used in vehicle dynamics investigations. The results of this study were published in [Tuononen, 2012]. A schematic of the model and the approximate natural frequencies of different vibration modes are shown in Figure 3.

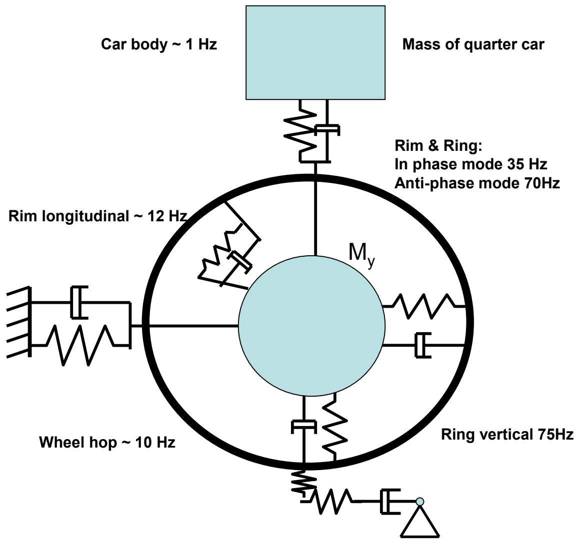

Figure 3. Schematic of a rigid ring tire model. Reprinted from [Tuononen, 2012].

The suspension of the vehicle poses a challenge in the parameterization of the rigid ring model [Schmeitz, 2004] [Sharp, 1998], because by adding a flexible suspension the boundary conditions of the system are changed, which influences the vibration modes of the tire. Alternative ways to derive the model parameters are laboratory test rig measurements with a fixed rim position, such as in [Bruni, 1997], and using finite element analysis, such as in [Balaramakrishna, 2009]. Using a test rig with a fixed wheel position of course requires access to such a dedicated test facility. In addition, similar to the vehicle suspension, all compliances of the test rig have the potential of changing the vibration modes of the tire, and when studying higher order tire modes, the vibration modes of the test rig may be difficult to distinguish from the ones of the tire. The limitation of the finite element approach is of course that a detailed enough FEA model may not be available to researchers working outside tire manufacturers R&D organizations.

2.3 Rubber friction and asphalt surface roughness

While the vehicle and brake system controllers have the potential to optimize the tire-road contact conditions, the forces are finally generated at the rubber-road contact. Rubber-road friction is therefore at the core of the present study.

It is well known that the main contributor to the gradual decrease in rubber-road wet friction during the lifetime of an asphalt concrete surface is the reduction in the surface micro roughness, or polishing. Typically, due to methodological limitations, asphalt surface micro roughness has been evaluated indirectly, using a friction test metric, such as the British Pendulum Number BPN [Giles, 1965] or one of the various other friction measurement devices [PIARC, 1995]. Direct measurements of micro roughness based on surface topography have typically been confined to laboratory studies, where more accurate methods are easier to apply. This is typically due to restrictions in the portability of surface roughness measurement instruments.

There are, however, currently devices available that are portable and that can reach a spatial resolution in the order of 10μm, while simultaneously having a field-of-view of over 1cm, which is critical for covering wavelengths introduced by the size of the largest aggregates in the pavement. Different surface scanning principles are reviewed for example in [Blais, 2004] and [Sansoni, 2009]. Usually devices with such a high resolution cannot be operated from a moving vehicle at traffic speeds, but are instead limited to static measurements. Another possibility is to take core samples of real road surfaces and then perform the topography measurements in a laboratory. This is, of course, a destructive method, which limits the number of possible applications.

In addition to the limitations in data acquisition, another constraint originates from the data analysis. Most studies where surface data is correlated to friction rely on simple surface metrics, such as the root-mean square roughness of the height profile, asperity sharpness, or relief angle. Surface profiles have also been analyzed qualitatively, but re-measuring the same exact line in a 2D-profile has proven to be difficult even in laboratory conditions, as mentioned for example in [Do, 2007]. Often some level of correlation between the simple surface metrics and friction is indeed found, but typically it applies only to a limited set of surfaces, as in [Yero, 2012], or to a specific aggregate type, as in [Do, 2009]. Simple surface metrics were also correlated against friction results in an aggregate gradation study presented in [Himeno, 2000], where modest levels of correlation were found. However, the correlation between the mean texture depth and friction showed decreasing friction values with increasing roughness, which did not match the expectations. The authors explained that this was due to the variations of the fine sand content used in the different mixes.

In the context of modern rubber friction theories the height-difference correlation function and the power spectral density, denoted here as $C(q)$, have been used as surface roughness metrics [Nayak, 1971] [Klüppel, 2000] [Persson, 2001]. The benefit of these methods is that they characterize the roughness of the surface on all measured length scales, none of which can be *a priori* excluded from contributing to friction [Persson, 2001]. The power spectral density of the surface roughness can be defined as [Nayak, 1971] [Persson, 2001]:

$$C(q) = \frac{1}{(2\pi)^2} \int d^2x \langle h(x) h(\mathbf{0}) \rangle e^{-iq \cdot x},$$

where x is a two-dimensional vector in the mean plane of the surface and q is a two-dimensional wave vector, or spatial frequency. The corresponding wavelength for each value of q can be calculated as $2\pi/q$. The $C(q)$ function is essentially the Fourier transform of the autocorrelation function of the surface height data.

This spatial frequency dependent description of the surface roughness is a central part of the calculation of kinetic friction by Persson, as can be seen in the following formula [Persson, 2001]. This version of the formula does not account for the flash temperature effect discussed in [Persson, 2006].

$$\mu = \frac{1}{2} \int_{q_L}^{q_1} dq q^3 C(q) P(q) \int_0^{2\pi} d\phi \cos\phi \, Im \frac{E(qv\cos\phi)}{(1-\nu^2)\sigma_0},$$

where q_L and q_1 are the limit spatial frequencies for the surface roughness, ϕ is the direction of the wave vector in relation to sliding, E is the complex viscoelastic Young's modulus of the rubber, v is the sliding velocity, ν ("nu") is the Poisson ratio of the rubber, and σ_0 is the mean perpendicular pressure in the contact. $P(q)$ is a magnification function, describing the relative contact area, and is in itself a function of all the above mentioned variables, including $C(q)$. Because of the central role in this very promising rubber friction theory the $C(q)$ function was used throughout this dissertation to characterize asphalt surface roughness.

An aggregate gradation study by Himeno et al. [Himeno, 2000] also included a power spectral density analysis of the studied asphalt surfaces. However, the results of the analysis were compared to the measured friction values qualitatively and no clear correlation was presented. Other signal processing methods have also been applied to surface data, such as the Hilbert–Huang transformation [Huang, 2006] by Rado and Kane [Rado, 2014]. Wavelet Analysis has also been employed to characterize surface roughness [Wei, 2004], albeit for longer wavelengths than the range covered here. The limitation of these two methods is that the surface roughness metrics they produce may not be physically meaningful, and that they are difficult to use in the context of modern rubber friction theories.

