THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

IN SOLID AND STRUCTURAL MECHANICS

# Thermal Capacity of Railway Wheels

## Temperatures, residual stresses and fatigue damage with special focus on metro applications

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Cover:

A metro bogie equipped with a tread brake system (upper), a brake block in contact with a railway wheel (lower right) and view of bogie interior with brake block, wheel and axle (lower left)

Photographed by Markus Meinel of Interfleet Technology

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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, important aspects of the thermal capacity of tread braked railway wheels have been assessed in a literature survey. Then two different railway wheel designs, with typical characteristics of freight and metro wheels, have been numerically studied with respect to standard design criteria for load cases of drag braking and stop braking. The influence of brake block materials, thermal parameters and brake pressure distribution on the wheel temperatures has been investigated. A general result is that hot spots only have a minor influence on the global heat partitioning in the wheel-block-rail system even though the hot spots have a major impact on local temperatures.

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. 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. In a pin-on-disc experimental study of railway braking materials, the heat partitioning characteristics between wheel and block material at controlled elevated disc temperatures were investigated by a finite element approach where a model was calibrated using measured temperatures.

In the final part of the present thesis, a modelling framework was proposed and developed that represents typical conditions in metro and suburban operations, in particular during sequential stop braking. A parametric study was done for analysing the influence of various loading levels and other important factors on temperatures, axial flange deflection, residual stresses and the fatigue life of the wheels. The model and the numerical results will be useful for assessing the thermal capacity of wheels and for developing new design rules and standards. It was found that the mechanical and thermal loadings have different influences on the web damage and on the estimated fatigue life depending on load cases and wheel design.

KEYWORDS: railway tread braking, finite element analysis, frictional heating, metro trains, temperatures, railway wheels, rig/field experiments, stop braking, fatigue damage

## PREFACE

This work has been performed in the Department of Applied Mechanics at Chalmers University of Technology during 2008-2014. 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.

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Most importantly, I like to dedicate this thesis to my beloved parents, Mojtaba and Farzaneh, and my brother Shayan, who always believed in the value of learning and who were patiently supportive through my prolonged education. Thank you for being with me along the road of life all these years. I love you!

Gothenburg, February 2014

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 generated by a metro train. *IMechE Journal of Rail and Rapid Transit*, 2014, **228**(2), pp 210-221.

**Paper C** Shahab Teimourimanesh, Tore Vernersson and Roger Lundén, Modelling of temperatures during railway tread braking: Influence of contact conditions and rail cooling effect. *IMechE Journal of Rail and Rapid Transit*, 2014, **228**(1), pp 93-109.

**Paper D** Saeed Abbasi, Shahab Teimourimanesh, Tore Vernersson, Ulf Sellgren, Ulf Olofsson and Roger Lundén, Temperature and thermoelastic instability at tread braking using cast iron friction material. *Wear*, 2013 (available on-line)

**Paper E** Shahab Teimourimanesh, Tore Vernersson and Roger Lundén, Thermal capacity of tread braked railway wheels – Part 1: Modelling. To be submitted for international publication.

**Paper F** Shahab Teimourimanesh, Tore Vernersson and Roger Lundén, Thermal capacity of tread braked railway wheels – Part 2: Applications. To be submitted for international publication.

## CONTRIBUTIONS TO CO-AUTHORED PAPERS

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 co-operation with the co-authors.

In Paper D, the author of the thesis took part in planning and writing of the paper and carried out the implementation and calibration of the thermal model.

In Papers E and F, the author was responsible for the planning of the papers, carried out part of the writing and a major part of the numerical simulations.

## CONTENTS

## REVIEW AND SUMMARY

An introduction to the subject is given and references are given to **Papers A-F**. 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,** and in the modelling framework within **Paper E**.

# 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. In **Paper D**, results from a series of pin-on-disc experiments are investigated to study in detail the thermomechanical behaviour of cast iron brake block material at controlled elevated disc temperatures.

