STAGE 9

TRIENNIAL REPORT
1 July 2018–30 June 2021

REVIEW
1 July 1995–30 June 2018

PLANS
1 July 2021–30 June 2024

CHARMEC

Chalmers Railway Mechanics – a NUTEK/VINNOVA Competence Centre
Chalmers University of Technology

FOREWORD

This Triennial Report documents the organization, operation, financing and results of Stage 9 (1 July 2018 – 30 June 2021) for the Swedish National Centre of Excellence in Railway Mechanics, CHARMEC. The presentation also contains a review of previous research activities going back to the establishment of CHARMEC which was based on a NUTEK/VINNOVA government grant for the period 1995–2005. Pages 92–95 display an overview of all 142 projects that have been (or are being) carried out within CHARMEC, but only the 40 projects running during Stage 9 are accounted for in detail. Some results from the period 1 July 2021 – 31 January 2022 have been added.

The report has been compiled by a number of contributors with Professor Roger Lundén and Professor Emeritus Bengt Åkesson providing major parts. The layout and typesetting was made by Graphic Designer Tomas Wahlberg based on Yngve Nygren's original design.

More details on the activities within CHARMEC (as well as electronic versions of this and previous triennial reports) are available on the CHARMEC website (www.chalmers.se/charmec).

Gothenburg in March 2022
ANDERS EKBERG
Director of CHARMEC

William Chalmers (1748–1811) from Gothenburg, Director of the Swedish East India Company, bequeathed a large sum of money to the start in 1829 of an industrial school that later became the Chalmers University of Technology

Front cover: Photoelastic experiment illustrating stress fields arising during two-point contact between wheel and rail

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REFLECTIONS FROM THE DIRECTOR

The railway sector continues to face a combination of large possibilities and major challenges all over the world. In addition to the short-term challenges due to the ongoing pandemic, rail transportation is in a longer perspective increasing on a network that in many cases was designed for conditions prevailing a hundred years ago. This calls for upgrading and maintaining of the technical status while time for maintenance of track and vehicles is getting scarcer and consequences of delays become more severe.

In general, the situation is welcome since a shift of transportation from road and air to train is one of the most efficient means of combating congestion and emissions while enhancing a high safety level. However, it implies challenges for all actors in the railway sector: The optimized and integrated design of the railway system allows for a massive transport capacity, but also relies on a stable and persistent operation of all parts. To ensure this, it is first vital to understand and be able to predict how different parts of the system deteriorate and fail, so that preventive actions can be taken. This is one of the main challenges of CHARMEC's research. However, to achieve a reliable railway system, it is also necessary to stop considering the railway as an infrastructure with independently running trains on an independent track, and instead start viewing the railway as an *integrated rolling process industry*. Such a paradigm shift has long-reaching consequences: The focus on how different components work for themselves must be combined with the implications they have in the whole railway system – issues should not be dealt with when, but before, they have consequences for the full system. In later years, this holistic approach has been more and more integrated into CHARMEC's research.

It can here be noted that railway mechanics is a topic that relates back to the 1850's. However, instead of becoming obsolete the area is becoming more relevant than ever and has evolved at an increased rate. The reason is that the increased need to avoid traffic disruptions makes the need for predictions of deterioration and failure obvious; here numerical simulations have a key role. With less time available for field tests and handling of larger consequences of malfunctioning equipment, the role of these simulations increases. This trend of "virtual homologation", "digitalization" and "digital twins" etc is nothing new. It has been around in many engineering sectors for decades. It has also been developed and used within CHARMEC since the establishment of our research centre. However, the current paradigm shift makes the benefits of these abilities much more visible. In addition, the need for a more holistic assessment of the railway system calls for more complex predictive analyses. It is no longer sufficient to answer what the consequences of a certain load will be on the life of the rail, but instead also to consider how the deterioration of the rail will increase the loading and deterioration on the rail, and also on other components of the track and on passing vehicles. With such predictive abilities, it will become possible to optimize maintenance and operational regulations with a much higher precision.

In the following you will get an overview of our research and how it relates to the overall aims of a more robust, (cost)efficient and even more environmentally friendly railway. The presentations go into the technical depths of the research, but keep in mind – as we do – that the overall aim is to use the research results to improve the rolling process industry which is the full railway system.

Finally, I would like to acknowledge all the individual professionals that have put in the hard and dedicated work required to achieve the research results that are presented. Just as a rolling process industry requires all parts to interact, so does our research require co-operation between our qualified industrial partners, our dedicated doctoral students and senior researchers, and our knowledgeable colleagues from all over the world.

Main entrance to Chalmers University of Technology with the Student Union building on the right

EXECUTIVE SUMMARY

The Competence Centre Chalmers Railway Mechanics (CHARMEC) was established in July 1995 at Chalmers University of Technology in Gothenburg, Sweden. It had its origin in a small-scale railway mechanics research programme which was set up in 1987 at the Department of Solid Mechanics in collaboration with the company Sura Traction (now Lucchini Sweden). A key factor to the success of CHARMEC has been the long-term commitment of the Swedish Transport Administration Trafikverket (previously Banverket) and the industrial partners. Four of the current ten partners during Stage 9 (including Lucchini) have been involved since 1995, and the remaining six have been involved for fifteen years or more. Another key factor is the core group of committed CHARMEC researchers at Chalmers University of Technology.

The Swedish Governmental Agency for Innovation Systems (VINNOVA) organized a third international evaluation of CHARMEC at the end of the Centre's Stage 3. Conclusions from the evaluators were: CHARMEC has established itself as an internationally recognized multidisciplinary Centre of Excellence in railway mechanics. No such evaluation has taken place since 2003. However, in 2011 VINNOVA initiated an investigation into the impact CHARMEC has had on the companies that participated in different research centres. CHARMEC and several of our partners contributed to this study. In a report from VINNOVA 2013 the impact of CHARMEC's research was quantified. It was concluded that "between 1995 and 2011, CHARMEC has altogether strongly contributed to an economic impact for society and industry that can be estimated to between 1 035 and 1 430 MSEK per year", see page 116 in the Triennial Report for Stage 7.

The annual budget for the three years of Stage 9 (1 July 2018 – 30 June 2021) has been MSEK 27.2 (about MEUR 2.7), see page 88. Three parties have provided funding: Chalmers University of Technology, Trafikverket, and an Industrial Interests Group comprising ten partners. Substantial funding also was provided by the European Union (EU). In total, 26 ordinary research projects, 6 EU projects and 8 development projects were carried out during Stage 9.

At Chalmers, 40 people (project leaders, academic supervisors, doctoral students and senior researchers) from 3 departments (out of a total of 13 at Chalmers, see page 97) have been involved. They published 65 scientific papers in international journals and conference proceedings and contributed to about 20 EU Deliverables during Stage 9 (including those in print). Three Licentiate degrees and nine PhD degrees were conferred during Stage 9.

A total of 63 Licentiate degrees and 54 PhD degrees in railway mechanics have been awarded up to June 2021 at Chalmers, see page 74. More than 60 partners (industries, universities, institutes, public agencies, consultancies) from 15 countries have been involved in our European projects during Stage 9.

CHARMEC endeavours to combine academic excellence and industrial relevance while generating first rate research and skilled PhDs, Licentiates and MScs. Our work includes mathematical modelling, numerical studies, laboratory experiments and full-scale field measurements. We have worked closely with Trafikverket and the Industrial Interests Group in order to promote implementation. Knowledge has been transferred in both directions through advisory groups and industrial site visits, regular seminars and other meetings as well as through co-authored journal papers, co-ordinated conference participation and joint field experiment campaigns. Implementation has been further supported by activities such as directed numerical and experimental studies, assistance in defining regulations and specifications, involvement in collaborative work, support to governmental investigations etc. Due to the internationalization of railway regulations, an increasingly important part in implementation is the international collaboration. Here CHARMEC's involvement in EU projects (see page 13) is one important part.

Funding (MSEK) of CHARMEC including EU projects

Stage	At start of Stage			At end of Stage		
	Cash	In-kind	Total	Cash	In-kind	Total
1	11.7	8.8	20.5	13.0	8.8	21.8
2	34.8	25.0	59.8	35.0	25.0	60.0
3	38.8	26.2	65.0	46.0	25.7	71.1
4	36.9	28.4	65.3	47.8	27.5	75.3
5	48.5	21.6	70.1	47.1	21.6	68.7
6	45.7	17.2	62.9	49.5	17.2	66.7
7	50.8	16.6	67.4	49.8	18.5	68.3
8	70.6	11.5	82.1	66.9	11.0	77.9
9	68.5	9.0	77.5	73.2	8.4	81.6
10	77.3 *	8.6 *	85.9 *			

Note that Stage 1 only lasted two years whereas the following Stages are for three years

The approximate exchange rate (December 2021) is 1 MSEK = 0.10 MEUR

* After Board Meeting on 14 September 2021

INTRODUCTION

CHARMEC is an acronym for *CHA*lmers *R*ailway *MEC*hanics. This Centre of Excellence, or Competence Centre, was established at Chalmers University of Technology in 1995. A formal agreement was reached at the Swedish National Board for Industrial and Technical Development (NUTEK) in Stockholm on 7 July 1995. The funding for Stage 1 (1 July 1995 – 30 June 1997) with a total of MSEK 20.5 was agreed on by NUTEK, the University and the four partners Banverket, Abetong Teknik, Adtranz Wheelset (now Lucchini Sweden) and SJ Machine Division. Research in railway mechanics began on a small scale at Chalmers Solid Mechanics in 1987, when a first bilateral contract was signed between Bengt Åkesson of that department and Åke Hassellöf of Sura Traction (later ABB Sura Traction and Adtranz Wheelset, and now Lucchini Sweden).