For the different studies presented in this dissertation, a portable static high-resolution 3D scanner was used to measure the surface roughness. The roughness was then characterized using $C(q)$ functions after specific post-processing steps. An example of surface height data after post-processing is shown in Figure 4. The bottom part of the height profile is cut out, as described in **Article II**. The height values are normalized using the average RMS roughness of all surfaces evaluated in **Article II**. During field measurements, a high number of surface scans were performed to account for the typical high local variations in road surface topography.

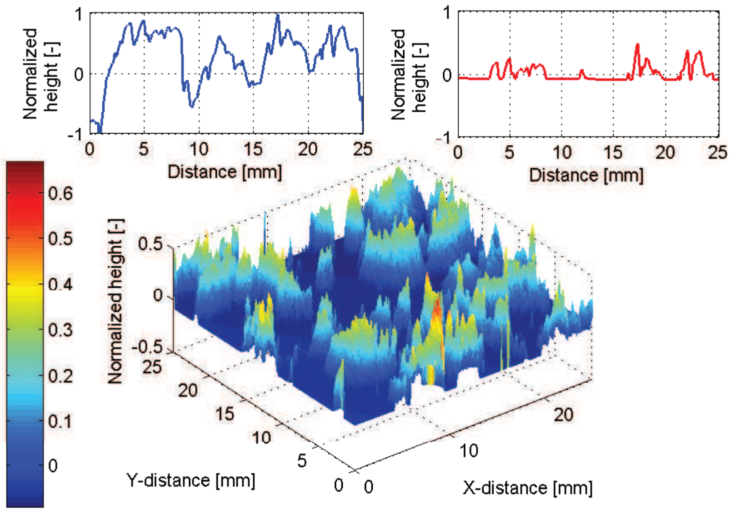

Figure 4. Asphalt surface data with an evaluation depth of 0.5*RMS roughness from spot C3 in Article II. An example of a profile line is shown above the 3D image. The curve on the left shows the original profile and the one on the right only the top layer. [Article II]

2.4 Surface topography evaluation depth

Roughness metrics from surface data are often calculated using the full range of the measurement. For a truly randomly rough surface this should be a good description of the surface in relation to rubber friction. However, asphalt road surfaces are typically quite skewed due to the compaction process during asphalt manufacturing and to the polishing effect of traffic. During manufacturing the asphalt surface is compacted to increase the strength of the pavement and to create a smooth surface layer. This is typically done by using a heavy roller with a dynamic load. This process reorients the aggregates so that the top faces of the aggregates at the top of the surface tend to align with the compaction plane. Due to this alignment, the peaks of the surface profile are truncated, while the valleys remain in a more randomly rough state, which leads to skewness in the surface profile, as illustrated in Figure 5.

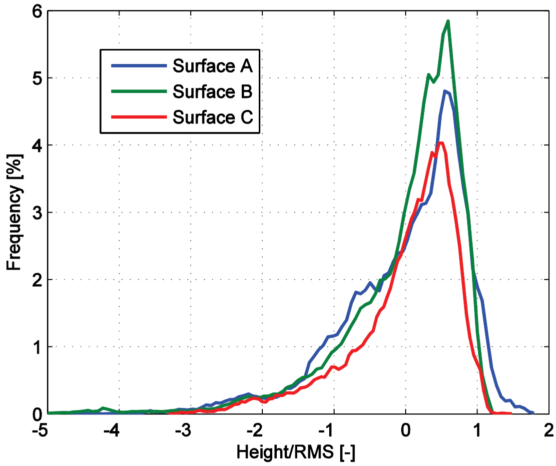

Figure 5. Full-profile height histograms from three surfaces from different locations evaluated in Article II showing skewed height distributions. [Article II]

The topmost layer of the asphalt, which is in direct contact with the tire, therefore consists of aligned stone faces covered with bitumen and smaller sand and filler particles, while the spaces between the larger aggregates are filled with a mixture of bitumen, sand, and filler particles. When shear stresses are applied to the newly created surface, bitumen and sand located on top of and in between the large aggregates gradually starts to be removed, exposing the aggregate surfaces, as shown in [Do, 2007]. The largest aggregates are typically made of crushed stone, which means that they have cracked surfaces with randomly rough characteristics. However, the polishing effect of tires only acts on the top layer of the surface, again leading to asymmetry in the height distribution. To account for these asymmetries, it has been suggested to cut the surface into two halves at the average plane followed by a division of the resulting $C(q)$ function by the portion of the data belonging to the top half [Persson, 2005]. As a part of this dissertation, a similar approach was applied, with the distinction that instead of cutting the surface at the mean plane, a much thinner slice of the surface top was used. The thickness of the layer was initially estimated based on the depth of binder removal observed in measured surface data. A thickness of approximately 0.5 times the average root mean square (RMS) roughness of all analyzed surfaces was found as an initial estimate and was used throughout the study presented in **Article II**. The analysis was then repeated at different evaluation depths and a summary of these results was presented.

Another way to estimate the cutting depth would be to use a theoretical approach by means of *interfacial separation* as described by Persson [Persson, 2007] or *penetration depth* as described by Klüppel and Heinrich [Klüppel, 2000]. However, a direct implementation of these methods for the asphalt surfaces included in **Article II** is difficult because the information on surface height skewness is not maintained in the surface descriptions used with these methods. For the former, the information is lost when calculating the autocorrelation of the height image. For the latter, it is lost similarly when calculating the height-difference correlation function. However, the studied asphalt surfaces were quite skewed due to the compaction process during asphalt manufacturing, as seen in Figure 5. Therefore, an extension of the above methods that takes into account the surface skewness would be highly desirable.

2.5 Aquaplaning

As mentioned earlier, all the significant forces and moments acting on a vehicle, except for aerodynamic forces and gravity, are generated by the tires. Aquaplaning of the tire interferes with the tire-road interaction by reducing the length of the direct tire-road contact patch, called the footprint. This may lead to a situation where the vehicle cannot be controlled by driver inputs. In addition, aquaplaning may also mislead vehicle controllers if not correctly recognized. Therefore, a direct measurement of the state of aquaplaning has two important applications. First, the knowledge of the real footprint length helps to set up the right conditions for wet rubber-road friction evaluations. Secondly, a real-time detection and quantification of aquaplaning would provide an important addition to friction-potential estimation carried out by vehicle control systems. Friction potential estimation is typically used as an input for systems such as ABS and ESC, as well as for ADAS applications, such as collision mitigation systems and Adaptive Cruise Control.

However, it is difficult to detect the early stages of aquaplaning with standard wheel speed sensors. Therefore, an optical sensor mounted inside the tire was used. The optical tire sensor was developed in the EC-funded APOLLO-project in 2002–2005 [APOLLO, 2005] and was further developed in the EC-funded FRICTI@N-project [FRICTI@N, 2009]. The operating principles of the measurement system and the sensor are explained in detail for example in [Tuononen, 2008] and [Tuononen, 2009, 2].

The measurement setup is illustrated in Figure 6. The system consists of a wide-angle Infrared Light Emitting Diode (IR-LED) mounted on the inside surface of the tire. The movements of the LED with reference to the wheel are measured using a Position Sensitive Device (PSD) mounted on the wheel. The signals are converted from analog to digital and preprocessed before sending them to the on-board receiver via a radio transmitter.