**Paper E**, and its companion **Paper F**, propose, develop and demonstrate a modelling framework that represents typical conditions in metro and suburban operations, in particular during sequential stop braking for assessing the thermal capacity of the wheels. Further, the applications are investigated by a parametric study for analysing the influence of loading levels and other important factors on temperatures, axial flange deflection, residual stresses and fatigue life of the wheels.

## 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 from 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, and they allow much more flexibility regarding space requirements compared to the other braking systems [2]. Since block braking roughens the wheel tread, it improves the wheel-rail interface friction 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 [3]. As part of the effort to reduce noise, brake blocks of organic friction materials (composite brake blocks) are increasingly being used. The thermal power distribution between brake block and wheel is less favourable for the wheel when using composite brake blocks. However, the service life of composite brake blocks is much longer than that of cast iron blocks [4]. Figure 1 shows tread braked railway wheel. The brake block is located on the left side of the railway wheel.

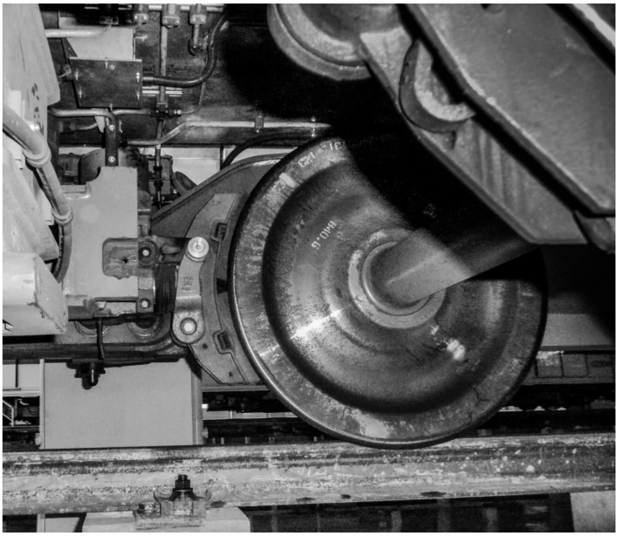

Figure 1: A view of bogie interior.

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 [5]. The standards / codes [5, 6] for technical approval of solid wheels define power levels and duration for drag braking cycles to be applied in brake rig tests. The code 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 significantly influence the temperature field and the residual stress levels in the wheels.

The work presented in this thesis forms the main 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 parameters of the thermal model, which has been introduced and described in [7].

The numerical models in **Paper C** are 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.

Results from a series of pin-on-disc experiments on railway braking materials were investigated in **Paper D** to study the thermomechanical behaviour of cast iron brake block material. The measured temperatures were used to calibrate the numerical thermal model. Temperature and heat partitioning between pin and disc are of interest.

The numerical modelling framework presented in **Paper E** aims at developing and demonstrating a method for assessing limiting phenomena for tread braked railway wheels. A calibrated elastoplastic material model for the wheel, mechanical load from wheel-rail contact forces, stresses from wheel-axle shrink fit and residual stresses from manufacturing process are included in the model. Parametric studies are performed in **Paper F** which demonstrate the influence of loading levels and other factors on the fatigue life of the wheels for different applications.

# 2 LITERATURE

## 2.1 Braking phenomena

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 the study of 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 [8, 9].

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 [10, 11] and then extensively in the late 1950´s by Newcomb [12-14]. The reader is referred to **Paper A** and the recent survey by Day [15] 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 (e.g. adhesion) 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 [16].

## 2.2 Modelling

The thermal loading and prediction of frictionally induced surface temperatures are of main importance when it comes to determine the braking capacity of wheels. A 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-state conditions have been attained if the motion concerns infinitely long bodies [11, 12]. 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 [16]. 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 [17, 18]. The thermal and mechanical properties of friction materials influencing hot spots have been studied. Furthermore, an advanced temperature-dependent material model is needed, in particular for the wheel, to realistically capture the material response.

