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SOLID AND STRUCTURAL MECHANICS

Railway tread braking temperatures

Numerical simulation and experimental studies

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Cover:

Shanghai metro train employed in the field test campaign in May 2010.

Photographed by Markus Meinel of Faiveley Transport Nordic

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ABSTRACT

Tread (block) braking is still one of the most common braking systems on railway vehicles. The action is carried out by pressing brake blocks against the tread of a wheel, which is also in rolling contact with the rail. The extensive use of tread brakes in metro and suburban applications has created a need for design guidelines or standards for wheels exposed to repeated stop braking. The thermal capacity of the wheels puts a limit to railway tread braking systems. With the exception of the drag braking cases described in the European standard EN 13979-1, there are no known standards or guidelines regarding the thermal capacity limits for wheels.

In the present work, an extensive literature survey has been made with special focus on the braking capacity of wheels. Several aspects of the tread braking system, important for the dimensioning of railway wheels, have been assessed, such as brake block materials and residual stresses and temperature gradients through wheel rim and wheel disc. Additionally, two different railway wheel designs, with typical characteristics of freight and metro wheels, have been numerically studied with respect to design criteria for load cases of drag braking and stop braking.

Brake rig experiments and a field test campaign were performed and aimed at measuring wheel and brake block temperatures during different service conditions for a metro line. It was concluded that even though the same nominal routes were simulated in the brake rig tests as those the field tests, the braking efforts are different. Therefore, simulation and calibration tools were employed in order to facilitate a comparison between measured temperatures. The results showed the importance of knowing the convection cooling parameters for different wagons if prolonged braking action is to be considered.

Heat partitioning between wheel, block and rail has been numerically studied in a broad parametric study to investigate the influence of brake block materials, thermal parameters and brake pressure distribution. By use of a plane model, the implication of temperature variations around the wheel circumference (hot spots) is studied in detail. Even though the hot spots have a major impact on local temperatures, they were found to have only a minor influence on the global heat partitioning in the wheel-block-rail system. By use of an axisymmetric model, it was found that a presumed constant axial position of the wheel-rail contact towards the flange side of the tread leads to substantially higher maximum tread temperatures than a wheel-rail contact centred at the brake block position.

KEYWORDS: field experiment, finite element analysis, frictional heating, heat partitioning, hot spots, metro, rail chill, railway tread braking, railway wheels, rig experiment

PREFACE

This work has been performed in the Department of Applied Mechanics at Chalmers University of Technology during 2008-2011. It is part of the project SD7 "Thermal capacity of tread braked railway wheels" within the Swedish National Centre of Excellence in Railway Mechanics CHARMEC (CHAlmers Railway MEChanics). The support from the project reference group with members from Bombardier Transportation, Faiveley Transport, Interfleet Technology and SL Technology is gratefully acknowledged.

I would like to express my deepest gratitude to Professor Roger Lundén and Dr Tore Vernersson who undertook to act as my supervisors. Thank you for waiting patiently as I progressed on my own and for helping me to overcome many difficult problems.

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Gothenburg, February 2012

Shahab Teimourimanesh

THESIS

This thesis consists of an extended summary and the following appended papers:

Paper A Shahab Teimourimanesh, Roger Lundén and Tore Vernersson, Braking capacity of railway wheels—state-of-the-art survey. *Proceedings 16th International Wheelset Congress (available on USB flash drive)*, Cape Town (RSA), 2010, 18 pp.

Paper B Shahab Teimourimanesh, Tore Vernersson, Roger Lundén, Fredrik Blennow and Markus Meinel, Tread braking of railway wheels – temperatures for a metro application. To be submitted for international publication

Paper C Shahab Teimourimanesh, Tore Vernersson and Roger Lundén, Modelling of railway tread braking temperatures – influence of contact conditions and rail chill. To be submitted for international publication

Appended papers were prepared in collaboration with the co-authors.

Paper A is an extensive literature survey of sixty references presented at the International Wheelset Congress in the Republic of South Africa in 2010. The author of the thesis is responsible for planning the paper, doing the numerical simulations and writing of the report.

In Paper B, the author of the thesis was present during the rig experiments and actively contributed to the planning and performing of the field experiments together with the co-authors. In addition, he carried out part of writing of the paper.

In Paper C, the author of the thesis was responsible for the major progress of the work including the planning and implementation of the circumferential model, carrying out the numerical simulations and writing the manuscript in cooperation with the co-authors.