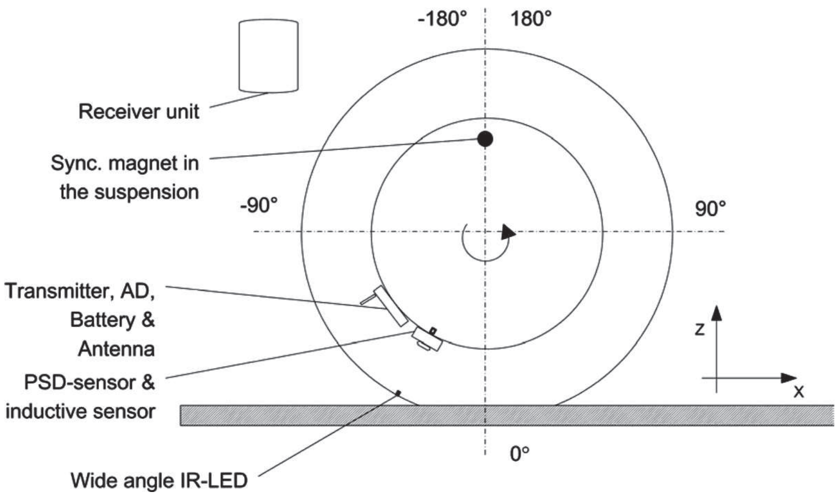

Figure 6. Optical tire sensor components consisting of an LED glued to the inner liner of the tire and a measurement and data transmission unit mounted on the rim. [Article IV]

The operating principle of the sensor is illustrated in Figure 7. The light from the LED passes through a lens that focuses the light on the PSD. The spatial distribution of light captured by the PSD measures the axial and tangential position of the LED, while the radial position is calculated from the total intensity of the light.

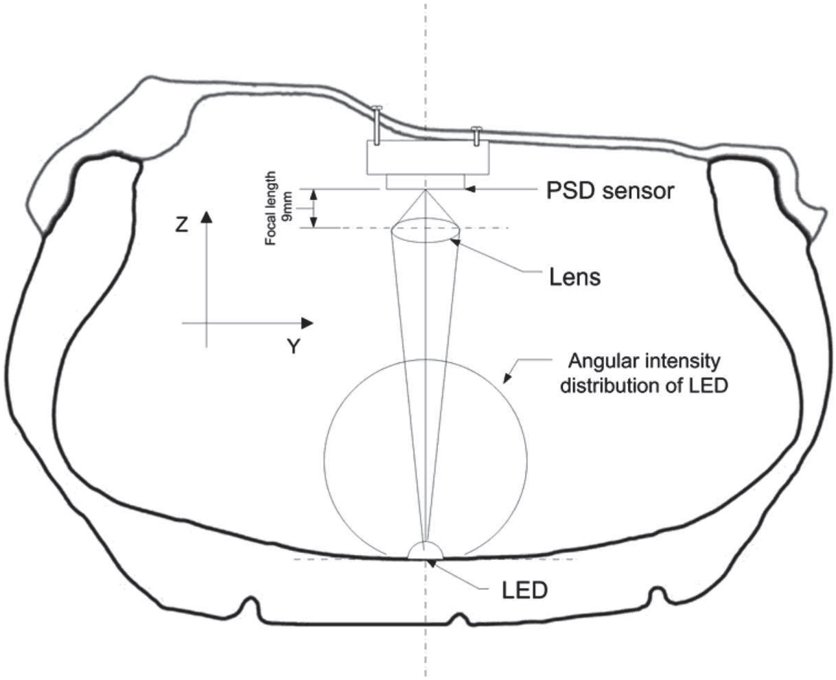

Figure 7. Measurement principle of the optical tire sensor. [Article IV]

The concept of aquaplaning has been assessed with simplified physical models like the so-called *Gleitfilmmodell* [Essers, 1987], as well as with more complex approaches that also model the tire geometry and the water flow around the tire. These studies use approaches like Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). Examples of such studies are shown for example in [Grogger, 1996], [Seta, 2000], [Cho, 2006], and [Cho, 2007].

The tire–road contact during aquaplaning has traditionally been divided into three zones [Browne, 1972]. The zones are shown in Figure 8. In zone A, the inertial effect of the water dominates and no contact between the tire and the road surface exists. In zone B, some rubber–road contact exists, but the viscous effect of the water squeezing out from the contact still has an effect on the true contact area. Zone C represents full wet road contact. However, even in this full contact region, the water still has an effect on the true contact area through sealing off local pools of water, where the rubber cannot penetrate [Persson, 2004].

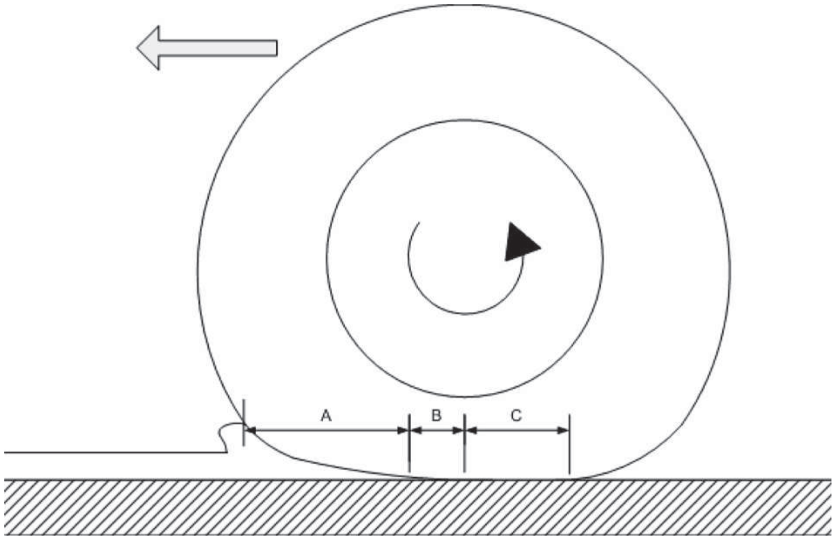

Figure 8. The three-zone aquaplaning concept. [Article IV]

The tire footprint length during aquaplaning has also been detected based on tread block deformations using the Darmstadt tire sensor [Stöcker, 1993]. The points where the instrumented tread block came into contact with the water surface, and then the road surface, were detected. A simple algorithm using the local maxima of these points was presented to detect the early stages of aquaplaning.

3 Results and discussion

Overall, the results showed that all the research questions listed in the Introduction of this dissertation could be addressed. The various advancements made in each associated sub-study can together provide the tools for characterizing the tire operating conditions during ABS braking at a high enough detail. An overview of the different advancements is shown in Figure 9. The top of the figure shows the results related to tire-vehicle interaction, and the illustrations shown at the bottom refer to the tire-road interaction. The tire-vehicle interaction is divided into quantification of the typical operating conditions of a tire during ABS-braking, and to the dynamics of the braking event. The tire-road interaction, on the other hand, is divided into asphalt surface roughness and aquaplaning. The results from each of these fields are discussed in detail in the following chapters.