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 [5] and UIC [6]. A limited change of wheelset gauge during and after braking together with the allowed level of residual tensile stresses in the wheel rim after cooling down determines the required braking performance. Fatigue is only considered for the wheel web at mechanical loading. However, consecutive stop braking cycles can influence the temperature field and the residual stress levels in the wheels and they may also cause fatigue failure of the wheel web. Therefore, there is a need for development of a verifiable set of guidelines and assessment criteria for wheels exposed to repeated stop brakings.

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 [19] 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 [20, 21]. Empirical studies show that tread braking in combination with mechanical loads have a crucial influence on tread damage [22]. Moreover, the influence of brake block material on wheel tread damage has been demonstrated [23]. It should be noted that wheel tread damage is not a focus in the present thesis.

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

Figure 2 shows an example of finite element mesh for an axisymmetric model of the wheel and axle assembly and the block and block holder. The wheel is in contact with the brake block and the axle at the tread surface and at the hub.

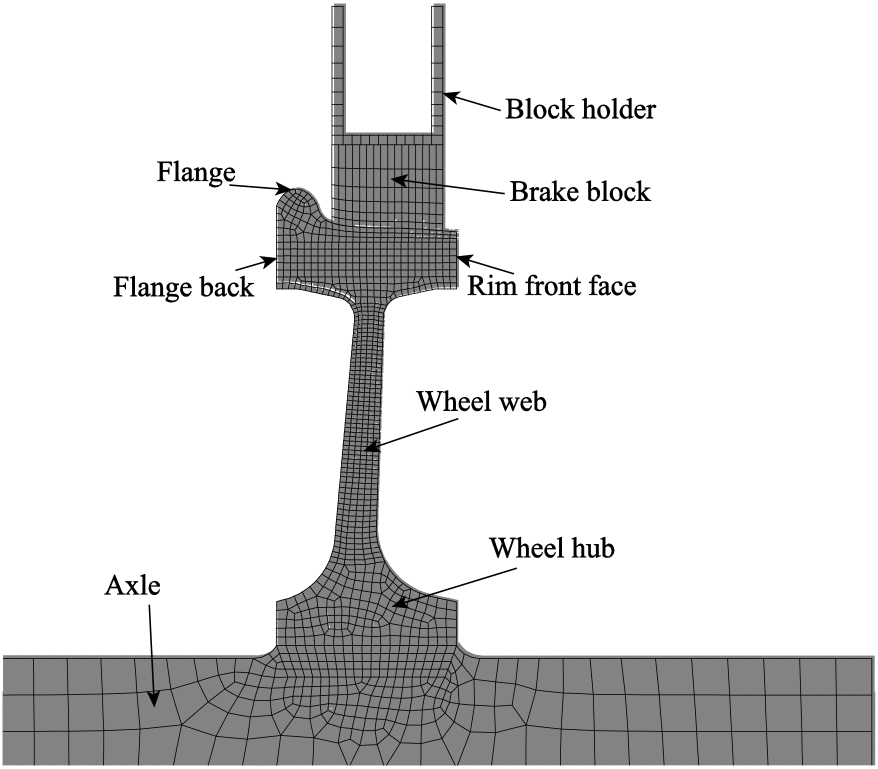


Figure 2: Example of finite element mesh for an axisymmetric model of the wheel and axle assembly and the block and block holder.

# 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.

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 [7] 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 cooling 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 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 generated by a metro train:* 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.

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 are used for measuring tread surface temperatures and embedded thermocouples for measuring temperatures below the surfaces of wheel web and brake block. Figure 3 shows some examples of the thermocouple arrangements in the rig and field tests.


Figure 3: 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 [7, 24, 25] 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 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 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 for field conditions.

## 3.3 Paper C

*Modelling of temperatures during railway tread braking: Influence of contact conditions and rail cooling effect:* 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 cooling effect 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 [26], 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 by 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 through the surface of the tread according to References [7, 27]. 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 performed 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 (spatial 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 cooling) 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 cooling power is small as compared to the stop braking 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 cooling 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 cooling effect 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 cooling generally has a minor influence on the resulting temperatures for a single stop braking cycle.