CHARMEC's Stage 2 (1 July 1997 – 30 June 2000) was agreed on at a meeting in Stockholm on 10 October 1997. Cardo Rail (later SAB WABCO Group, now Faiveley Transport Nordic), Duroc Rail and Inexa Profil then joined as new industrial partners. An agreement for CHARMEC's Stage 3 (1 July 2000 – 30 June 2003) was reached at NUTEK's office in Stockholm on 22 June 2000. Adtranz Sweden (later Bombardier Transportation, now Alstom) then joined the Industrial Interests Group. During Stage 3, Inexa Profil went into receivership and left CHARMEC. As of 1 January 2001, NUTEK's responsibility for CHARMEC was taken over by the Swedish Governmental Agency for Innovation Systems (VINNOVA).

An agreement for CHARMEC's Stage 4 (1 July 2003 – 30 June 2006) was reached at VINNOVA's office in Stockholm on 19 June 2003. Green Cargo AB (a Swedish freight operator), SL Technology (a division of AB Storstockholms Lokaltrafik) and voestalpine Bahnsysteme GmbH & CoKG (Austrian rail and switch manufacturer) joined as new industrial partners. VINNOVA's MSEK 6.0 per annum was only paid during the first two years of Stage 4. TrainTech Engineering Sweden (later Interfleet Technology and SNC-Lavalin, now Atkins Sverige) replaced SJ Machine Division.

In the Principal Agreement for CHARMEC's Stage 5 (1 July 2006 – 30 June 2009), Banverket was directly included in the agreement and also assigned part of the administrative role that was previously filled by VINNOVA. SJ AB and SweMaint AB joined the Industrial Interests Group during Stage 5. One member, Duroc Rail, left CHARMEC at the end of Stage 4. Jan-Eric Sundgren, President of Chalmers University of Technology, and Karin Markides, new President from 1 July 2006, signed the contracts for Stage 5 on 19 June and 19 September 2006, respectively. The Principal Agreements for Stages 6 and 7 were constructed in the same form as those for Stages 4 and 5 and involved the same members of the Industrial Interests Group. President Karin Markides signed the contract for Stage 6 on 9 June 2009. As of 1 April 2010, Banverket was merged into the new governmental authority Trafikverket. The contract for Stage 7 was signed by President Karin Markides on 19 June 2012. During Stage 7, SL Technology was transformed into SLL Trafikförvaltningen. The consultancy ÅF joined CHARMEC in 2014, but left at the end of Stage 7 together with SLL.

In the Principal Agreement for CHARMEC's Stage 8 (1 July 2015 – 30 June 2018), the financial terms with Trafikverket are detailed in a separate contract. During Stages 8 and 9, voestalpine were represented by their two companies voestalpine Schienen GmbH and voestalpine VAE GmbH. The contract for Stage 8 was signed by Stefan Bengtsson, President of Chalmers University, on 1 October 2015 and the contract for Stage 9 was signed by him on 27 August 2018. For a brief outline of CHARMEC's Stage 10 (1 July 2021 – 30 June 2024), see page 91. The volume of CHARMEC's activities since the start is set out in the table on page 6.

The three parties to the agreement on Stage 9 were:

Chalmers University of Technology

Trafikverket – the Swedish Transport Administration (being responsible for the construction, operation and maintenance of all state owned roads and railways, and also for the development of long-term plans for the transport system on road, railway, sea and flight) with its administrative centre in Borlänge

The Industrial Interests Group

Abetong – a *HeidelbergCement Group* company and concrete sleeper manufacturer headquartered in Växjö

Bombardier Transportation (now Alstom) – an international train manufacturer with Swedish headquarters in Västerås

Faiveley Transport (now part of Wabtec Corporation) – an international manufacturer of braking systems with Swedish headquarters in Landskrona

Green Cargo – a railway freight operator with headquarters in Stockholm / Solna

SNC-Lavalin (now Atkins) – an international consultancy with Swedish headquarters in Stockholm / Solna

Lucchini Sweden – a wheelset manufacturer (the only one in the Nordic region) located in Surahammar

SJ – a passenger train operator with headquarters in Stockholm

SweMaint – a maintainer of freight wagons with headquarters in Gothenburg (owned by *Kockums Industrier*)

voestalpine Schienen – an Austrian manufacturer of rails with headquarters in Leoben

voestalpine VAE – an Austrian manufacturer of switches and crossings with headquarters in Zeltweg

VISION AND GOALS

CHARMEC is a strong player among world-leading research centres in railway mechanics and contributes significantly towards achieving lower production, maintenance, operating and environmental costs and to overall improvement in the safety, sustainability and quality of railway transportation. The University, Trafikverket and the Industry collaborate in realizing this vision.

CHARMEC successfully combines the identification, formulation and solution of industrially relevant problems with high academic standards and internationally viable research. CHARMEC disseminates its research results and contributes to industrial development and growth in Sweden and abroad.

CHARMEC maintains an up-to-date body of knowledge and preparedness which can be put to use at short notice in the event of unexpected damage or an accident during railway operations in Sweden or abroad. The scientific level and practical usefulness of CHARMEC's academic and industrial achievements are such that continued long-term support to CHARMEC is profitable for the Government, the University and the Industry.

CHARMEC's specific goals include the national training and examination of MScs, Licentiates and PhDs and the international presentation and publication of research results. Fundamental and applied research projects are integrated. CHARMEC's industrial partners are supported in the implementation of the solutions that are reached and the use of the tools that are developed. CHARMEC attracts able and motivated PhD students and senior researchers. The MScs, Licentiates and PhDs who graduate from CHARMEC make attractive employees in the railway industry and associated R&D organizations.

CHARMEC's research focuses on the interaction of various mechanical components. Analytical, numerical and experimental tools are developed and applied. New and innovative materials, designs and controls are explored. The life-cycle optimization of parts and systems for track structure and running gear is intended to slow down the degradation of ballast and embankments, increase the life of sleepers, slabs and pads, improve track alignment stability, reduce rail and wheel wear, reduce the tendency towards rolling contact fatigue of rails and wheels, reduce the levels of vibration and noise in trains, tracks and their surroundings, and improve systems for the monitoring and operation of brakes, bearings, wheels etc.

BOARD AND DIRECTOR

Professor Stefan Bengtsson, President of Chalmers University of Technology since 1 August 2015, in consultation with Trafikverket and the Industrial Interests Group, appointed the following people members of the Board of the Competence Centre CHARMEC at the end of Stage 9 (decision dated 9 December 2020):

Ingemar Frej (chair)	Trafikverket
Rikard Bolmsvik	Abetong
Maria Edén	Atkins Sverige
Roger Deuce	Bombardier Transportation / Alstom
Fredrik Blennow	Faiveley Transport
Markus Gardbring	Green Cargo
Erik Kihlberg	Lucchini Sweden
Susanne Rymell	SJ
Tilo Reuter	SweMaint
Björn Drakenberg	voestalpine Railway Systems
Sebastian Stichel	Royal Institute of Technology (KTH)
Per Lövsund	Chalmers

Ingemar Frej of Trafikverket was appointed member and chairperson of the Board from 1 July 2015. Björn Paulsson of Banverket held this position from the start of CHARMEC on 1 July 1995 until 31 december 2008. He was then succeeded by Tomas Ramstedt (of Banverket / Trafikverket) and from 1 July 2012 by Annika Renfors (of Trafikverket) who resigned as member and chairperson on 30 June 2015. Maria Edén of Atkins Sverige succeeded Sven-Ivar Karlsson as member of the Board on 1 January 2021.

Docent (now Professor) Anders Ekberg was appointed Director of CHARMEC from 1 October 2012 (decision by President Karin Markides dated 29 August 2012). The Centre's first Director was Bengt Åkesson, now Professor Emeritus of Solid Mechanics. He was succeeded on 1 April 1997 by Roger Lundén, now Professor in Railway Mechanics at the Chalmers Department of Mechanics and Maritime Sciences, who held the position until 30 September 2012.

BOARD MEMBERS

Ingemar Frej
of Trafikverket (Chairperson, Stages 8+9+10)

Rikard Bolmsvik
of Abetong
(Stages 5+6+7+8+9+10)

Maria Edén
of Atkins Sverige
(Stages 9+10)

Roger Deuce of
Bombardier Transportation / Alstom in Germany
(Stages 9+10)

Fredrik Blennow
of Faiveley Transport
(Stages 8+9+10)

Markus Gardbring
of Green Cargo
(Stages 9+10)

Erik Kihlberg
of Lucchini Sweden
(Stages 6+7+8+9+10)

Susanne Rymell
of SJ
(Stages 6+7+8+9+10)

Tilo Reuter
of SweMaint
(Stages 8+9+10)

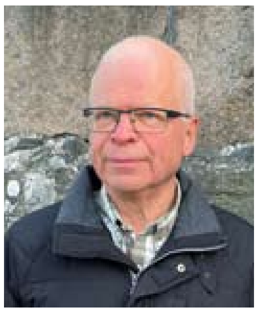
Björn Drakenberg
of voestalpine Railway Systems
(Stages 7+8+9+10)

Sebastian Stichel
of KTH Railway Group
(Stages 7+8+9+10)

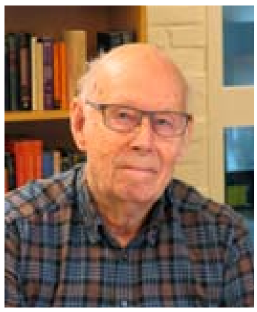
Per Lövsund
of Chalmers
(Stages 6+7+8+9+10)

Uday Kumar
of JVTC in Luleå is invited to CHARMEC's Board meetings, see page 81

Anders Ekberg
of Chalmers Mechanics and Maritime Sciences
(Director of CHARMEC)