CONTENTS

REVIEW AND SUMMARY

An introduction to the subject is given and references are given to **Papers A, B** and **C**. The present summary and reference list are intentionally made fairly short. Further background information can be found in the state-of-the-art survey which has been compiled within **Paper A.**

1 INTRODUCTION

1.1 Motivation of study

The work performed in the present report covers tread braking of railway wheels. The thermal capacity of the wheels puts a limit to railway tread braking systems. In Reference [1], the heat partitioning between brake block, wheel rim and rail was investigated focussing on drag braking. The extensive use of tread brakes in metro and suburban applications has created a special need for studying the thermal capacities of railway wheels for these applications. In the present work, the range of tread braking applications to be studied will vary from light, medium and heavy metro to mainline coach and freight locomotive applications with the focus being on wheels for metros where frequent stop braking occurs. In **Paper A** of this work, several aspects of the tread braking system, important for the dimensioning of railway wheels, are surveyed to provide an overview of documented research on braking capacity of railway wheels and to investigate the thermomechanical behaviour of tread braking systems in different applications. In **Paper B**, results from brake rig tests and in-field testing of a metro train are presented and used for calibrating a numerical simulation model. **Paper C** focusses on developing thermal models for studying temperatures and heat partitioning between block, wheel and rail for stop braking cycles.

1.2 Tread braking overview

Tread (block) braking is still one of the most common braking systems on railway vehicles. Block braking is the ordinarily used system on freight wagons and is also commonly used on passenger trains, often in combination with disc brakes and electrodynamic brakes. The tread braking (or block braking) action is carried out by pressing the brake block(s) against the tread of a wheel. The vehicle can be equipped with four different standard block configurations. Furthermore, a brake block is generally manufactured of cast iron, organic composite or sinter materials.

The total heat generated during braking is partitioned between the wheel and the block at their contact interface. The elevated temperatures of wheel and block will be accompanied by heat transfer through convection and radiation to the surrounding. In addition, heat will be conducted from wheel to rail.

Tread braking systems have both advantages and disadvantages. They are simpler and cheaper than systems with axle- or wheel-mounted disc brakes. Since block braking roughens the wheel tread, it improves the wheel-rail interface conditions at traction and braking. Unfortunately, the roughness may also cause an increased level of rolling noise which is typical for trains with cast iron brake blocks [2].

Previously, different projects have been carried out at Chalmers/CHARMEC to investigate the thermomechanical interaction between brake blocks and wheel tread for studying the generation of “noise-related tread roughness” and for determining “dimensioning wheel temperatures” and braking heat partitioning [1]. These studies and experiments were focussed on drag braking in freight applications while the present work brings stop braking and metro application into focus. Moreover, within the public domain there are only standards or guidelines regarding the determination of thermal capacity limits of wheels for drag braking load cases as, for example, in the European norm EN13979-1 [3]. The standards / codes [4, 5] for technical approval of solid wheels define power levels and duration for drag braking cycles to be applied in brake rig tests. The leaflet UIC510-5 also defines, in general terms, a method to consider consecutive stop brakings. However, different metro routes with various distances and numbers of stations can to a high degree affect the thermomechanical behaviour of railway wheels. Therefore, there is a need for development of a verifiable set of guidelines and assessment criteria. An important fact is that the consecutive stop braking cycles can influence the temperature field and the residual stress levels in the wheels.

The work presented in this thesis is part of the project SD7 “Thermal capacity of tread braked railway wheels” performed within the Swedish National Centre of Excellence in Railway Mechanics (CHARMEC), and it is an extension of the work performed by Tore Vernersson within the previous project SD4 “Control of block braking”. The aim of the project is to develop methods and provide data that can form a basis for future design guidelines for determining the thermal capacity of tread braked wheels. The project tries to identify those phenomena which put limits on the capacity of the tread braking system and to outline methods for setting such limits and, finally, to quantify the limits.

1.3 Method of research

In the present work, various methods of investigation have been used: literature studies, brake rig experiments and field tests, in addition to numerical modelling and simulations.

The state-of-the-art survey combined with the numerical examples, see **Paper A**, demonstrates principal dimensioning parameters in frictional braking regarding thermomechanical aspects and temperatures. Moreover, the numerical examples illustrate the influence of wheel geometry together with temperatures and residual stresses in the wheel rim for different braking modes.