## 3.4 Paper D

*Temperature and thermoelastic instability at tread braking using cast iron friction material:* Results from a series of pin-on-disc experiments are investigated to study in detail the thermomechanical behaviour of cast iron brake block materials. Previously, results from these experiments were presented with respect to wear properties of composite, sinter and cast iron railway brake block materials at controlled elevated disc temperatures, see Vernersson et al. [28].

Laboratory studies of the wear of friction materials were performed in August and September 2011 in co-operation with the Royal Institute of Technology (KTH) Department of Machine Design in Stockholm, Sweden. Here, a novel set-up was used in a pin-on-disc tester at KTH employing a supplementary induction heating system to control the disc temperature. Figure 4 shows the pin, disc and the infrared (IR) mirror for reflecting to the thermal camera. The induction heating unit is active in the MHz range and generates concentrated heating in the rotating disc and negligibly heating in other parts of the rig. The arrangement of IR mirror, laser displacement sensor, induction heating unit and inductive displacement sensor can be seen in the original paper.

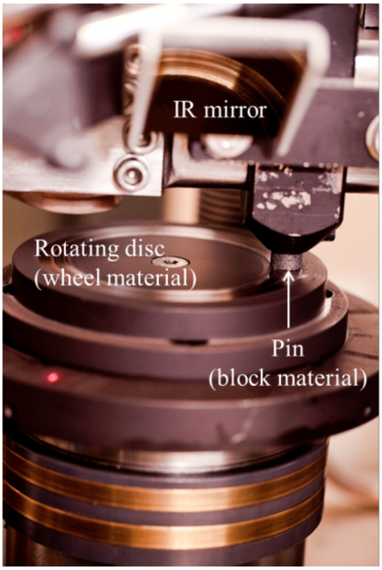


Figure 4: Detail with disc and pin in the conventional pin-on-disc machine.

According to the experimental results, the cast iron block material shows decreasing wear rates at temperatures higher than 500 °C. Additionally, the generation of hot spots on the contacting surface of the cast iron pin was an interesting phenomenon which can be explained with thermoelastic effects. Two approaches are considered separately. In the first approach, the thermal problem is studied where frictional heat is generated in the contact between the stationary pin and the rotating disc and is partitioned between the two bodies. The heat partitioning for the pin-on-disc configuration is studied using a transient heat transfer analysis employing a finite element model of the pin-on-disc set-up. Like in **Paper C**, the "third body approach" is used for modelling the temperature jump at the interface [29]. In the calibration process, the parameters controlling the convection cooling and the thermal resistances have been determined by minimising the differences between the measured temperatures and the simulated results at several time points during a test.

In the second approach, a thermomechanical boundary element (BE) model is established to study the transient thermoelastic behaviour of the pin during pin-on-disc tests. The proposed numerical method is based on a framework for estimating thermoelastic instability (TEI) in contact surfaces that integrates four submodels to determine pressure, temperature, wear and updated geometry, respectively.

The thermal study has shown that the heat flux to the pin (and the pin temperature) increases by increasing disc temperatures up to an elevated temperature of 500 °C. This also corresponds to an increase in wear rate that was found in the experimental study [28]. The results show that the part of the heat that goes to the pin drops by about 25% for disc temperatures higher than the transition temperature 500 °C. The thermoelastic instability approach shows that the contact pressure increases over time as the temperature increases. Both temperature and pressure vary over the contact area which can explain the hot spot movement on the pin.