Roger Lundén
of Chalmers Mechanics and Maritime Sciences
(Director of CHARMEC 1997–2012)



Bengt Åkesson
of Chalmers Mechanics and Maritime Sciences
(Director of CHARMEC 1995–1997)

QUALITY ASSESSMENT AND KNOWLEDGE TRANSFER

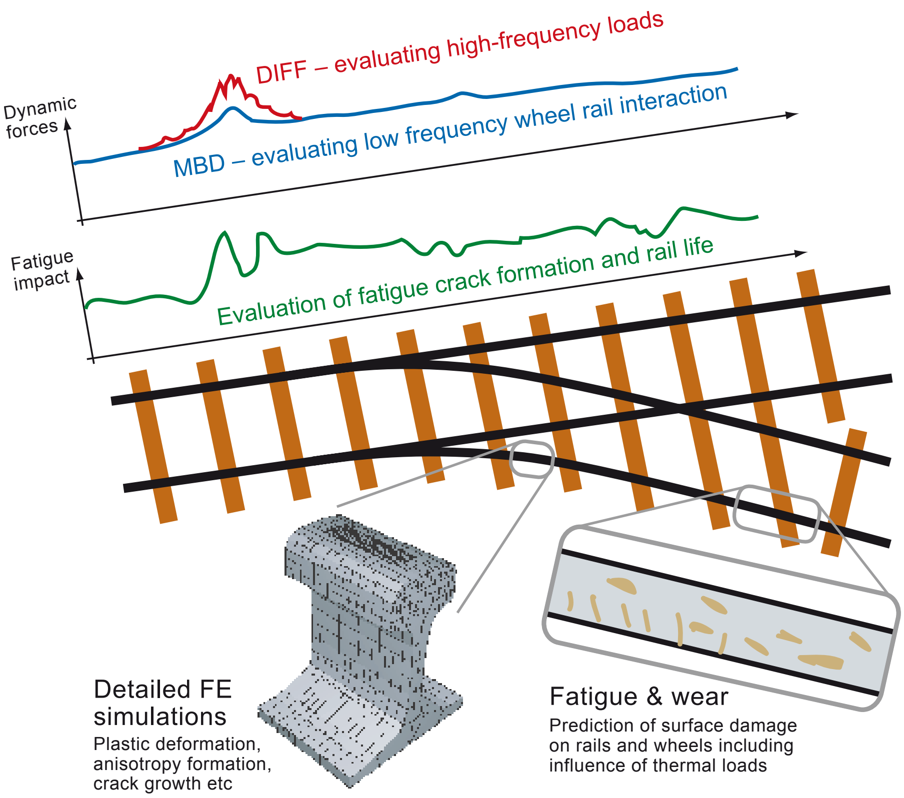
In our opinion, an assessment of the quality and quantity of the results and effects achieved by a Competence Centre like CHARMEC should take the following points into consideration:

- The ability to understand, formulate and "make scientific" the current problems and aims of Trafikverket and the Industrial Interests Group
- The ability to initiate and run general future-oriented projects within the Centre's field of activity
- The publication of scientific works in recognized international journals
- The publication of read papers in the proceedings of recognized international conferences
- The conferring of Licentiate and PhD degrees and the appointment of Docents and Research Professors
- The transfer to Trafikverket and the Industrial Interests Group of information about the results achieved and the implementation of these results at their sites
- The development, nationally and internationally, of the role of the Centre as a partner for dialogue, as an information hub, and as a network builder
- The development and maintaining of high-quality postgraduate education in core areas

During Stage 9, the scientific quality of CHARMEC's research results has been assured through public presentation and criticism at national licentiate seminars and defences of doctoral dissertations, through the presentation of papers at recognized international conferences, and the publication of papers in recognized international journals.

The relevance of our research has been secured through discussions at Board meetings, at seminars, at reference group meetings, and through visits to industrial sites. Our participation in worldwide railway technology congresses, conferences, symposia, workshops and seminars has also contributed to the calibration of CHARMEC's research.

The transfer of knowledge to Trafikverket and the Industry has taken place by means of networking and staff exchanges, through co-operative projects, through orientation and summarizing at seminars, and through informative reports and the handing over of test results and computer programs etc. An important part of this knowledge transfer is the employment of people with a Licentiate or PhD degree from the University at Trafikverket or in the Industry, either directly or through consulting companies.



Overview of simulation models on different scales and with target on different aspects of wheel–rail interaction

PROGRAMME AREAS CHARMEC STAGE 9

According to the Principal Agreement for Stage 9, the Competence Centre CHARMEC should work within six overall programme areas as set out below. The choice of projects within each area is decided by the Board of the Centre. These programme areas for Stage 9 are the same as those during Stages 3, 4, 5, 6, 7 and 8.

Programme area 1

Interaction of train and track

Samverkan Tåg/Spår, TS

A rolling train is a mobile dynamic system that interacts, via the wheel–rail interface, with the stationary track structure, which in turn is a dynamic system. This interaction is a key area within all railway mechanics research. The mechanisms behind vibrations, noise and wear depend on the interplay of the rolling train and the track structure. The activities of this programme area are directed towards being able better to understand, model and predict the dynamic interaction for different types and conditions of trains, tracks and operations. Analytical, numerical and experimental methods are used.

Programme area 2

Vibrations and noise

Vibrationer och Buller, VB

A considerable reduction in vibrations and noise from railway traffic seems to be of crucial importance to the future acceptance of this type of transportation. The generation and spread of vibrations in trains, tracks and environment and the emission of noise are phenomena that are difficult to approach, both theoretically and experimentally. The activities in this programme area are directed towards achieving a better understanding of the underlying mechanisms. Advanced analytical and numerical tools and well-planned laboratory and field experiments and measurements are required. The goal is to establish a basis for effective modifications and counter-measures against vibrations and noise in trains and tracks and in their surroundings.

Programme area 3

Materials and maintenance

Material och Underhåll, MU

Suitable and improved materials for axles, wheels, rails, pads, sleepers, ballast, slabs and embankments are a prerequisite for good mechanical performance, reduced wear, lower maintenance costs and an increased technical/economic life of the components mentioned. The activities in this programme area are directed towards analysing existing materials and developing new materials. A knowledge base should be created for the rational maintenance of train and track components. Co-operation between several different competences are required for this research.

Programme area 4

Systems for monitoring and operation

System för övervakning och Drift, SD

Brakes, bearings, axles, wheels and bogies are important mechanical components of a train with regard to its operational economy and safety. There seems to be considerable potential for improvement for both passenger and freight trains. New components and new ways of improving and supplementing existing functions should be studied. A systems approach is emphasized and the work is performed in a cross-disciplinary environment, drawing on several different academic and industrial competences, including solid mechanics, machine elements, signal analysis, control theory, and computer engineering and mechatronics.

Programme area 5

Parallel EU projects

Parallella EU-projekt, EU

CHARMEC has represented Chalmers University of Technology as a partner in several EU (European Union) projects in railway mechanics since the Fourth Framework Programme in 1996 up to Horizon 2020 including Shift2Rail. All our EU projects are closely related to CHARMEC's ongoing research in programme areas 1, 2, 3 and 4, and CHARMEC contributes to the funding of these EU projects.

Programme area 6

Parallel special projects

Parallella SpecialProjekt, SP

At a meeting on 10 September 2002, the CHARMEC Board decided to gather and list a number of our bilateral agreements and separate research and development projects in railway mechanics under the above heading. This programme area includes both short-term and long-term projects, several of which have been established for the industrial implementation of CHARMEC's research results.

SUMMARY OF CHARMEC STAGE 9

Research at the Centre during Stage 9 (1 July 2018 – 30 June 2021) has been carried out as planned. The Board of CHARMEC met as follows:

7 September 2018	6 February 2020
23 November 2018	28 May 2020
7 February 2019	17 September 2020
23 May 2019	27 November 2020
25 September 2019	16 February 2021
28 November 2019	27 May 2021

Detailed minutes were recorded at all meetings. Early decisions were made concerning the content and funding of projects carried over from Stage 8 and of new projects started during Stage 9. As all CHARMEC parties are represented on the Board, the Board meetings have served as an efficient combination of working group and decision-making body.

Through interviews and with the CHARMEC partners, research needs have been identified and have influenced the Board's decisions regarding the start of new projects during Stage 9. Keywords that summarize the views expressed by Trafikverket and the ten companies are:

faster and lighter vehicles / heavier load,
operationally more reliable and robust,
safer, lower life cycle costs, and
environmentally friendlier

The achievement of these goals requires a holistic employment of cutting-edge knowledge, methods and tools in different areas. To this end, collaboration and research exchange within CHARMEC is highly encouraged.

When selecting new projects to be run by CHARMEC, the Board has, in addition to the potential in achieving the above objectives, also accounted for balances as follows:

fundamental research vs applied research,
doctoral students vs senior researchers,
applicable for the Industry vs
researchable for the University, and
track focus vs vehicle focus

A project catalogue, first developed during Stages 6 and 7 and updated during Stages 8 and 9, contains project ideas that are used when selecting new CHARMEC projects. During Stage 6, a committee from the Board adopted a plan in which stakeholders, competences, visions, strategies and broad and specific goals etc are identified. The document "CHARMEC Corporate Plan – Focus Areas" was produced, and was updated during Stages 7, 8 and 9. Five Focus Areas, in which CHARMEC has a special capability to contribute, were identified: (i) Rails and running gear, (ii) Switches & crossings, (iii) Sleepers and other types of rail support, (iv) Brake systems, and (v) Vibrations and noise.

Furthermore, CHARMEC will be increasingly involved in implementation-oriented research (see figure).