The brake rig experiments and field tests, see **Paper B**, were performed to simulate the tread braking application for a certain metro line and to observe the temperature fields during real service for a comparison to the results of rig tests. In the brake dynamometer, components having the same design as that on the metro were mounted, such as wheel, brake blocks and brake block unit. The field test was carried out with the train travelling on the actual route for different scenarios, ranging from normal operation with electrodynamic brakes to braking by friction only. The main instruments for data acquisition used at the rig and field tests were thermocouples with different arrangements for measuring the surface and under surface temperatures.

Results from experimental measurements on wheels have been compared with the numerical results to calibrate the influential parameters of the thermal model, which has been introduced and described in [6].

The numerical modelling in **Paper C** consists of two types; plane and axisymmetric. In particular, heat partitioning between block, wheel and rail and the maximum temperatures over the wheel tread for stop braking cycles are of interest. The work aims at studying phenomena such as hot spotting and lateral movement of the wheel-rail contact which occurs at curve negotiation and hunting of the railway vehicle.

2 LITERATURE

The braking action generates heat by transformation of frictional energy. The high interface temperature and a severe thermal environment can affect the tribological characteristics of the contacting surfaces such as friction and wear. Moreover, contact pressure and interface temperature are mutually dependent, a fact which plays an important role in the process of thermoelastic deformations through localized surface effects. Therefore, the contact, the heat conduction and the thermal stress problems show a complex interconnection. In fact, for the heat conduction problem one needs the contact area and contact pressure distribution from the mechanical contact problem solution. For the thermal stress problem, one then uses the temperature distribution from the heat transfer solution and, again, the thermal stress results should be used for solving the contact problem [7, 8].

There are several factors which influence frictional energy transformation at the friction interface of a brake such as the amount of energy generated and partitioned between the mating surfaces and also transferred to the surrounding, the thermophysical properties of the materials, the distribution of frictional heat generation over the interface, and macroscopic surface effects. Several aspects of the friction braking systems, from both theoretical and experimental viewpoints, have been classically studied by Blok and Jaeger early in the 1940´s [9, 10] and then extensively in the late 1950´s by Newcomb [11-13]. The reader is referred to **Paper A** and the recent survey by Day [14] for a detailed background of friction brakes.

Railway tread braking is one of the forms of friction brakes. Block braking is the ordinarily used system on freight wagons and is also used on passenger trains often in combination with disc brakes and electrodynamic brakes. Tread brakes are simpler and cheaper than axle- or wheel-mounted disc brakes. Since block braking roughens the wheel tread, it improves the wheel-rail interface conditions at traction and braking. However, the capacity of tread brakes is limited by the excessive frictional heat conducted to the wheels. The research so far on tread braking systems focusses on several important aspects like temperature field, thermomechanical aspects, wheel damage, wheel design and brake blocks [15].

The thermal loading and prediction of frictionally induced surface temperatures are of main importance when it comes to determine the braking capacity of wheels. One of the classical assumptions when calculating the transient surface temperatures at braking is that the average friction surface temperatures of the two contacting bodies can be used and that steady conditions have been attained if the motion concerns infinitely long bodies [10, 11]. In this case a one-dimensional analytical analysis of the heat flow can be applied. In addition, this model considers the heat partitioning between the two sliding bodies to be constant. However, experiments show that the interaction between two bodies in sliding frictional contact is not at all straightforward. A more advanced assumption is that the two contacting bodies have different surface temperatures which in modelling can be introduced by use of thermal contact resistances. The phenomenon is principally due to surface tribological properties. In **Paper A**, different heat partitioning models are discussed.

The mechanical loads in the wheel-rail contact, the thermal loads from tread braking and the centrifugal loads from rotation, together with residual stresses from the heat treatment, are the main stress sources in a railway wheel. An extensive literature review on thermoelastic instabilities (TEI) with focus on tread braking is given in [15]. In friction brakes, the heat generated at the sliding interface causes thermal distortion leading to frictionally excited thermoelastic instability followed by the evolution of hot spots at the interface. The occurrence and pattern of hot spots in braking applications have been investigated in several experimental studies [16, 17]. In addition, the thermal and mechanical properties of friction materials influencing hot spots have been studied.