## 3.5 Paper E

*Thermal capacity of tread braked railway wheels - Part1: Modelling:* Safety related issues that can be related thermal capacity of wheels at tread braking are discussed and a modelling framework is proposed for assessment of tread braked wheels. Conditions typical for metro and suburban operations with particular focus on sequential stop braking are studied. Also the traditional drag braking load cases, used when designing wheels, that could result from brake malfunction are investigated. Moreover, aspects of mechanical loading on wheels induced by wheel-rail contact, influence of manufacturing residual stresses and wheel-axle interference fit are considered. Wheel performance is investigated with respect to thermomechanical behaviour at braking and also considering fatigue damage analyses of the wheel web. Failure modes of a wheel that limit its use in a tread braking situation are identified: (1) too large a change of the gauge in the wheelset, making it incompatible with the rail infrastructure, (2) a build-up of tensile residual stresses followed by a fracture of the wheel with cracks from rim to hub, (3) reduction of the strength of the wheel-axle assembly, or (4) fatigue failure of the wheel web. Issues relating to local damage at the wheel tread are considered to be out of the scope of the present paper.

The starting point for assessing the thermal capacity of a tread braked wheel is the use of a calibrated thermal model. Here, the basically axisymmetric model from **Paper B,** calibrated using measured data from an in-field test campaign on a metro train, is used to predict wheel temperatures. Wheel temperatures as calculated from a train route are then introduced in a consecutive finite element analysis to find stresses, strains and wheel displacements due to braking. In the present paper, an advanced material model of viscoplastic type with a combination of nonlinear isotropic and kinematic hardening is used for capturing the material response at elevated temperatures. The model is calibrated for temperatures up to 650 °C and at the finite element implementation, also the inherent yield stress variations and residual stress variations in the wheel rim as introduced at rim-chilling of the wheels at manufacturing are accounted for.

The mechanical loading acting on the wheel is considered to be given by the three load cases given by the EN 13979-1 standard: 1) train travelling on straight track, 2) train passing a curve and 3) passing a switch or a crossing. Randomized loading sequences are constructed from these three load cases to simulate the loading during an assumed train route.

Fatigue of the wheel web is considered for the thermal and the mechanical load cases (assumed to act separately in the wheel) by use of The Coffin-Manson relationship and the total damage is calculated using the Palmgren-Miner cumulative damage rule.

Finally, a numerical application example is given where a typical metro wheel with a straight, slightly inclined web, is analysed for a simulated route where the train is assumed to be acting in a friction only braking mode. Typical result are presented and discussed.

## 3.6 Paper F

*Thermal capacity of tread braked railway wheels – Part 2: Applications:* The modelling efforts presented in **Paper E** are used for investigating the capacity of railway wheels with respect to a number of failure criteria. A parametric study is presented where the influence from various thermal and mechanical loading levels are investigated with respect to temperatures, axial flange deflections, residual stresses and the fatigue life of the wheels are analysed. Also aspects that are interesting from an engineering modelling perspective are studied to find the influential important phenomena. The focus is on repeated stop braking cycles on generic metro train routes, but also malfunctioning brakes are investigated that would results in a drag braking situation. The results should be useful for finding performance limits of wheels under tread braking applications since the wheel is often a limiting component. In the paper, a situation is investigated where friction braking is the only active brake system, which is a severe braking situation for the tread braking system and the wheels. However, the methods are useful also for investigating the wheel performance at a blending situation when the tread brakes only takes a part of the total required braking effort of the train (e g  with a fully, or partially, functioning electrodynamic braking system).

The parametric study for different load cases of repeated stop braking shows that the thermomechanical performance of a wheel (design) during and after braking will provide distinct limits for the use of the wheels. It is found that too severe stop braking cycles result in too large axial flange deflections, both during braking and upon cooling down, but also that too large residual tensile stresses build up in the rim of the wheels. For instance, it is found that the load cases with 2 and 3 km assumed distances between stations and a maximum, speed of 80 km/h produce wheel performances that are in line with the requirements in available standards [5]. However, when the distance is reduced to 1 km, the residual axial displacements are (negligibly) outside of the allowed range and, furthermore, the residual stresses also are lower than allowed after a rig testing in the standards but larger than allowed after field testing. This load case seems to be just a bit too severe for this wheel, having a straight-inclined web, to fulfil the braking requirements. However, in the paper also a wheel with an S-shaped web is investigated and this wheel is found to fulfil also the requirements for this braking load case. The temperature gradients in the wheel generated by the tread braking also have the drawback that they reduce the force that can be transmitted between wheel and axle at the interference fit. It is found that the new wheel is the limiting case (not the worn wheel as discussed above), which shows the largest reduction in the wheel axle contact pressure and in the force that can be carried. For severe braking there is a risk that a lateral forces acting on wheel that is somewhat larger than the one assumed at curving could reposition the wheel on the axle. It is found that more severe braking can be tolerated for an S-shaped wheel than for a wheel with a straight web.