Updated overviews and diagrams of the above balances are distributed and discussed at Board meetings.

Chalmers has profiled its research activities into so-called Areas of Advance (in Swedish: Styrkeområden). During Stage 9, CHARMEC has received financial support from the area Transport.

In 2021, Trafikverket initiated the identification and establishment of so-called areas of excellence in which key research should be carried out. Important objectives were to recognize synergies and enhance implementation, and to find out about further research needs. CHARMEC was involved in this work, and our research is now an important part of this initiative, see page 87.

The staff attached to the Centre during Stage 9 both at Chalmers (21 project leaders/principal advisers/senior researchers and 19 PhD students), at Trafikverket, and in the Industrial Interests Group, have been actively involved. Generally, CHARMEC projects have reference groups, see page 81. Most of these groups consist of members from Trafikverket and the Industrial Interests Group and they normally meet twice per year. These and other meetings between university researchers and industry representatives have led both to an increased involvement in long-term industrial knowledge development and to a deeper insight into the working potential of the University. Mutual learning has been achieved.

Three licentiate theses and nine PhD dissertations in railway mechanics were presented by CHARMEC's doctoral candidates during Stage 9, see page 74. In addition, 54 articles were published (or accepted for publication) in international scientific journals with a referee system, 11 papers were published in the proceedings of international conferences with a referee system, 49 EU reports were delivered, 21 research reports were edited in our own series of research publications, 6 BSc and MSc theses were edited in our own series of student reports, and several other works were published and presented at minor seminars etc.

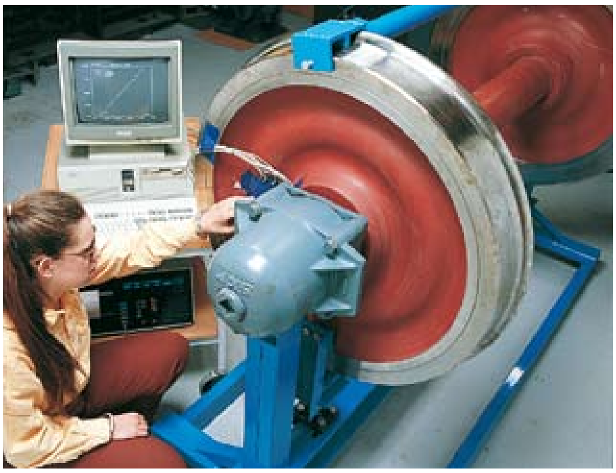
As during Stages 1–8, four seminars (two if held at industrial partners) are usually scheduled in the morning of the day when the Board meets in the afternoon. During these seminars project leaders/supervisors and PhD students present and discuss their projects. As from Stage 4, one partner from Trafikverket or the Industrial Interest Group is also scheduled to present their organizations and expectations for CHARMEC. All CHARMEC Board members, project leaders, researchers and involved persons in the industry (approximately 140 people) are invited to attend these seminars.

Continued participation by CHARMEC researchers in EU projects (Seventh Framework Programme and Horizon 2020) has expanded our collaboration with companies, universities, institutes, public agencies and consultancies all over Europe. The CHARMEC network linked to EU projects during Stage 9 comprised more than 60 organizations in 15 countries; see under projects EU15 and EU17 – EU21. We also co-operate with railway bodies in Australia, Canada, China, Japan, South Africa and the USA.

An indication of the high scientific standards achieved in the activities of the University and the Industry at CHARMEC is the high level of acceptance of articles for journals and contributions to conferences. Around 635 such articles and contributions have been published internationally so far. A total of 63 Licentiate degrees and 54 PhD degrees in railway mechanics have been awarded at Chalmers up to June 2021, see again page 74.

During Stage 9 the presentations from the partners were:

Sven-Ivar Karlsson (at Chalmers)	SNC-Lavalin	7 Sept 2018
Igor Tegeltija (in Gothenburg)	SNC-Lavalin	23 Nov 2018
Anders Ekberg (at Chalmers)	Chalmers	7 Febr 2019
Ann-Christine Svärdby Bergman (in Stockholm)	Trafikverket	23 May 2019
Angela Hillemyr (at Chalmers)	Chalmers	25 Sept 2019
Markus Gardbring (in Eskilstuna)	Green Cargo	28 Nov 2019
Roger Deuce (at Chalmers) Bombardier Transportation		6 Febr 2020
Jan Bergstrand (online)	Trafikverket	17 Sept 2020
Fredrik Blennow (online)	Faiveley	27 Nov 2020
Susanne Rymell (online)	SJ	16 Febr 2021
Ingemar Frej (online)	Trafikverket	27 May 2021



PhD student of project TS3 inspecting an instrumented wheelset in the Chalmers Solid Mechanics laboratory

In contrast to previous reports, the Triennial Reports for Stages 8 and 9 only contain details on those projects (now 40) which have been active during the stage. A list of all 142 projects run by CHARMEC during the years 1995–2021 is given on pages 92–95. The publications listed under the projects have not previously been registered (with exception of project EU17) in CHARMEC's Biennial and Triennial Reports 1 July 1995–30 June 2018 (Stages 1, 2, 3, 4, 5, 6, 7 and 8), or were incomplete at the time (not yet internationally printed). Several minor reports have been omitted. Internal reports that later resulted in international publication, during the same Stage 9, have also been excluded.

The EU1–EU5 projects (all now concluded) belonged to Brite/Euram III under the European Union's Fourth Framework Programme. A list of partners in the EU1–EU5 projects is presented in CHARMEC's Biennial Report for Stage 1. The EU6, EU7 and EU8 projects (also now concluded) belonged to the Fifth Framework Programme. The scope of the EU6, EU7 and EU8 projects and a list of the partners in these projects are presented in CHARMEC's Triennial Report for Stage 3.

The EU9 and EU10 (and EU11) projects belonged to the Sixth Framework Programme. The total scope of the EU9 and EU10 projects and a list of the partners in EU10 are presented in CHARMEC's Triennial Report for Stage 4. The projects EU12, EU13 and EU14 belonged to the Seventh Framework Programme. The total scope of the EU12 and EU13 projects is presented in CHARMEC's Triennial Report for Stage 6. CHARMEC's European project EU15 belonged to the Horizon 2020 Programme whereas EU16–EU21 are part of the Shift2Rail Research and Innovation Action.
The total scope of the EU14 and EU16 projects is presented in CHARMEC's Triennial Report for Stage 8. It should be noted that external access to EU documents supplied by us and others is often limited.

The departments where the 41 listed CHARMEC projects are being (or have been) run are as follows. It should be noted that a new research organization at Chalmers University of Technology came into effect on 1 May 2017 when 13 large departments replaced the previous schools and departments, see page 68 in the Triennial Report for Stage 8.

As for the project budgets presented for Stage 10, these include the sums allocated by the Board up until the meeting on 16 February 2022. The abbreviation LicEng for the doctoral candidates stands for the intermediate academic degree Licentiate of Engineering. The abbreviation S2R for Shift2Rail is used in some of the budgets.

TS8. INTEGRATED TRACK DYNAMICS

Integrerad spårdynamik

Project leader	Professor Jens Nielsen, Mechanics and Maritime Sciences / Division of Dynamics
Doctoral candidate	None (only senior researcher in this project)
Period	2003-10-01 – 2021-06-30 (– 2024-06-30)
Chalmers budget (excluding university basic resources)	Stage 4: KSEK 2 550 Stage 5: KSEK 1 000 Stage 6: KSEK 300 Stage 7: KSEK 850 Stage 8: KSEK 600 Stage 9: KSEK 761 Stage 10: KSEK 400
Industrial interests in-kind budget	Stage 4: KSEK 0 + 400 Stage 5: KSEK 50 + 200 Stage 6: KSEK 50 + 100 Stage 7: KSEK 50 + 100 Stage 8: KSEK 100 + 0 Stage 9: KSEK 100 + 0 Stage 10: KSEK 100 + 0 *(Abetong + Trafikverket)*

For a photo of Jens Nielsen, see page 15

The overall aim of project TS8 is to develop user-friendly computer tools for the rational design of both the whole track and its individual components. Available software from CHARMEC projects for the analysis of dynamic vehicle–track interaction, of wear and rolling contact fatigue (RCF) of wheel and rail, and of ground vibrations and railway noise, is being extended and integrated. Calculated high-frequency wheel–rail contact forces have been validated against measured ones. Our in-house computer program DIFF for simulation of high-frequency vertical vehicle–track interaction has been applied in several CHARMEC projects. Examples of performed studies are analysis of the effect of impact loads generated by wheel flats, design of concrete sleepers for higher axle loads, and specifications of optimum vertical stiffness for ballasted tracks. Part of the project work is devoted to memberships in the scientific committee of IAVSD (International Association for Vehicle System Dynamics), the international committee of IWRN (International Workshop on Railway Noise), and the editorial boards of International Journal of Rail Transportation and Railway Engineering Science.

At the international symposium on Vehicle System Dynamics at Chalmers in August 2019, Jens Nielsen was a member of the organization committee and chaired the international scientific committee, and was co-editor of the proceedings. At the 13th International Workshop on Railway Noise (IWRN13) in Ghent (Belgium) in September 2019, he presented an invited keynote lecture on railway noise and vibration induced by wheel–rail impact. Papers submitted for the book Noise and Vibration Mitigation for Rail Transportation Systems, which includes contributions presented at IWRN13, have been reviewed by Jens Nielsen. He has also evaluated abstracts for the IAVSD symposium in St Petersburg (Russia) in August 2021 and he was an invited speaker at UIC Railway Noise Days in February 2021.

Jens Nielsen reviewed the final report, as issued by KTH, on the influence of different types of wheel tread brakes on railway noise. He participated in meetings with Abetong and Trafikverket regarding cracks in sleepers that have been detected in switches and crossings.