Specifically, the importance of the footprint length on the tire-vehicle, as well as the tire-road interaction was highlighted in **Article I**. A method for measuring the footprint length on any road surface, and specifically during partial or full aquaplaning, was developed in **Article IV**. The measured footprint length, together with the relationships established in **Article I** can then be used for finding the exact operating conditions for rubber-road friction in the tire-road contact, with the help of the surface roughness analysis methods developed in **Article II** and **Article III**.

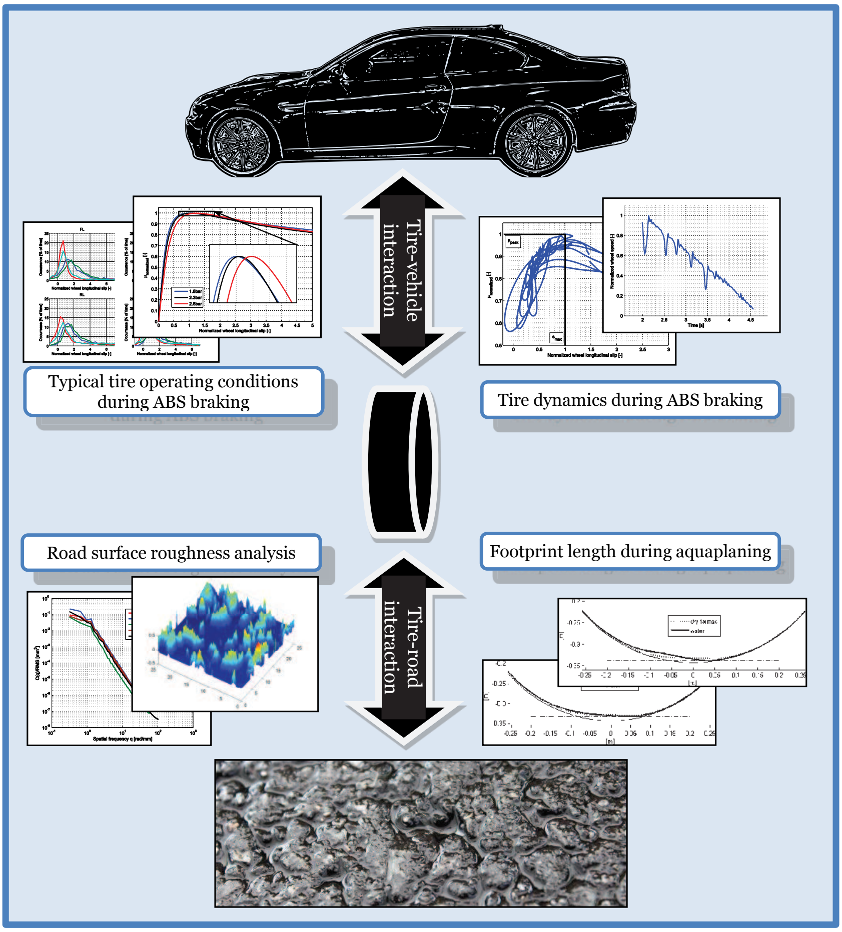

Figure 9. Overview of the advancements made as a result of this study.

3.1 Tire-vehicle interaction – Typical tire operating conditions during ABS-braking (Article I)

The study presented in **Article I** showed that the average, i.e. typical, slip conditions a tire experiences during ABS braking are affected by several factors that typically change during normal use and tire lifetime. A decrease in ambient temperature, and consequently the temperature of tire tread blocks, resulted in a decrease in the wheel slip (Figure 10). It was found that the best numerical metric to describe the most typical wheel slip values was the median value, due to the asymmetric distribution of the slip values, as shown in Figure 10.

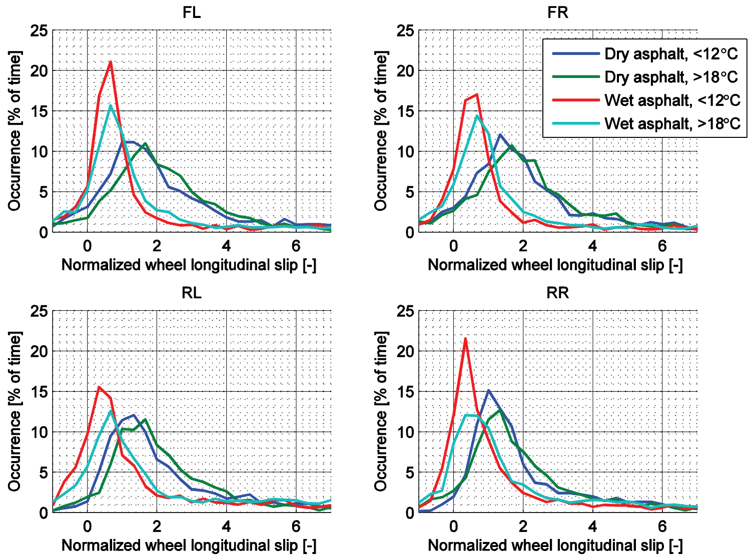

Figure 10. Changes in wheel slip histograms due to changes in ambient temperature. Lower temperatures resulted in lower slip values. FL denotes the front left wheel, FR the front right, RL the rear left, and RR the rear right wheel. [Article I]

A decrease in tire tread depth, as the tire wears down, also resulted in a decrease in wheel slip (Figure 11). A decrease in the tire inflation pressure, which can for example be a result of slow diffusion of air, or a decrease in the tire air cavity temperature, resulted in a decrease in the slip (Figure 12).

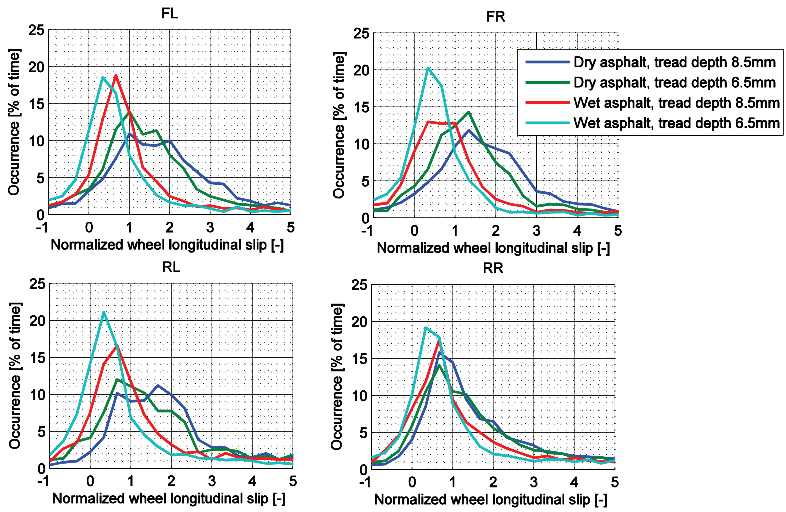

Figure 11. Changes in wheel slip histograms due to changes in tire tread depth. Lower tread depth resulted in lower slip values. [Article I]