The analyses of fatigue damage as induced by the thermal loading and also by the mechanical loads at the wheel-rail contact show that both studied wheel designs show relatively long lives. It should here be considered that the studied most severe stop braking cases constitute an extreme loading case for a metro train that only occurs when the electrodynamic braking for some reason is not operative at all.

The parametric study also analyses the case where a brake malfunctioning occurs and results for prolonged braking at constant power 20 kW and 30 kW are given in detail. These load cases reveal that the wheel with a straight slightly inclined web show a permissible behaviour at 20 kW, but already at 30 kW braking the residual axial flange deflections and the rim stresses are outside of the allowed limits in the standards. For the drag braking load cases, there are also problems with the force that can be transmitted at the wheel-axle interface. For the new wheel, braking at 30 kW means that the force that can be transferred is about as large as the lateral forces at curving, whereas braking at 20 kW gives some safety margin at curving. Here, a minimum allowed interference between seat on axle and wheel hub has been assumed (according to the standard EN 13260 [30]) and it could be advisable to choose the interference towards the upper limit of the allowed range for such situations. The analyses emphasize the problems with prolonged drag braking; the wheel web must be specifically designed with respect to drag braking to avoid performance issues. A different route would be to install some warning systems that can detect unintentional drag braking of wheels.

Additional efforts have been made to investigate the complicated interactions of load cases by performing sequentially combinations of load cases. Moreover, results are also given for an effort to study the case when the thermal stresses in the wheel are acting simultaneously as the mechanical loads from the wheel-rail contact.

# 4 CONCLUDING REMARKS AND FUTURE DEVELOPMENTS

## 4.1 General

The present thesis has reported the results of the doctoral project CHARMEC SD7 “Thermal capacity of tread braked railway wheels”. The project was formulated in 2006 with the aim to provide data that can form a basis for future design guidelines for assessing the thermal capacity of tread braked wheels. The project aim was to identify those phenomena which put limits on the capacity of the tread braking system, outline methods for determining such limits and, finally, quantify the limits. It is deemed that these aims have been fulfilled well by the project.

The study is motivated by the fact that tread (block) braking still is one of the most common braking systems on railway vehicles. 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 have both advantages and disadvantages. They 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.

## 4.2 Discussion of results

The present work has already resulted in two conference presentation / proceeding publications (Papers A and D), in three journal papers (Papers B, C and D) and, hopefully in the near future, in two further journal papers (Papers E and F). In the following condensed summaries and some results and aspects of the six papers and how they relate to the aims of the total project, are highlighted.

*Paper A: Braking capacity of railway wheels – state-of-the-art survey*. This overview of design methods for tread braking systems has a special focus on the braking capacity of the wheels. Several aspects of the tread braking system, important for the dimensioning of railway wheels, are assessed, such as brake block materials, residual stresses and temperature gradients through wheel rim and wheel disc. The influence of heat partitioning between wheel, brake block and rail on wheel temperatures for different braking cycles is considered. Two examples with numerical results on thermomechanical behaviour of tread braking systems are given regarding freight and metro applications. A comparison of temperatures and axial flange deflections are given for the wheels in new and worn condition.

The paper constitutes a necessary and elaborate starting point and knowledge base for the continued work in the projects, both through its literature survey and through the calculation examples carried out.