The work in project TS8 also includes the planning, preparation, support and follow-up of research proposals. Examples are the newly launched projects TS21 and TS22, and also contributions to the EU project proposal In2Track3. Jens Nielsen gave his lecture 'Introduction to train–track dynamics' at NBIU (Nordisk Banteknisk Ingenjörsutbildning) in Tällberg in September 2019.

Matthias Germonpré, Jens Nielsen, Geert Degrande and Geert Lombaert: Contributions of longitudinal track unevenness and track stiffness variation to railway induced vibration, *Journal of Sound and Vibration*, vol 437, 2018, pp 292–307
doi.org/10.1016/j.jsv.2018.08.060

Peter Torstensson, Giacomo Squicciarini, Matthias Krüger, Björn Pålsson, Jens Nielsen and David Thompson: Wheel–rail impact loads and noise generated at railway crossings – influence of vehicle speed and crossing dip angle, *Journal of Sound and Vibration*, vol 456, 2019, pp 119–136
doi.org/10.1016/j.jsv.2019.04.034

Matthijs Klomp, Fredrik Bruzelius, Jens Nielsen and Angela Hillemyr (editors): Advances in Dynamics of Vehicles on Roads and Tracks, *Proceedings 26th Symposium of the International Association of Vehicle System Dynamics (IAVSD2019)*, Gothenburg (Sweden) August 2019. *In: Lecture Notes in Mechanical Engineering*, Springer Nature Switzerland AG, Cham (Switzerland) 2020, 1917 pp

Geert Degrande, Geert Lombaert, David Anderson, Paul de Vos, Pierre-Etienne Gautier, Masanobu Iida, James Nelson, Jens Nielsen, David Thompson, Thorsten Tielkes and David Towers (editors): Noise and Vibration Mitigation for Rail Transportation Systems, *Proceedings 13th International Workshop on Railway Noise (IWRN13)*, Ghent (Belgium) September 2019. *In: Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, Springer Nature Switzerland AG, Cham (Switzerland), vol 150, 2021, 720 pp

Jens Nielsen, Astrid Pieringer, David Thompson and Peter Torstensson: Wheel–rail impact loads, noise and vibration – a review of excitation mechanisms, prediction methods and mitigation measures, *Proceedings 13th International Workshop on Railway Noise (IWRN13)*, Ghent (Belgium) September 2019, pp 3–40 (also listed under project VB12)

TS15. IMPROVED AVAILABILITY AND REDUCED LIFE CYCLE COST OF TRACK SWITCHES

Förbättrad tillgänglighet och minskad livscykelkostnad för spårväxlar

Project leader and supervisor	Professor Jens Nielsen, Mechanics and Maritime Sciences / Division of Dynamics
Assistant supervisors	Professor Elena Kabo, Mechanics and Maritime Sciences, and Docent Peter Torstensson, VTI (see page 85)
Doctoral candidate	Ms Xin Li (from 2012-01-09; Lic Eng November 2014; PhD September 2019)
Period	2011-07-01 – 2019-09-30 (–2020-04-30)
Chalmers budget (excluding university basic resources)	Stage 6: kSEK 725 Stage 7: kSEK 2704 Stage 8: kSEK 1757 Stage 9: kSEK 545 (+ 195 in S2R)
Industrial interests in-kind budget	Stage 6: kSEK 0 + 0 + 0 Stage 7: kSEK 200 + 200 + 200 Stage 8: kSEK 200 + 0 + 200 Stage 9: kSEK 50 + 0 + 100 *(Abetong + Trafikverket + voestalpine)*

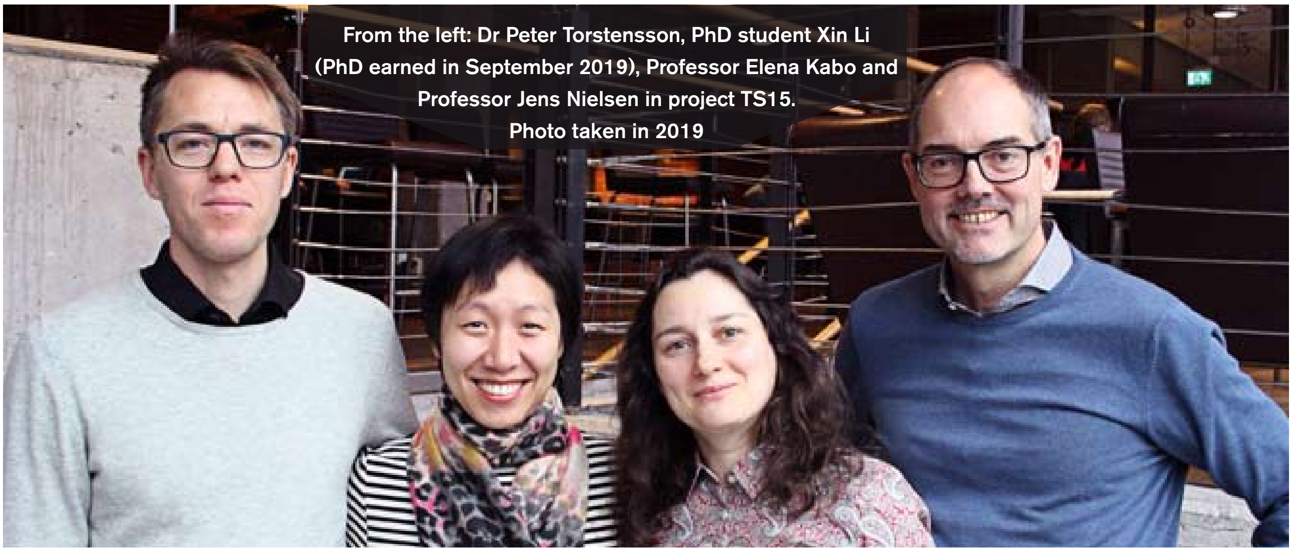
The project was mainly financed by Trafikverket via LTU (through CHARMEC's budget)

The aim of project TS15 has been to develop methods that will reduce the need for maintenance of switches and crossings (S&C), thereby bringing down traffic disturbances and life cycle costs. In particular, the understanding of parameters affecting track geometry degradation caused by the settlement of ballast and soil has been increased. Product development of S&C, based on optimal use of resilient elements and leading to lower dynamic forces and reduced irregularities in track geometry, has been supported.

Models of wheel–rail contact and dynamic interaction between vehicle and S&C, and finite element (FE) calculations of stresses and strains in ballast/soil, have been used to predict wheel–rail contact forces and track geometry degradation. The methodology developed by us in INNOTRACK (our project EU10) has been applied.

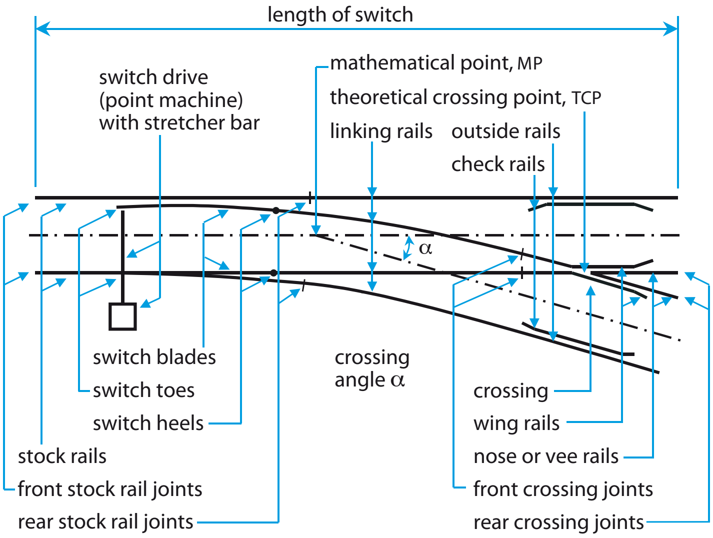
A model for the simulation of high-frequency vertical dynamic vehicle–track interaction in a railway crossing has been launched. Here the vehicle–track interaction is simulated in the time-domain based on a moving Green's function approach for the track in combination with an implementation of Kalker's variational method to solve the problem of the non-Hertzian, and potentially multiple, wheel–rail contact. Non-symmetric vertical loading on the inner and outer rails in the crossing panel is considered, and the variation of cross-sectional properties in the FE model of the rails, as well as the properties of rail pads and sleepers (bearers), have been specified according to data supplied by the CHARMEC partner voestalpine. The variation in three-dimensional contact geometry of crossing rail, wing rail and wheel has been described by use of linear surface elements. In each time step of the contact detection algorithm, the lateral position of the wheelset centre is prescribed but the contact positions on wheel and rail are not, allowing for an accurate prediction of the wheel's transition between wing rail and crossing rail.

It was found that the magnitude of the impact load is influenced more by the wheel–rail contact geometry than by the selected rail pad stiffness. A parameter study has been performed to investigate the influence of the sleeper bottom width, the rail pad stiffness and an implementation of under sleeper pads (USP) on the variation in vertical static track stiffness at rail level, the maximum wheel–rail contact force and the load transferred to the track bed. Based



From the left: Dr Peter Torstensson, PhD student Xin Li (PhD earned in September 2019), Professor Elena Kabo and Professor Jens Nielsen in project TS15. Photo taken in 2019

TS15. (cont'd)



Sketch of a right-hand railway turnout with terminology for "switch and crossing work" according to the European standard EN 13232-1 of September 2003. The tangent of the turnout angle is usually given, e g, tan $\alpha = 1{:}9$ or 1:12. Often one of the terms "switch" or "turnout" is used for the complete structure consisting of the so-called switch, closure and crossing panels. Switches are sometimes referred to as "points"

on the investigated design space for the crossing panel and the calculated maximum values of the selected dynamic responses, it was concluded that a design with a combination of increased sleeper width, softer rail pads and implementation of USP will reduce the track stiffness gradients in the crossing panel and thereby mitigate the risk of differential track settlement through the lowering the sleeper–ballast contact pressure.