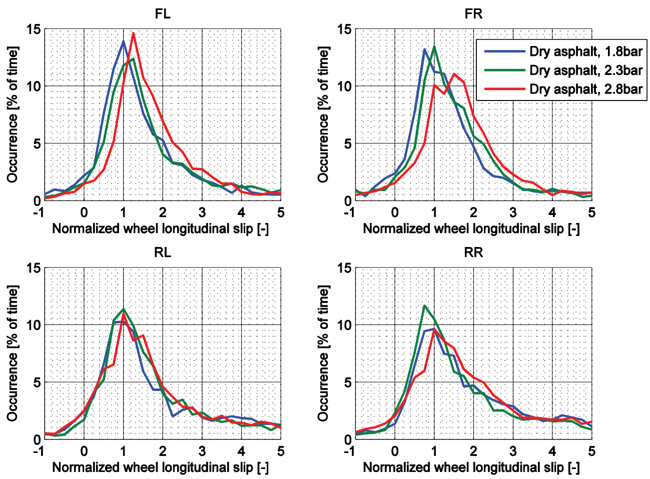

Figure 12. Changes in wheel slip histograms due to changes in tire inflation pressure. Lower inflation pressure resulted in lower slip values. [Article I]

The ambient temperature and tread depth effects can be explained through changes in the tire tread block stiffness. This effect is illustrated in Figure 13, which shows fitted μ-slip curves for two tires with different longitudinal stiffness levels. The curves are normalized by dividing each curve by its maximum value.

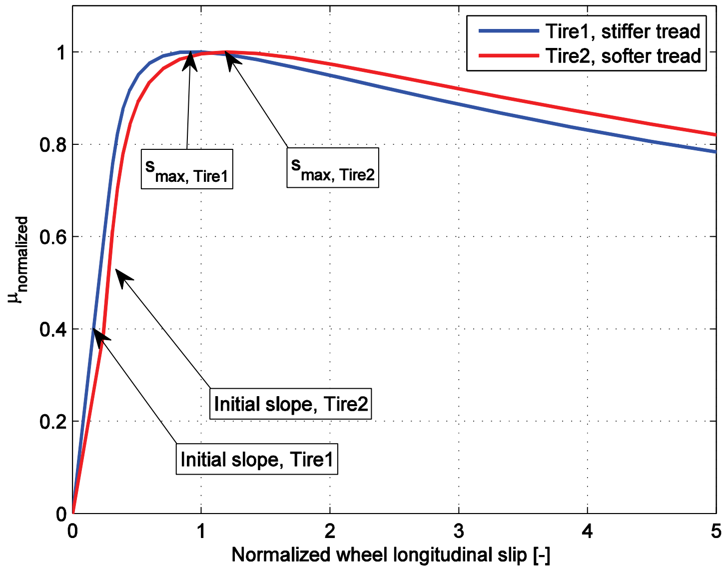

Figure 13. The effect of the tire tread longitudinal stiffness on the force-slip characteristics. Lower stiffness shifts the curve toward higher slip values. [Article I]

The effect of the inflation pressure, on the other hand, can be explained by a change in the tire footprint length, which also changes the force-slip characteristics of the tire. The change in the force-slip characteristics is illustrated in Figure 14, where increased inflation pressure shifts the μ-slip curves toward higher slip values. The curves are again normalized by dividing each curve by its maximum value.

An important consequence of the observed changes in the slip of the tire is a corresponding change in the deformation rate and especially the sliding speed of the rubber. In the light of the frequency- and temperature-dependent properties of rubber friction this is an important result and serves as a starting point for further research and development.

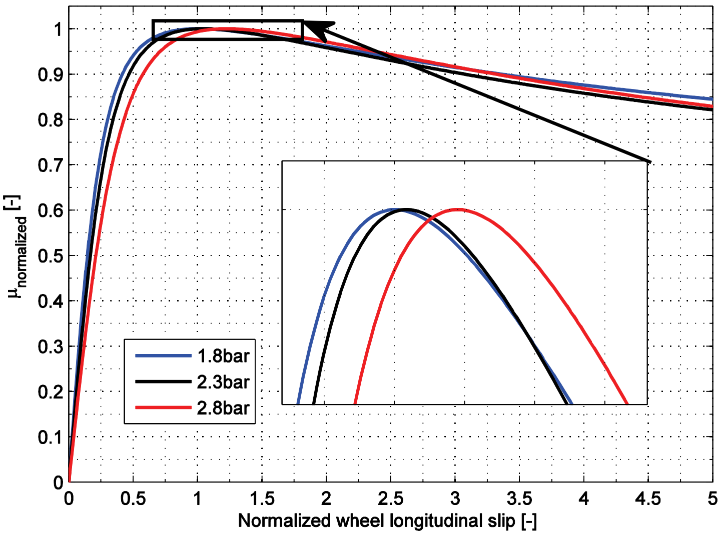

Figure 14. Change in tire force-slip characteristics due to changes in tire inflation pressure. Increase in inflation pressure shifts the curves toward higher slip values. [Article I]

3.2 Tire-road interaction – Road surface roughness and rubber friction (Articles II and III)

The study published in **Article II** showed for the first time wavelength-wise correlations between asphalt surface roughness and tire wet friction, as shown in Figure 15. The article also provided experimental evidence that only a thin layer of the asphalt surface topography should be analyzed in relation to rubber friction studies, instead of the full profile. The study included about 250 skid trailer tests, and 1250 surface scans measured at three locations around Europe.

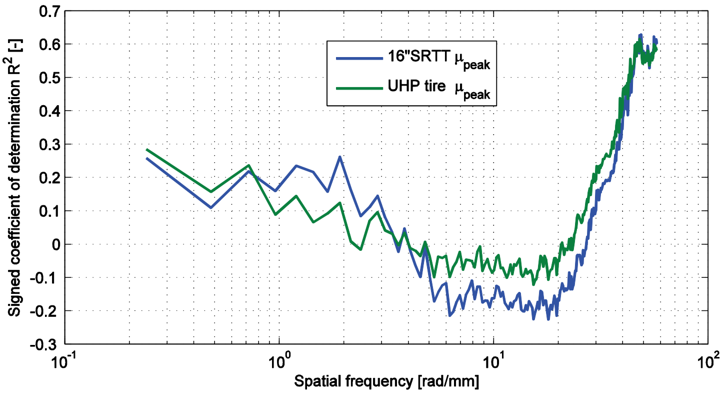

Figure 15. Signed R^2 between $C(q)$ and skid trailer μ_{peak} as a function of surface roughness spatial frequency after averaging R^2-values from three locations. The highest correlations are found at the highest measured spatial frequencies. [Article II]

The study also quantified the optimum surface cutting depth for the studied surfaces, which gives an indication for the analysis of other types of surfaces as well. The result is presented in Figure 16. The figure shows the highest frequency-wise correlations found using different evaluation depths. The experiment was repeated using three different analysis methods. In the first approach, the $C(q)$ function of the cut-out surface data was divided by the relative contact area covered by the points above the evaluation depth. In the second approach, this division was not done, and in the third approach, instead of fixing the cutting depth, the relative surface area was fixed and the evaluation depth was adjusted accordingly for each analyzed surface scan result. The figure shows that the highest correlations were found at an evaluation depth of about 0.5-0.6 times the average RMS of all the analyzed surfaces. The figure also shows that the method using a fixed evaluation depth results in stronger correlations that the one using a fixed surface area ratio.