Dimensioning of tread braked wheels is performed with respect to thermal loading from the brake application. According to European network standards, the design is assessed using extreme thermal brake load cases consisting of drag braking rig tests at prolonged periods of time, see CEN [18] and UIC [5]. A limited change of wheelset gauge during and after braking along with the allowed level of residual tensile stresses in the wheel rim after cooling down determine the required braking performance.

The brake blocks used at tread braking are normally made from cast iron, sinter materials or organic composite materials. The material influences the wheel temperatures on both a global and a local level, by controlling the heat partitioning between brake blocks and wheel and by controlling the thermoelastic interaction between block and wheel in the contact, respectively. Nowadays, cast iron brake blocks are being replaced by mainly composite blocks in order to reduce the levels of rolling noise. In Europe, the brake blocks should be approved according to the standard UIC541-4 [3] in which friction characteristics and wheel temperatures are specified.

Another important aspect of tread braking is the wheel tread damage which influences both the life cycle cost and the safety of the wheels. This issue is important for wheel manufacturers and railway operators. Wheel tread damage can be classified in different categories and the most common ones are flats, shelling and thermal cracks [19, 20]. Empirical studies show that tread braking in combination with mechanical loads have a crucial influence on tread damage [21]. Moreover, the influence of brake block material on wheel tread damage has been demonstrated [22].

All the mentioned issues and the increasing demand of metros and suburban trains with higher comfort and safety, raise the importance of understanding the limiting parameters in friction brake technology.

3 SUMMARY OF APPENDED PAPERS

3.1 Paper A

Braking capacity of railway wheels – state-of-the-art survey: Several important aspects of the tread braking system for the dimensioning of railway wheels are studied in this general survey. An overview of design methods and their background for tread braking systems is provided with special focus on thermal capacity of the wheels. Advantages and drawbacks of the braking system are presented and recent research on the braking capacity of railway wheels is summarized. For example, a discussion is given on the three different commonly used materials for brake blocks: cast iron, sinter and organic composite. Here brake performance, noise emissions and environmental concerns are changing the standards and regulations.

The preliminary studies for modelling the temperature increase at friction heating are discussed to understand the evolution of heat partitioning between the two bodies in sliding contact. The recent experimental results from dynamometer experiments and in-field tests are given along with the computational methods for calculating the temperature fields and thermal characteristics during drag and stop braking. The backgrounds of other important aspects such as thermomechanical properties, wheel design and brake block and wheel tread damage are given.

Two different railway wheel designs, with typical characteristics of freight and metro wheels, are studied with respect to design criteria for load cases of drag braking and stop braking. The behaviour of the two wheel designs is studied for a typical metro loading, with consecutive stop braking cycles. Also design load cases for freight wheels are considered.

The previously developed thermal model in Reference [6] is used with an axisymmetric finite element model of wheel and brake blocks. The thermal and stress analyses are done in a sequentially coupled method, *i e*, they are performed by first calculating the temperature field without consideration of the stress/deformation and then the stress/deformation response depending on the temperatures is calculated. The drag braking application is composed of a heating phase (when the block is applied) and a cooling phase (train running with constant speed). The stop braking load case consists of stopping at consecutive stations. Moreover, the influence of rail cooling on the maximum temperature of railway wheel tread and on axial flange deflection (change of gauge) and residual stresses in wheel rim is investigated for different wheels and braking modes.

It is concluded that rail chill can substantially decrease the calculated maximum temperatures, axial flange deflections and residual stresses in different cases. It is also important to consider the different wheel designs and the metro routes. Additionally, comparative studies can be useful to investigate the behaviour of an existing wheel design when it is to be considered for a new route.

3.2 Paper B

Tread braking of railway wheels – temperatures for a metro application: The temperatures in wheel and blocks are studied in brake rig tests and at in-field testing of a metro train, and they are used for calibrating a numerical simulation model. The temperature is a main factor for finding the thermal capacity of tread braking systems and in particular of the railway wheels.

Brake rig experiments and a field test campaign were performed during the spring 2009 and in May 2010, respectively, in cooperation with Faiveley Transport. The aim was to measure wheel and brake block temperatures during different service conditions for the metro line 8 in Shanghai, China. The brake rig testing was performed in a dynamometer at Federal Mogul in Chapel-en-le-Frith, England, UK. The controlled experimental conditions in the dynamometer were simulated with the same nominal routes as in the field test. Simulation tools are used to simplify the comparison with the measured temperatures.