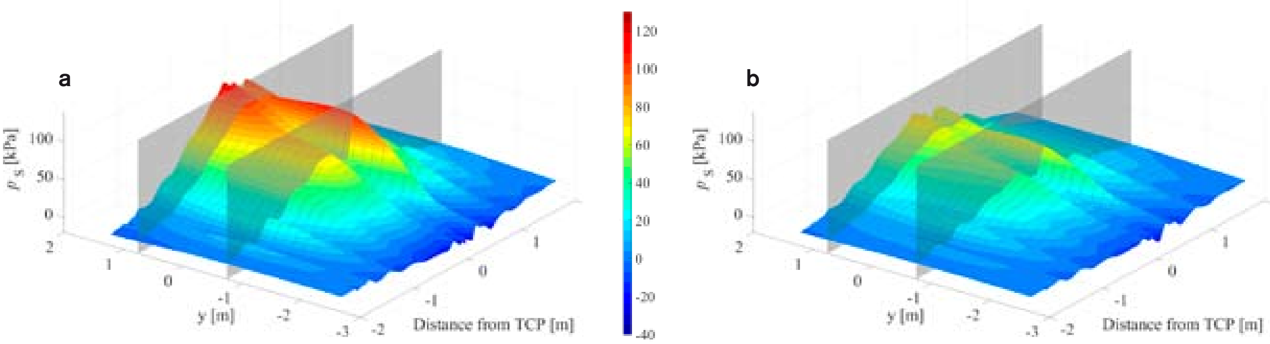
The reference group for the present project had members from Abetong, voestalpine, Vossloh Nordic and Trafikverket. Project TS15 was presented and discussed during the biannual workshops with participants from University of Leoben (Austria), Virtual Vehicle (Austria), voestalpine and CHARMEC, see page 83. Xin Li successfully defended her doctoral thesis, see below, on 26 September 2019 with Dr Yann Bezin from University of Huddersfield (UK) as the faculty-appointed external examiner.

Xin Li continued her employment for about three months during the spring 2020. A user's guide for the model and the computer program, as developed in TS15, were then written. A script has been created that can generate a solid element track structure including rails, sleepers and ballast for the purpose of being implemented into the MBS code SIMPACK (part of the work in project EU19 In2Track2). Different techniques for modelling the coupling between rail and sleeper in a track model constructed from solid elements have been evaluated.

Xin Li, Jens Nielsen and Peter Torstensson: Prediction of vertical dynamic vehicle–track interaction and sleeper–ballast contact pressure in a railway crossing, *Proceedings 26th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2019)*, Gothenburg (Sweden) August 2019, pp 397–403

Xin Li: Wheel–rail impact loads and track settlement in railway crossings, Doctoral Dissertation, *Chalmers Mechanics and Maritime Sciences*, Gothenburg September 2019, 131 pp (Summary and four appended papers)

Xin Li, Jens Nielsen and Peter Torstensson: Simulation of wheel–rail impact load and sleeper–ballast contact pressure in railway crossings using a Green's function approach, *Journal of Sound and Vibration*, vol 463, 2019, article 114949, 16 pp (also listed under project EU19)



Calculated time history of sleeper–ballast contact pressure distribution p_S for sleeper below the crossing for (a) nominal crossing panel design and (b) design with wider sleeper bottom and implementation of USP. Co-ordinate y along sleeper with centre line of through route at $y = 0$ m, crossing rail seat at $y = -0.75$ m and outer rail seat at $y = 0.75$ m. Time axis has been converted to distance from theoretical crossing point (TCP)

TS17. OPTIMIZATION OF MATERIALS IN TRACK SWITCHES

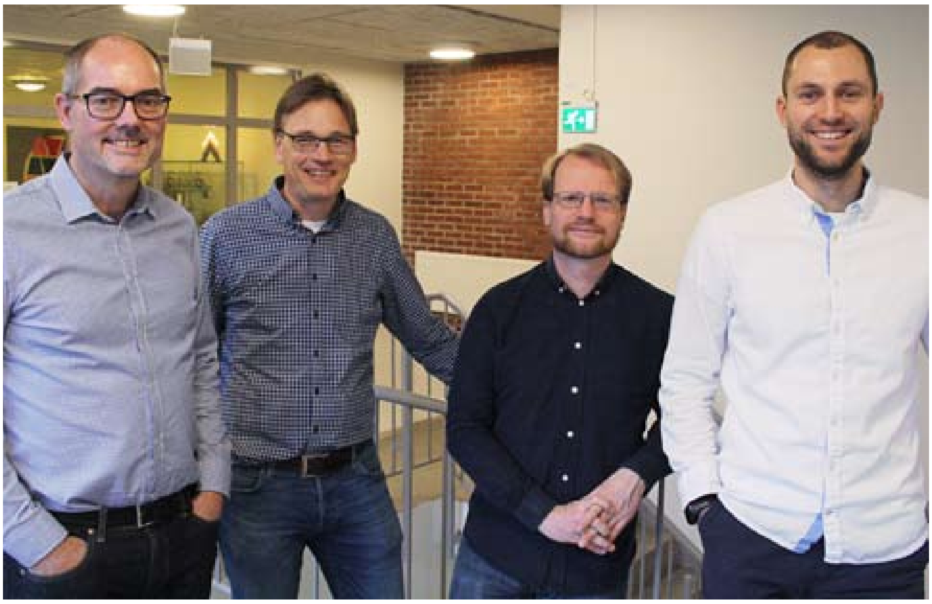
Optimering av material i spårväxlar

Project leaders and supervisors	Professor Jens Nielsen, Mechanics and Maritime Sciences / Division of Dynamics, and Professor Magnus Ekh, Industrial and Materials Science / Division of Material and Computational Mechanics
Assistant supervisor	Dr (now Docent) Björn Pålsson, Senior Lecturer, Mechanics and Maritime Sciences
Doctoral candidate	Mr Rostyslav Skrypnyk (from 2015-05-26; Lic Eng June 2018, PhD June 2020)
Period	2015-05-26–2020-06-30 (–2020-12-31)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 150 Stage 8: KSEK 2 200 (+ 1090 in S2R) Stage 9: KSEK 67 (+ 2016 in S2R)
Industrial interests in-kind budget	Stage 7: KSEK 15 + 50 + 100 Stage 8: KSEK 0 + 0 + 300 Stage 9: KSEK 0 + 0 + 300 *(SL + Trafikverket + voestalpine)*

The aim of project TS17 was to increase the understanding of the long-term degradation and damage modes of different crossing materials. The selected material should produce a crossing that for a given traffic scenario is stable in rail profile geometry and has a long service life and a low life cycle cost. The iterative methodology, developed in INNOTRACK (our project EU10), for the prediction of rail profile degradation in track switches by integrating several cross-disciplinary numerical models and tools, was applied and extended. Robustness and computational efficiency of the methodology was improved by formulating a meta-model for the elastoplastic wheel–rail contact, see the Triennial Report for Stage 8. The models were calibrated and validated versus damaged rail profiles measured in the field.

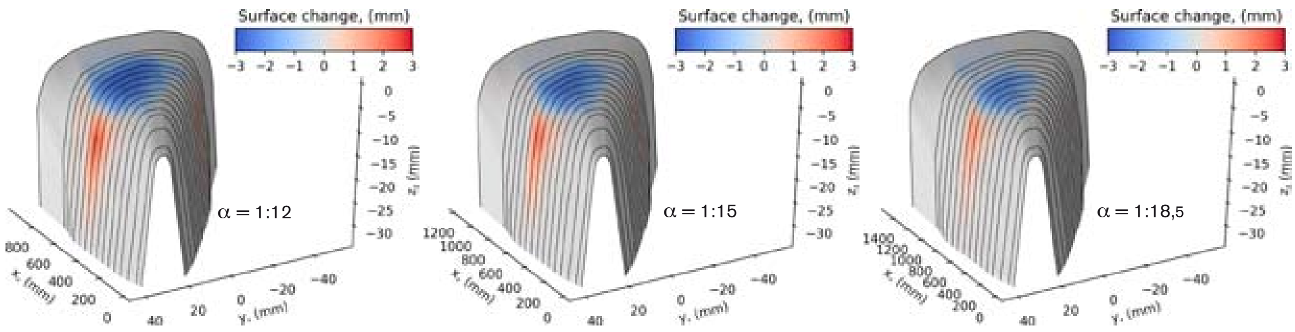
Based on work in project TS13, a model of the three-dimensional dynamic interaction between a vehicle and the crossing panel has been developed and used to assemble a load collective for a crossing accounting for variations in vehicle speed, in worn wheel profile and in wheel–rail friction. Each combination of simulation parameters was constructed using Latin hypercube sampling, assuring a certain spread of random variables in each sample. For the considered traffic conditions, the load collective provides information about the distribution of locations and magnitudes of the high-frequency impact loads generated on the crossing.

Using laboratory data from cyclic testing, calibrations of material models for the simulation of accumulated plastic deformation have been performed for the two rail grades rolled Mn13 and R350HT. The calibrated models are able to capture the ratchetting strain from the laboratory experiments, and the calculated plastic deformations have been compared for the most loaded cross-section of the crossing nose for an accumulated traffic load equivalent to 0.80 million gross tonnes (MGT). The rolled manganese steel deformed about 3.5 times more than the R350HT. A numerical tool for the calculation of rail wear using FASTSIM and the Archard model has also been developed. In this case, the wear model was calibrated versus field measurements of wear in a manganese crossing in Austria. The estimated wear was found to be about only 2% of the predicted plastic deformation.