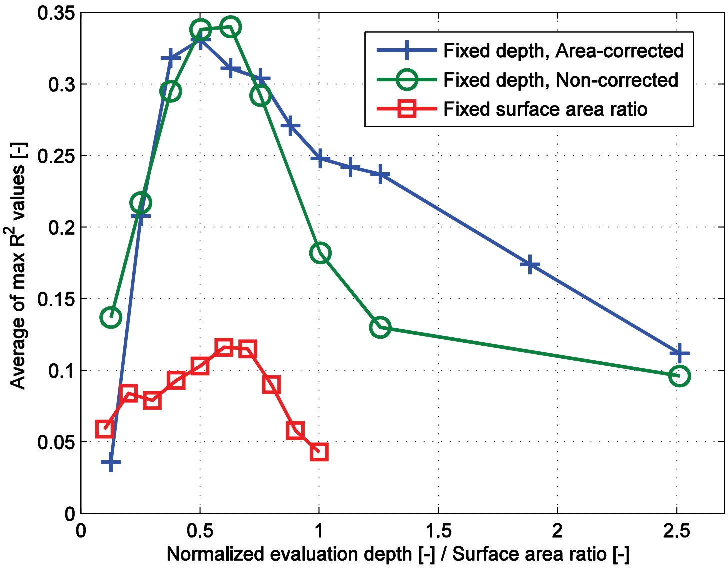

Figure 16. Effect of surface evaluation depth on maximum frequency-wise R^2 value between the surface roughness power spectrum and the tire μ_{peak}. The highest correlations are found at evaluation depths of 0.5-0.6 times the average RMS of all analyzed surfaces. [Article II]

To take temperature into account in the correlation analysis, the surface roughness data was condensed into a micro- and macro roughness metrics, and the road surface temperature was added as a third input variable. The results of the multiple linear regression using these variables showed a good correlation between the measured tire wet friction levels and the input variables, as shown in Figure 17. This result was achieved despite the fact that the range of analyzed road surfaces only included different states of the same asphalt specification. The results also gave experimental evidence for the fact that when studying rubber friction, temperature needs to be taken into account to be able to compare any test results. The results also strongly indicated that surface roughness power spectrums should be used for analyzing asphalt surface roughness in the context of rubber friction.

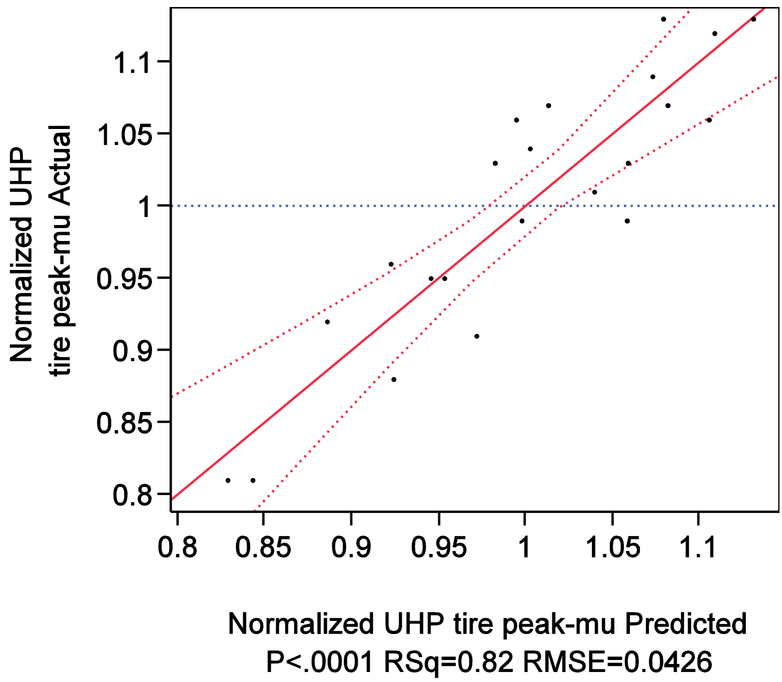

Figure 17. Linear least squares fit result of the UHP tire μ_{peak} using the macro and micro roughness and the surface temperature as model inputs. The horizontal axis shows the predicted friction values and the vertical axis the actual ones. P signifies the probability of attaining such a good fit if there was no actual correlation. R^2 is the coefficient of determination of the linear fit and RMSE is the Root-Mean-Squared Error of the fit. A good fit is attained despite a relatively large number of data points. [Article II]

The study presented in **Article III** provided a new type of asphalt sample for lab friction testing of rubber and the methodology for manufacturing such samples. The methods used for comparing the different surface candidates in terms of surface roughness were developed by the author earlier in the main research project. Specifically, the wavelength-wise correlations presented in **Article II** were applied for the data set of **Article III** to verify the accuracy of the surface and friction characterization methods applied in **Article III**. This provided further evidence that the surface roughness power spectrum is a good method for analyzing asphalt surface roughness with regard to rubber friction.

The importance of taking temperatures into account when interpreting rubber friction results was again highlighted in **Article III**.

A comparison of the surface roughness power spectrums of all the candidate surfaces is presented in Figure 18. The figure shows that all candidates, except for the concrete sample, replicated the roughness of the target asphalt quite well. The lower roughness of the concrete-bound sample was perhaps due to the high cement content needed for strengthening surface. The closest match was found using the epoxy sample, or the bitumen sample with polished stones.

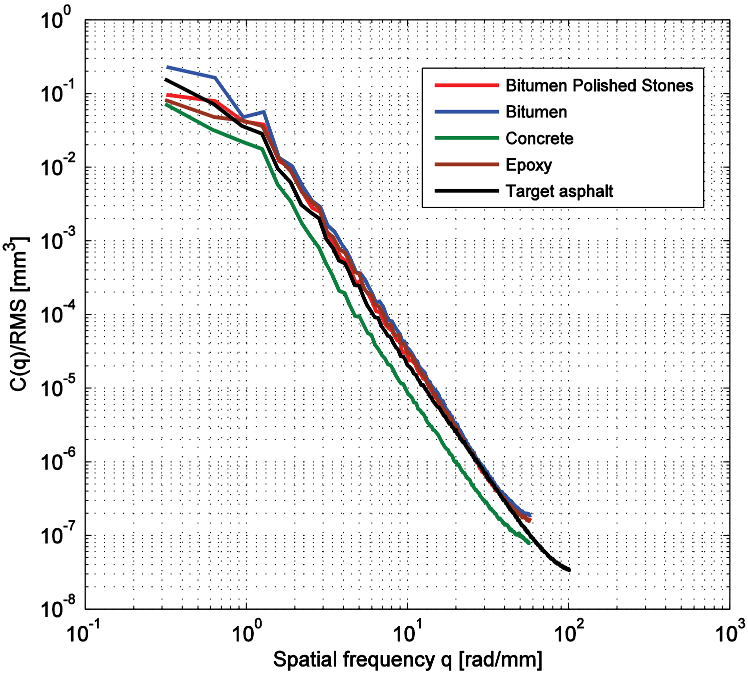

Figure 18. Normalized *C*(*q*) functions of the target road surface and the laboratory replicates. A good match was achieved with the epoxy and bitumen samples, while the concrete sample provided much lower roughness amplitudes. [Article III]

The *C*(*q*) functions were used for monitoring the changes in the asphalt sample surface roughness throughout the test program, consisting of repeated rubber sliding friction tests performed on the surface. The evolution of the epoxy sample roughness is presented in Figure 19. In addition to the average *C*(*q*)-

function, the graph also shows the 95% confidence intervals for both curves. The result shows that no significant change was found in the surface roughness of the epoxy surface even after 1000 test sweeps.