*Paper B: Tread braking of railway wheels – temperatures generated by a metro train*. Results from brake rig tests and from in-field testing of a metro train are presented and used to calibrate a simulation model. It is found that the cooling level of the wheels of the metro train is substantially lower than for the wheels of a freight wagon. Moreover, it is found that the first axle on the metro train is exposed to higher cooling levels than the remaining axles. In a numerical example, temperatures of tread braked wheels are calculated using the new findings for a metro train, and the results obtained are compared with wheel temperatures as calculated assuming freight wagon conditions.

The experimental study performed together with the CHARMEC partner Faiveley Transport gave valuable experiences. The parallel modelling and calibration work resulted in an important development of an existing model for drag braking to be useful also for repeated stop brakings. For the special metro train studied, interesting information on cooling conditions could be identified through the combined experimental and numerical work.

*Paper C: Modelling of temperatures during railway tread braking: Influence of contact conditions and rail cooling effect*. The generated temperatures and heat partitioning between wheel, block and rail during tread braking have been studied. First, by use of a circumferential model, the effects of short time period braking at powers typical for a stop braking cycle were analysed under the assumption that hot spots appear on the tread. Second, by use of an axisymmetric model, the influence of the position of the rail cooling effect (constant offset wheel–rail contact from rolling circle or oscillatory lateral movement of the contact) was studied for braking over longer time periods. Also, the influence from banding during a stop braking cycle has been studied.

The study gave important results to the project by concluding that a local temperature variation in the wheel-block contact does not significantly affect the global build-up of residual stresses, that the cooling effect of the rail is important for drag braking and repeated stop brakings but not for a single stop braking, that the choice of brake block material is affecting not only rolling noise levels but also the heat input to the wheel, and that the proposed method can be used by engineers to shed light on the local stress distribution and damage in the wheel tread and on wheel deflections and thermal capacity of a wheel design or braking system.

*Paper D: Temperature and thermoelastic instability at tread braking using cast iron friction material*. The study demonstrates two different approaches for studying the thermomechanical interaction at a pin-on-disc test on the braking material cast iron, at ambient and at elevated disc temperatures. First, the thermal problem was studied by a finite element approach where a model was calibrated using measured temperatures to clarify the heat partitioning in the pin-on-disc test. It was shown that the heat flux to the pin (and the pin temperature) increases by increasing disc temperatures up to an elevated temperature of 500°°C. This also corresponds to an increase in wear rate that was found in the experimental study. The results show that the part of the heat that goes to the pin drops by about 25% for disc temperatures higher than the transition temperature 500°°C. The two-dimensional model and methodology developed may be used to predefine the heat partitioning factor for thermoelastic analysis in a sequential multiphysics workflow. In the second part of the work, a numerical model has been developed to study the transient thermoelastic behaviour of the pin during pin-on-disc tests by assuming that the pin has been built up by finite rectangular elements. It is shown that the contact pressure increases over time as the temperature increases. However, the thermoelastic model is suitable for qualitative study of the phenomenon, but further experimental and numerical investigations are needed.

Although the paper is a bit off the main topic of the project it contributes well to the understanding of the phenomena in tread braking. It reports a unique experimental set-up and study performed in collaboration with tribology researchers. It shows that the thermal model, which was contributed from the SD7 project, is useful for interpreting the experimental result, particularly regarding the heat partitioning factor. The reported high-temperature tribological behaviour of cast iron is interesting and important.

*Paper E: Thermal capacity of tread braked railway wheels, Part 1: Modelling*. A modelling framework is established for assessing the thermal capacity of metro wheels. The mechanical stresses as induced by the wheel–rail contact forces are accounted for but also the temperature loading and the thermal stresses as induced by a repeated stop braking of the metro train. In a numerical example, temperatures are calculated for a simplified route having 30 stations at equal distances 3 km and the stresses and strains in the wheel are analysed for the fatigue assessment of the web. Also residual stresses from manufacturing are included. The mechanical and thermal loadings on the wheel web were found to have influence on the calculated damage magnitudes. The estimated fatigue life is for the studied example almost entirely controlled by the mechanical loading.