From the left: Professor Jens Nielsen, Professor Magnus Ekh, Senior Lecturer Björn Pålsson and PhD student Rostyslav Skrypnyk (PhD earned in June 2020) in project TS17. Photo taken in 2019

TS17. (cont'd)



Calculated normal surface change due to accumulated wear and plastic deformation after 65 MGT of traffic on a crossing nose of grade Mn13 for three turnout angles α. Negative values represent inward direction

The wear code has been optimized by parallelization and by pre-allocation of arrays, while the plasticity code has been improved to enable convergence with larger time steps. The simulation time for each iteration (corresponding to an accumulated traffic load of 0.05 MGT) of long-term damage was in the order of 3.5 hours.

In parallel, an extensive measurement campaign was carried out by our partner voestalpine at a test site in Austria on a particularly severely loaded crossing manufactured from an explosion depth-hardened manganese steel grade. For an accumulated traffic load of 65 MGT, the evolution of profile degradation for 16 cross-sections along the crossing rail was recorded on multiple occasions. The results from the measurement campaign were used to validate the simulation methodology. It was found that the predicted rail profile degradation exceeded the measured degradation for some of the cross-sections but generally a good qualitative agreement was observed. Possible reasons for the higher predicted damage were the uncertain distribution of traffic at the test site and differences in material properties between the crossing in the field and the laboratory test specimens used for calibration of the cyclic plasticity model. It was shown that the frequency of updating the rail profiles in the simulations of short-term vehicle–track dynamics is important when the crossing is new but plays a less significant role over time, i e, different frequencies of updating yield similar results after about 3 MGT of simulated traffic. This serves as a verification of the assumptions made in the simulation methodology.

For a given traffic scenario, the long-term rail damage evolution of three crossings with different crossing angles α has been evaluated and compared. For an accumulated traffic load of 65 MGT, the simulations confirmed that a larger crossing angle is associated with more plastic deformation and wear. It was predicted that a crossing with (the largest) 1:12 crossing angle would experience about two times more plastic deformation and three times more wear than a crossing with (the smallest) 1:18.5 angle, see figure above.

Project TS17 was presented and discussed during bi-annual workshops with participants from University of Leoben (Austria), Virtual Vehicle (Austria), voestalpine and CHARMEC, see page 83. Rostyslav Skrypnyk succesfully defended his doctoral thesis on 5 June 2020 with Dr Valeri Markine from Delft University of Technology (The Netherlands) as the faculty-appointed external examiner.

Rostyslav Skrypnyk continued his employment until 2020-12-31. The methodology developed in the project has been used in a collaborative study aiming at benchmarking different tools for the prediction of rail damage in S&C (part of the work in project EU19 In2Track2). A user's guide for the simulation methodology has been written.

Rostyslav Skrypnyk, Jens Nielsen, Magnus Ekh and Björn Pålsson: Metamodelling of wheel–rail normal contact in railway crossings with elasto-plastic material behaviour, *Engineering with Computers*, vol 35, issue 1, 2019, pp 135–155

Rostyslav Skrypnyk, Magnus Ekh, Jens Nielsen and Björn Pålsson: Prediction of plastic deformation and wear in railway crossings – comparing the performance of two rail steel grades, *Wear*, vols 428–429, 2019, pp 302–314

Rostyslav Skrypnyk, Jens Nielsen, Björn Pålsson and Magnus Ekh: Prediction of long-term damage in railway crossings accounting for variability in dynamic traffic loads, *Proceedings 26th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2019)*, Gothenburg (Sweden) August 2019, pp 376–381

Rostyslav Skrypnyk, Uwe Ossberger, Björn Pålsson, Magnus Ekh and Jens Nielsen: Long-term rail profile damage in a railway crossing – field measurements and numerical simulations, *Wear*, vols 472–473, 2021, article 203331, 13 pp (also listed under project EU19)

Rostyslav Skrypnyk, Björn Pålsson, Jens Nielsen and Magnus Ekh: On the influence of crossing angle on long-term rail damage evolution in railway crossings, *International Journal of Rail Transportation*, 2021, 18 pp, (also listed under project EU19) doi.org/10.1080/23248378.2020.1864794

Rostyslav Skrypnyk: Long-term rail damage evolution in railway crossings, Doctoral Dissertation, *Chalmers Mechanics and Maritime Sciences*, Gothenburg June 2020, 116 pp (Summary and four appended papers)

TS18. NUMERICAL SIMULATIONS OF TRAIN–TRACK DETERIORATION AS A BASIS FOR RAMS AND LCC ANALYSES

Numeriska simuleringar av tågets och spårets nedbrytning som bas för RAMS- och LCC-analyser

Project leader	Docent Björn Pålsson, Mechanics and Maritime Sciences / Division of Dynamics
Doctoral candidate	None (only senior researcher in this project)
Period	2014-03-01 – 2021-06-30 (–2024-06-30)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 000 Stage 8: KSEK 780 (+ 191 in S2R) Stage 9: KSEK 300 (+ 1 749 in S2R) Stage 10: KSEK 300 (+ 1 600 in S2R)
Industrial interests in-kind budget	Stage 7: KSEK 15 + 50 + 0 + 100 Stage 8: KSEK 0 + 0 + 0 + 0 + 0 Stage 9: KSEK 0 + 0 + 200 + 0 Stage 10: KSEK 0 + 0 + 100 + 0 *(SL + Trafikverket + voestalpine + ÅF/AFRY)*

For a photo of Björn Pålsson, see page 25

Project TS18 aims to develop methods that can provide high-quality deterioration estimates as input to RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life Cycle Cost) analyses of railway components. RAMS and LCC are general frameworks which are highly sensitive to the quality of input parameters. The goal is thus to enhance predictive capabilities of these methods leading to significant cost reductions for railway operations due to improvements in investment and maintenance strategies. To this end, the methods developed should provide robust estimates of degradation rates for chosen components in the railway system as functions of given traffic scenarios. The methods are being based on numerical simulations of train–track interaction that can account for the scatter in traffic parameters such as vehicle type, train speed, wheel and rail profiles etc.

A framework for simulation of dynamic interaction between vehicles and switches and crossings (S&C) has been established using the commercial multibody simulation code SIMPACK. The framework allows for an automated evaluation of different S&C configurations under load collectives. This is made possible via a parameterized generation of finite element S&C track models, a procedure that allows for the realization of different S&C track designs, for example, with different radii or rail profile geometries.

This framework has been applied to evaluate the structural loading for a crossing panel as a function of crossing geometry degradation spanning 65 MGT of traffic. The results showed that the maximum sleeper–ballast contact pressure, the maximum bending moments in the crossing rail and the sleeper underneath the crossing transition all increase monotonically with increasing crossing geometry degradation, which is coupled to the accumulated traffic load. The wheel–rail contact pressure was found to have a contrasting trend in that it started at a high level and then decreased as the crossing geometry adapted itself to passing wheels but then rose again for the crossing geometry corresponding to the highest tonnage (65 MGT).

The simulation framework has been developed as part of a greater effort within the EU projects In2Track and In2Track2 (our EU17 and EU19) to develop a so-called Whole System Model (WSM). The purpose of the WSM is to allow for virtual LCC performance evaluations of S&C designs by combining state-of-the-art simulation models. A demonstration of the WSM procedure has been made together with Virtual Vehicle and Materials Center Leoben, both in Austria, within the In2Track2 project.

An international S&C simulation benchmark has been organized by us together with Yann Bezin at the University of Huddersfield in the UK. The purpose of this Benchmark has been to (a) compare the capability of different software to simulate dynamic vehicle–track interaction in S&C and (b) create a published reference case including input rail geometry and track data that can be used by academia as well as industry. Nine different software were used and eighteen independent institutions participated in the Benchmark.

Björn Pålsson: A parameterized turnout model for simulation of dynamic vehicle-turnout interaction with an application to crossing geometry assessment, *Proceedings 26th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2019)*, Gothenburg (Sweden) August 2019, pp 351–358 (also listed under project EU19)

Yann Bezin and Björn Pålsson: Multibody simulation benchmark for dynamic vehicle-track interaction in switches and crossings – modelling description and simulation tasks, *Vehicle System Dynamics*, 2021, 16 pp (also listed under project EU19) doi.org/10.1080/00423114.2021.1942079

Yann Bezin, Björn Pålsson, Walter Kik, Patricia Schreiber, James Clarke, Volker Beuter, Michel Sebès, Ingemar Persson, Hugo Magalhaes, Ping Wang and Peter Klauser: Multibody simulation benchmark for dynamic vehicle-track interaction in switches and crossings – results and method statements, *Vehicle System Dynamics*, 2021, 38 pp doi.org/10.1080/00423114.2021.1959038

Klaus Six, Kamil Sazgetdinov, Nishant Kumar, Gabor Müller, Dino Velic, Werner Daves, Rostyslav Skrypnyk and Björn Pålsson: A whole system model framework to predict damage in turnouts, *Vehicle System Dynamics*, 2021, 21 pp doi.org/10.1080/00423114.2021.1988116

Björn Pålsson, Ramakrishnan Ambur, Michel Sebès, Ping Wang, Jou-Yi Shih, Demeng Fan, Jingmang Xu and Jiayin Chen: A comparison of track model formulations for simulation of dynamic vehicle-track interaction in switches and crossings, *Vehicle System Dynamics*, 2021, 27 pp (also listed under project EU19) doi.org/10.1080/00423114.2021.19831832021