Both of the tests concerned the train travelling on the actual route for different scenarios, ranging from normal operation with electrodynamic brakes to braking by friction only (degraded mode). The main instruments for measuring the temperature in these tests are thermocouples. They are used in different forms and configurations, for example rubbing thermocouples used for measuring tread surface temperatures and embedded thermocouples for measuring temperatures below the surfaces of wheel web and brake block. Figure 1 shows some examples of the thermocouple arrangements in the rig and field tests.

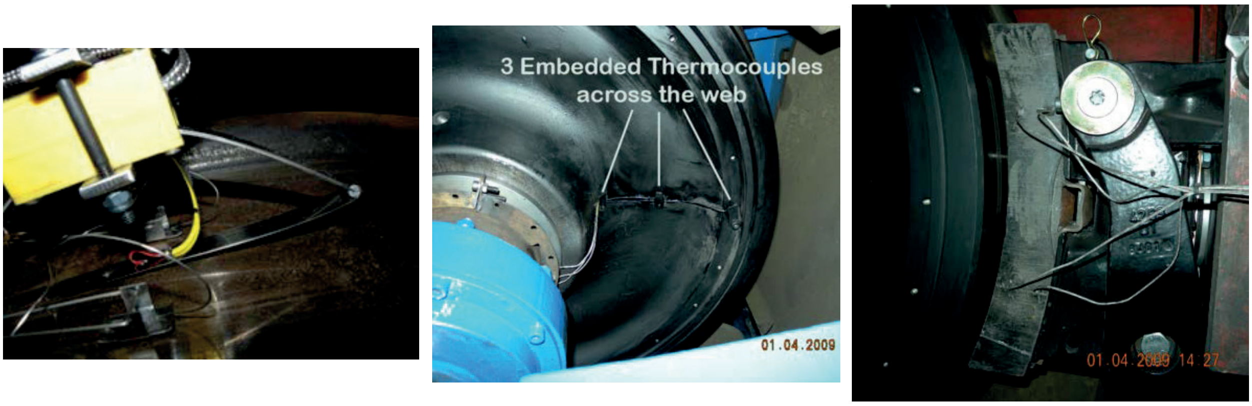

Figure 1: Different arrangements of thermocouples. Rubbing thermocouples for measuring wheel tread temperatures (left), embedded thermocouples for measuring wheel web temperatures (middle), and embedded thermocouples for measuring brake block temperatures (right)

A model which has been developed by CHARMEC [6, 23, 24] is used for the simulation and calibration process and it includes the cooling influence from the rail. However, this model was calibrated by using data from freight application experiments. Here, it is employed in a metro application and the history of train speed and frictional brake power (per wheel) is calculated using real route information as input for calculating the wheel and block temperatures. Cooling by convection and by radiation is considered for the wheel surfaces.

An extensive study and discussion of the rig test and field test results show the differences between measured temperatures. It is clear that the cooling conditions are not the same for these tests and therefore different sets of cooling parameters are introduced during calibration. The calibration process is based on minimizing the sum of squared differences between measured temperatures and simulated results. The calibration model is based on a common statistical technique called Response Surface Methodology (RSM) and the optimization analysis uses the Matlab code.

It was possible to equip three different axles of the train (trailer and motor cars) for measuring the temperatures. This gives the option for comparative studies of the conditions valid for different wheelsets. The measurements on the metro train also show that the temperatures of the first axle in the train are lower than those of the other sampled axles. In other words, cooling is poorer for the non-guiding axles than for the guiding axle (first axle according to train movement direction). Therefore two corresponding sets of convection cooling parameters have been established at the calibration of the simulation model.

3.3 Paper C

Modelling of temperatures at railway tread braking – influence of contact conditions and rail chill: The temperature rise of wheels and blocks due to frictional heating during railway tread braking along with the transfer of heat through the wheel-rail contact is studied. Heat partitioning between wheel, block and rail for stop braking cycles is the main focus in this work. The contact conditions and the rail chill are investigated by numerical analysis to find the circumferential and axial temperature variations of the wheel tread for non-uniform pressure distributions between wheel and brake block. Two different thermal models, circumferential (plane) and axisymmetric, are used to simulate the hot spotting phenomenon and the lateral movement of wheel-rail contact, respectively. The finite element method (FEM) is used for these two-dimensional models.