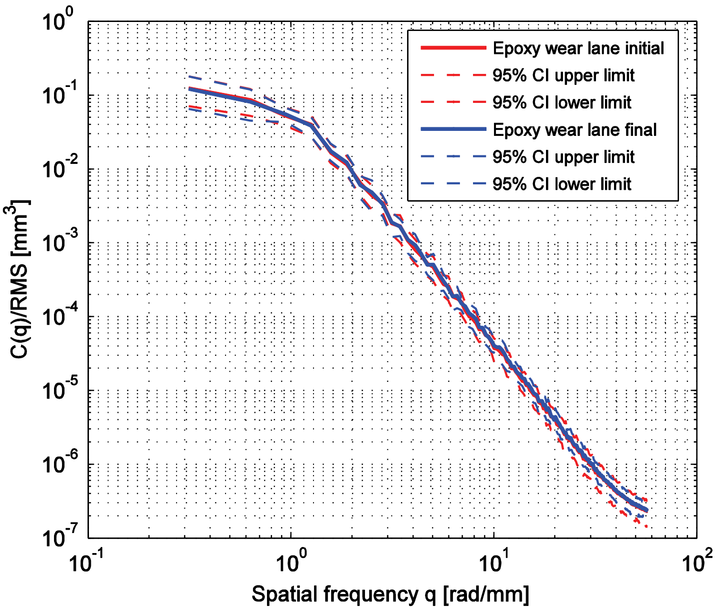

Figure 19. Normalized *C*(*q*) functions of the epoxy wear lane at the initial state and at the end of the study. No significant change in the roughness power spectrum can be observed. [Article III]

The evolution of the measured friction levels of the epoxy and concrete surfaces during the test program are shown in Figure 20. The values are derived by dividing the average friction coefficient measured during the test by the value measured on a reference lane next to the test lane. The results show that no clear trend can be found, indicating that the friction levels on the test lane did not deteriorate during the test program. This is in line with the surface roughness results shown in Figure 19.

The results achieved in the area of road surface analysis provide two important contributions to the overall understanding of ABS braking performance. First, the developed road surface samples provide a consistent countersurface for laboratory friction studies, fixing a major variable affecting the measurement result. Secondly, the developed surface roughness analysis method provides both a tool for analyzing asphalt surface roughness in the context of tire friction on dry and wet surfaces, but also provides important experimental evidence for theoretical considerations, regarding for example rubber penetration depth.

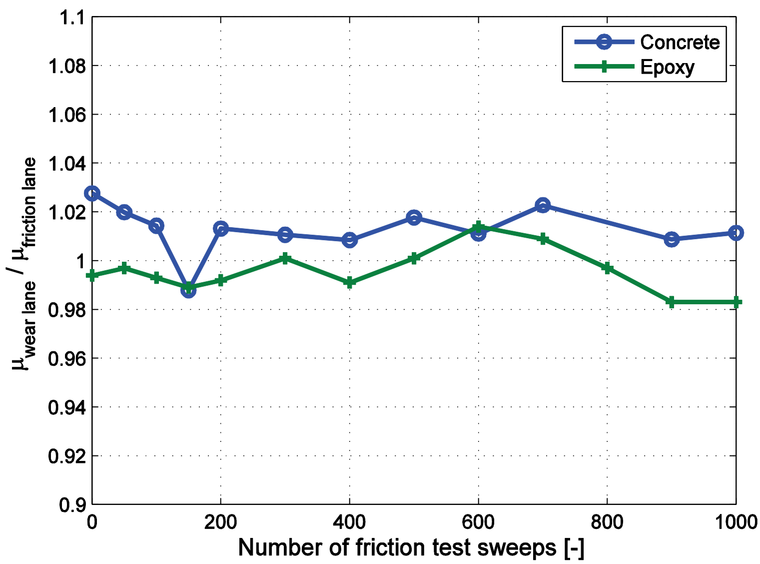

Figure 20. Average friction coefficient measured on the wear lane divided by the values measured on the reference lane. No clear trend can be established. [Article III]

3.3 Tire-road interaction - Aquaplaning (Article IV)

The study presented in **Article IV** showed that aquaplaning can be detected and quantified using an optical tire sensor. The sensor also provided a tool for detecting the tire footprint length on any road surface, and specifically during partial or full aquaplaning. The results from **Article IV** highlighted the use of the standard deviation of the radial displacement signal as an indicator for the existence of a water layer between the tire and the road. The benefit of a tire-based sensor, such as the one used in this study, is that measurements can be made on any arbitrary surface, including asphalt, which is not possible using road-based measurements, such as a glass-plate facility, or road-based contact pressure sensing. The knowledge generated in the analysis of the data is directly applicable to data from other tire-based point-type sensors, such as accelerometers or lasers.

The mean intensity, related to the radial movement of the sensor LED, and the corresponding standard deviation during an aquaplaning test are presented in Figure 21. The figure shows how the radial displacement starts earlier and has a larger amplitude when driving on an 8 mm thick water layer. The difference between driving in water and on dry asphalt is even clearer in the standard deviation curve.

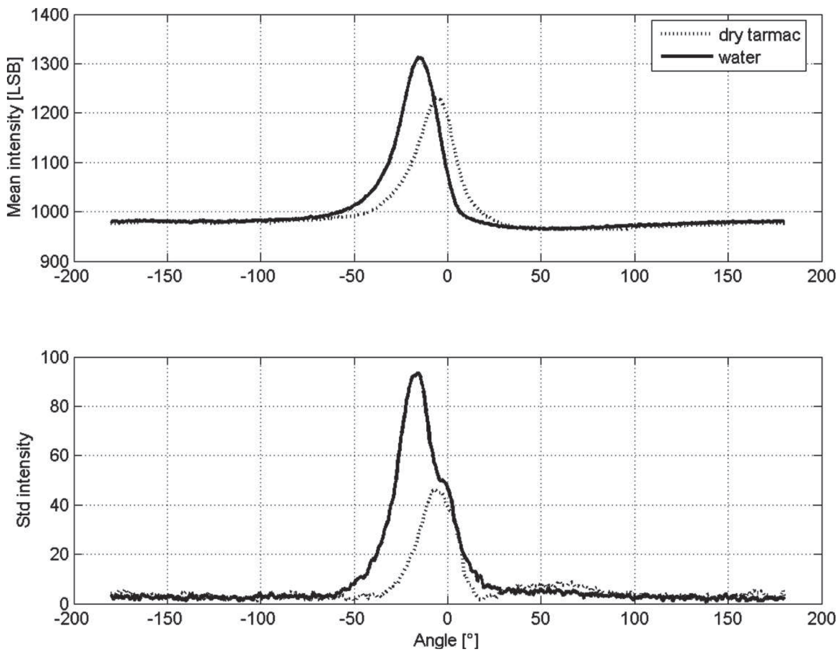

Figure 21. The mean intensity and standard deviation before and after driving onto an 8 mm thick water layer at 110 km/h. [Article IV]

To illustrate the radial displacement of the tire, the measured radial displacements are shown in Cartesian coordinates in Figure 22. The zero points of both axes are at the center of the wheel. The tire deformation on dry asphalt is shown with a dotted line and the tire deformation in the water with a thick solid line. For reference, the figure also has a perfect circle drawn with a thin solid line and a dash-dot line to represent the road surface for the data measured in the water. The curves show how the front part of the footprint is lifted off when entering the water, providing a way to evaluate the length of the remaining nominal contact area.