This paper is a significant step forward in developing a tool that can quantify the build-up of residual stresses in the rim and the fatigue of the web, accounting for the main contributing factors such as thermal load, mechanical load, wheel design, material behaviour and residual stresses. Naturally, it constitutes a necessary base for the numerical study performed in Paper F.

*Paper F: Thermal capacity of tread braked railway wheels, Part 2: Applications*. In the present paper, application examples are given employing a modelling framework which have been developed in Paper E. The examples represent typical conditions in metro and suburban operations, in particular during sequential stop braking. Also results for drag braking, mechanical loading, residual stresses and wheel-axle interference fit are given. Parametric studies are performed which demonstrate the influence of loading levels and other factors on the fatigue life of the wheels. The results should be useful for establishing design rules that consider the thermal capacity of tread braked railway wheels.

The parametric study for different load cases of repeated stop braking shows that the thermomechanical performance of a wheel (design) during and after braking will provide distinct limits for the use of the wheels. It is concluded that the short distances (1 km) between the metro stations can deviate from the traditional decision criteria given in the standard EN 13979-1. Additionally, investigating the interference fit between wheel and axle for the mentioned load case, shows a significant decrease for the force that can be sustained by the assembly.

Paper E and F provide important data that can form a basis, in the public domain related to thermal capacity limits for wheels. It also considers in-service rejection criteria for wheels that have endured a (potential) overheating event. Examples are maximum residual stress levels, wheelset gauge changes and integrity of the wheel-axle assembly.

## 4.3 Future development

There are a number of aspects of the present thesis that could be worth developing further. Four such aspects will be described shortly in the following: modelling and experiments, deterioration of the wheel tread, system aspects, and implementation.

The models of wheel material could be further developed regarding creep and hardening and also to include other steel qualities. Such work has recently started in the doctoral projects CHARMEC MU28 “Mechanical performance of wheel and rail materials” and CHARMEC MU32 “Modelling of thermomechanical behaviour of wheel and rail steels”. Regarding fatigue, the effect of the biaxiality of the stresses in the wheel web should be investigated. More rig and field experiments could further contribute to making the model reliable and useful. Pin-on-disc tests for other brake block materials than cast iron would be valuable. An important aspect so far not thoroughly investigated, neither numerically nor experimentally, is wheel web fatigue for a realistic combination of mechanical and thermal loading, which means that they are simultaneously applied.

Tread deterioration may be a limiting factor to the braking capacity of railway wheels. Such deterioration is often dominated by rolling contact fatigue (RCF). This is studied in the ongoing doctoral project CHARMEC MU21 “Thermal impact on RCF of wheels”. The focus is on RCF of railway wheels under the interaction of mechanical loading (due to rolling and/or sliding wheel–rail contact) and thermal loading (due to tread braking and/or wheel-rail friction). The project aims at developing predictive models for surface initiated RCF in railway wheels where thermal effects are included. Ultimately, the knowledge and methods will be employed to refine engineering models of RCF prediction. The emphasis is on an in-depth investigation and understanding of the influence of combined thermal and mechanical loadings.

System aspects relating to the capacity of tread braked railway wheels should be investigated. This work has already started in the combined senior and doctoral project CHARMEC SD10 “Enhanced block braking systems for modern trains”. The project aims at investigating different aspects of braking systems, where the braking effort is performed by use of interacting braking systems. The focus is on an overall cost-effective partitioning of braking power between the parts in the braking systems. Tread brakes are an important part of the project and the braking capacity to the wheels is here of great importance.

Finally, implementation and innovation aspects of the thesis should be exploited. This is motivated by the fact that CHARMEC is financed by Trafikverket and by an Industrial Interests Group, since they anticipate that the projects carried out will enable new methods, standards/regulations and products to be realized. Recently, also Chalmers University, which CHARMEC is a part of, has adopted a policy of innovation for the research. A first effort on this, for the present project, will be performed during the spring 2014 in which a number of aspects for implementation will be identified and discussed with CHARMEC partners.

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