For the circumferential problem, the streamline upwind/Petrov-Galerkin formulation for the time-dependent convection-diffusion equation, as implemented in the commercial software Abaqus/Standard [25], is used to determine the temperature fields in the wheels and in the brake blocks at hot spotting. This method gives the opportunity to calculate the temperature fields with high accuracy. However, the analysis is computationally time consuming because the characteristic element length and time steps are constrained with the local Péclet number and the local Courant number, respectively. Wheel, brake block and rail bodies are modelled as thin plane structures to reduce the time of the analysis. The hot spots are modelled as repetitive hot zones which are spatially fixed to the wheel. Different pressure distributions between wheel and block are used to study the influence of hot spot patterns. A suitable mesh density is found by comparing the results for different mesh densities with an analytical solution for a semi-infinite solid subjected to a prescribed heat flux at the surface of the tread according to References [6, 26]. Heat partitioning between wheel and block is modelled using a “third-body approach”. The heat transfer from wheel to rail is modelled using thermal contact resistance between the wheel and rail bodies.

The parametric studies are done using typical stop braking conditions for a metro wheel during a short period of time. Different brake block materials and configurations are used to investigate maximum tread and brake block temperatures along with the heat entering wheel, block and rail bodies. Additionally, different thermal resistances are assumed between wheel and brake block to investigate their influences on heat partitioning for various brake block materials and different prescribed wheel-block pressure distributions. Firstly, the hot spots (temperature oscillations in circumferential direction) are found to have a negligible influence on the heat partitioning in the wheel-block-rail system. Secondly, the wheel to rail contact (rail chill) is found to reduce the maximum tread temperatures at the end of the braking cycles for the parts of the tread passing the contact. The rail is then found to take about 22 % of the braking heat. However, only a small part of the tread passes through this contact and as a whole the rail chill power is small as compared to the brake power. Moreover, the choice of materials in the brake blocks influences the heat partitioning. The composite blocks make the largest part go to the wheel (about 83 %), sinter is intermediate (about 72 %) and cast iron makes the smallest part go to the wheel (about 50 %).

The axisymmetric model is similar to the one used in **Paper A** and **Paper B**, and it accounts for wheel-block and wheel-rail heat partitioning, but also convection and radiation cooling of exterior surfaces. The influence of rail chill on the heat partitioning and wheel temperatures is studied using simulated drag braking cycles. The choice of drag braking cycles could be seen as a simplification of a scenario where a train is travelling on a route with multiple consecutive short stops as is the case for a metro train with short distances between stations. To study the rail chill influence on the wheel, the axial position of the simulated wheel-rail contact, which on straight track is at the rolling circle, is varied over the tread. The case when the contact has a stationary position shifted away from the rolling circle is studied. Also the situation when the contact moves periodically over the tread (assumed travel on curved tracks or so-called hunting) is considered. The stationary case shows that the maximum tread temperature decreases to a minimum level for wheel-rail contact at a central brake block position and that it increases when the wheel-rail contact moves to the flange side. Furthermore, modelling the hunting phenomenon shows that the maximum tread temperature is influenced by the amplitude and period of movement. For such cases it was found that slow oscillations gave maximum temperatures somewhat lower than for travelling on straight track (constant rolling at the rolling circle). However, for faster oscillations, the maximum tread temperature decreased.

In addition, the influence of so-called banding during braking is studied by introducing stop braking cycles on a wheel having elevated temperature, with the brake heat input being non-uniform in the axial direction. It is found that non-constant brake pressure can highly influence the maximum tread temperature and its location on the wheel rim. Furthermore, the rail chill generally has a minor influence on the resulting temperatures.

4 FUTURE PLANS

The plan for the author´s upcoming work is to shift the focus from studying the thermal problem to studying the thermally induced stresses. An overall aim is to investigate the thermal capacity limits of wheels exposed to mainly stop braking cycles.

A model will be developed that simulates block and wheel contact variations. Local pressure, friction and wear in the contact between brake block and tread will be studied. The influence of the stiffness of the brake block mounting and the geometry of the wheel web on the thermomechanical block and tread interaction, and the following axial oscillations of the wheel rim, will be surveyed.

Finally, residual stresses in wheels that are initially induced by rim chilling at manufacturing and later exposed to plastification by the tread braking will be studied. A material model will be implemented that allows for modelling of both the initial wheel stress states and the high-temperature behaviour at braking.

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