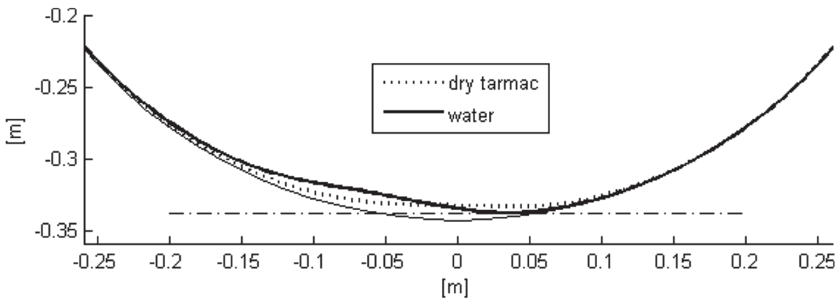

Figure 22. Tire inner ring deformation during full aquaplaning at 110 km/h. A clear lift-off can be seen in the data measured in the water. The dash-dot line represents the road surface for the data measured in the water. [Article IV]

The same phenomenon can be found also during partial aquaplaning, presented in Figure 23. The difference between the curve measured on dry asphalt and in the water is smaller, as expected. There is, however, a distinguishable difference between the curves, which facilitates the detection of partial aquaplaning, as well as the estimation of the remaining footprint length during partial aquaplaning.

The tool presented here provides a method for estimating changes in the tire footprint length, especially during aquaplaning. The footprint length is needed in the estimation of the tire contact mechanics, complementing the diagnostic tools presented in Chapter 3.1.

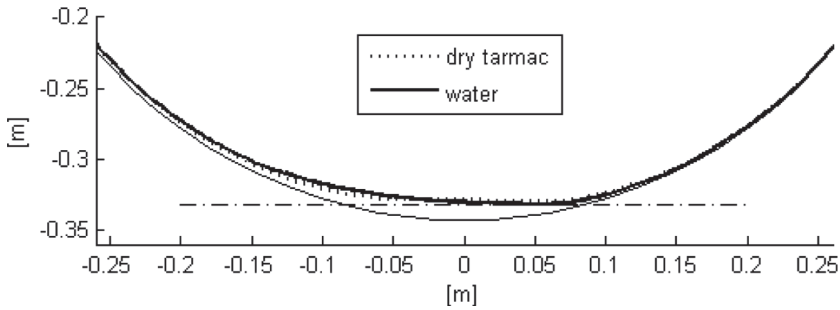

Figure 23. Tire inner ring deformation during partial aquaplaning at 80 km/h. A slight difference can be found between the data measured on dry asphalt and in the water. [Article IV]

4 Conclusions and outlook

The multi-disciplinary approach chosen for this research project resulted in a deeper understanding of the generation of longitudinal forces in tire-road contact during ABS braking on dry and wet asphalt surfaces. The results and the corresponding new methodologies will immediately be used in the development of new tires with even better braking performance. And because a tire typically wears out faster than an average vehicle or pavement section, new improvements in tire performance start impacting real-world road safety earlier than improvements in vehicle or road technology, for example. Referring to the original research questions presented in the chapter "Scientific contribution", the results can be summarized as follows:

1. In the area of tire-vehicle interaction, it was found that the most critical parameter in terms of tire operating conditions from the point-of-view of ABS braking performance is tire longitudinal slip. This was quantified using slip histograms and median values. It was found that increasing ambient temperature, increasing tread depth and increasing tire inflation pressure all increased the average wheel slip.
2. In the area of tire-road friction and asphalt surface topography, it was discovered that some surface roughness wavelengths correlate better with tire wet friction than others. In the studied data set, the best correlations were found for the shortest measured wavelengths. The roughness components were quantified using power spectral densities and by applying a top-cutting technique to the surface topography data.
3. In the area of aquaplaning, the study showed that the measurement results of a tire-based optical sensor provide a way to estimate the remaining footprint length during aquaplaning, and that both full and partial aquaplaning can be detected using the sensor.

The results also provide multiple opportunities for further research and in fact further advancements have already been reached during the preparation of this dissertation. The aquaplaning detection presented in **Article IV** has meanwhile been developed into a real-time application, as presented in [Tuononen, 2009, 1] and the work has continued using accelerometers instead of the optical sensor [Matilainen, 2012]. Further refinements in this area will provide even better possibilities for on-board contact length measurement.

The changes in wheel slip operating ranges found in **Article I** could be used in the development of better ABS, ESC, and ASR systems for example. All these systems would benefit from a prior knowledge of the force-slip characteristics of the tire and as shown in the article, these characteristics can change even during one driving cycle.

The effect of the surface roughness evaluation depth on the correlation between the surface roughness and tire wet friction established in **Article II** is a topic that should be explored further. The optimum depth could for example be compared to the theoretical rubber penetration depth. A current obstacle for such a study, however, is the handling of the skewness of asphalt surface roughness in the theoretical approaches.

In **Article III**, the duration of the study measuring the wear resistance of lab rubber friction test countersurfaces was set up-front and no significant changes were observed for two of the candidate samples at the end of the defined test period. It would, of course, be interesting to study how the surface roughness characteristics would evolve if more wear cycles would be applied.

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Aalto-DD 210/2014

Wet grip of vehicles has a crucial effect on traffic safety. One of the main components affecting the wet grip of a vehicle is the tire. To bring advancements to this important performance area, some of the underlying physics need to be understood better. During this project, the interaction of the tire with the brake control system of the vehicle, as well as the interaction between the tire and the road were studied. The study included instrumented vehicle and skid trailer braking tests, laboratory friction tests, as well as road surface topography scans. The results showed that with the road surface analysis methods developed in the project, a good correlation between road surface roughness and tire wet friction can be established. In addition, diagnostic tools were developed for quantifying the tire force generation characteristics and their dependency on ambient temperature, tread depth, road surface type, and tire inflation pressure. The increased understanding of these key areas is already being used in the development of new tires and is expected to contribute to improvements in road safety.

9 789526 060231

ISBN 978-952-60-6023-1 (printed)
ISBN 978-952-60-6024-8 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

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