TS19. DESIGN CRITERIA FOR SLAB TRACK STRUCTURES

Designkriterier för ballastfria spår

Project leader and supervisor	Professor Jens Nielsen, Mechanics and Maritime Sciences / Division of Dynamics
Assistant supervisors	Dr Rikard Bolmsvik, Abetong, and Professor Anders Ekberg, Mechanics and Maritime Sciences
Doctoral candidate	Mr Emil Aggestam (from 2016-07-01; Lic Eng May 2018; PhD June 2021)
Period	2016-07-01 – 2021-06-30
Chalmers budget (excluding university basic resources)	Stage 8: KSEK 1 760 (+ 145 in S2R) Stage 9: KSEK 1 515 (+ 1 630 in S2R)
Industrial interests in-kind budget	Stage 8: KSEK 0 Stage 9: KSEK 250 *(Abetong)*

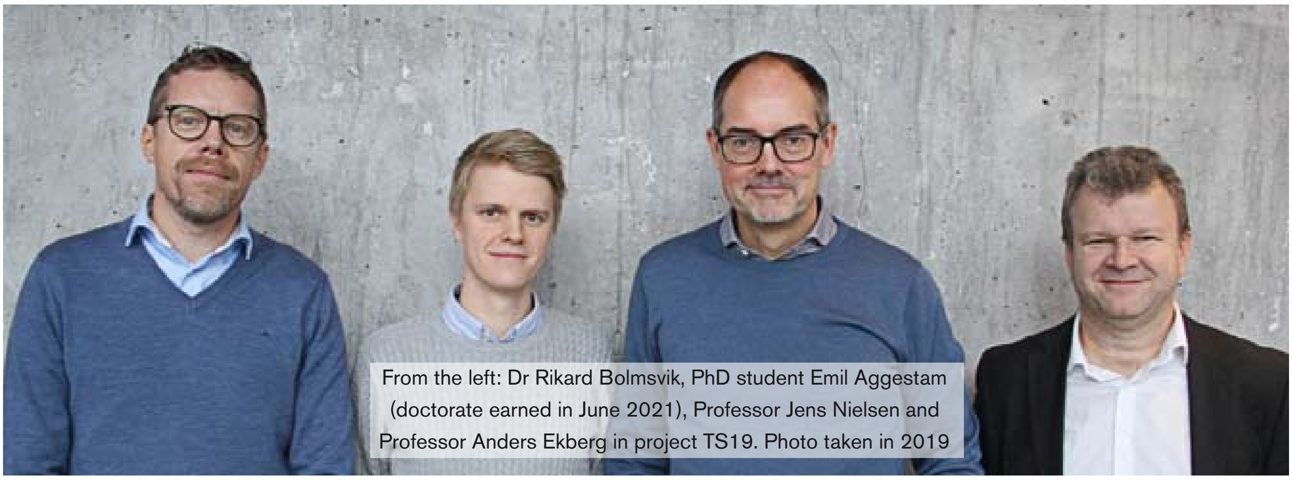
According to technical specifications issued by Trafikverket, the construction of future high-speed lines in Sweden may be based on a slab track design (see photo on page 24). Project TS19 aims at providing a scientific foundation for the specification of slab tracks under Swedish conditions. Vertical dynamic interaction between high-speed trains and track has been studied using a model that includes a three-dimensional description of the slab track structure on a Winkler-type foundation. The influence of stiffness gradients in the supporting foundation along and across the slab has been investigated and transition zones between different track forms have been studied. Wheel–rail contact forces, contact pressure between slab and foundation, and stresses in the concrete structure have been analysed considering wheel/track irregularities and the influence of cracks. Different slab track designs available on the market have been compared with a conventional ballasted track design. Project TS19 was run in parallel with work in the EU programme Shift2Rail.

Two- and three-dimensional models of the vertical dynamic interaction between vehicle and slab track have been implemented in the in-house computer program DIFF (see project TS8), and procedures to assess the performance of the track have been derived. The vehicle model is a mass–spring–damper model of one car body and two bogies. Based on the input to a PYTHON script, the track representation is a generic finite element model in ABAQUS that includes two discretely supported rails modelled as beams and a 3D description of the panel and roadbed using shell or hexahedral (brick) elements. The continuous or decoupled sections of concrete panel rest on a Winkler foundation, see figure. The system matrices are exported to MATLAB, where a 3D version of DIFF has been developed.

It was observed that geometric wheel and rail imperfections may have a significant impact on the wheel–rail contact force and on the bending moments in the concrete panels. A thicker roadbed will distribute the load on the foundation over a longer distance, while a lower rail pad stiffness will reduce the bending moments in the concrete panels.

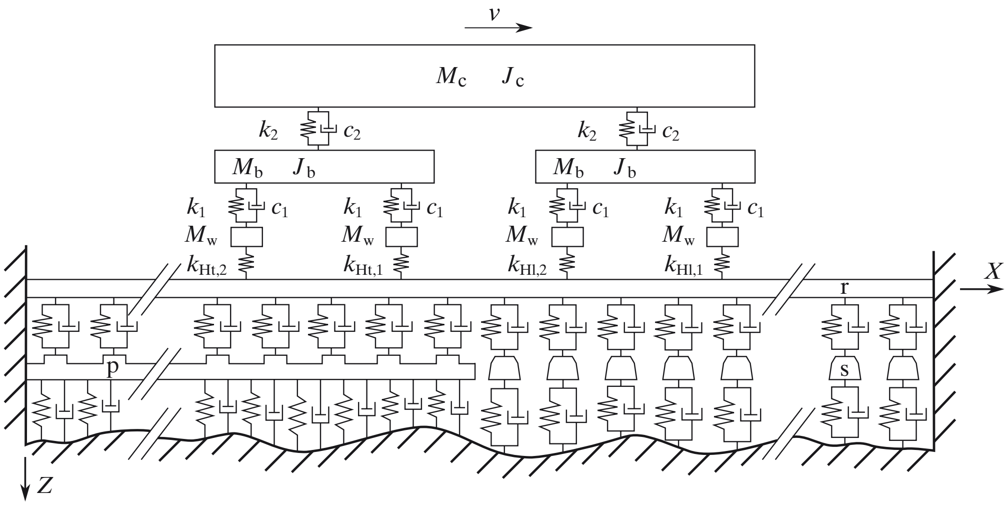
Models of ballasted track and slab track have been combined to study dynamic vehicle–track interaction in transition zones. Based on a genetic algorithm, a multi-objective optimization methodology has been developed to minimize the dynamic loads. By using an optimum distribution of rail pad stiffness and sleeper spacing in the transition zone, the wheel–rail contact force, the load between sleeper/panel and foundation and the vertical bogie acceleration can be reduced significantly. To reduce dynamic loads, a short transition zone (< 5 m) was found to be sufficient, whereas a longer transition zone may be required to minimize dynamic vehicle responses, e g, related to ride comfort.

Emil Aggestam and Jannik Theyssen (project VB13) visited the Southwest Jiaotong University (SWJTU) in Chengdu (China) and performed measurements of slab track dynamics in their full-scale test rig during two weeks in April 2019.



From the left: Dr Rikard Bolmsvik, PhD student Emil Aggestam (doctorate earned in June 2021), Professor Jens Nielsen and Professor Anders Ekberg in project TS19. Photo taken in 2019

TS19. (cont'd)



Schematic cross-section of 3D slab track model under a travelling train model in project TS19

Calculated frequency response functions (FRFS) have been compared with the corresponding FRFS measured in the test rig. For the multiple excitation positions and sensor locations, it was found that the calibrated track model captures the trend of the Single-Input Multiple-Output measurements with relatively small deviations compared to the overall dynamic range.

A disadvantage of slab track compared to conventional ballasted track is that the overall environmental impact of the construction is larger due to the significant amount of concrete required. Here, the dimensions of the rectangular cross-sections and types of concrete used in slab tracks have been optimized with the objective to minimize greenhouse gas emissions, while considering the constraint that the design must pass the static dimensioning analysis described in the European standard 16432-2. The optimized track design was also analysed using the three-dimensional (3D) model of vertical dynamic vehicle–track interaction. The magnitude of the dynamic loads was found to vary significantly depending on which track class from the European standard 13848-6 that was considered. For the given traffic scenario at vehicle speed 250 km/h, the ratio between the maximum dynamic wheel–rail contact force and the static load is around 1.2 for track class A and 1.7 for track class E. This can be compared with the standard where the prescribed ratio is 1.50 independent of train speed and level of track irregularities.

In parallel, a model of reinforced concrete has been developed to predict crack widths and bending stiffness of a cracked panel section, and also to assess whether the amount of steel reinforcement can be reduced.

Emil Aggestam successfully defended his PhD thesis (see below) on 11 June 2021, with Professor Ernesto García Vadillo from the University of the Basque Country in Spain acting as the faculty-appointed external examiner. For the joint reference group, see under project VB13.

The employment of Emil Aggestam was prolonged until 2021-12-31 and from 2021-09-01 he was employed as a post-doc and continued his work in In2Track3 (EU21). In terms of structural integrity and robustness, life cycle cost (LCC) and environmental footprint, innovative requirements for next-generation slab track solutions have been established. Setting out from current standards, possible improvements were addressed, and guidelines on how to handle new innovative slab track designs have been presented.

Emil Aggestam, Jens Nielsen and Niklas Sved: Simulation of dynamic vehicle–track interaction – comparison of two- and three-dimensional models, *Proceedings 26th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2019)*, Gothenburg (Sweden) August 2019, pp 415–422 (also listed under project EU19)

Emil Aggestam and Jens Nielsen: Simulation of vertical dynamic vehicle–track interaction using a three-dimensional slab track model, *Engineering Structures*, vol 222, 2020, article 110972, 16 pp (also listed under project EU19)

Jannik Theyssen, Emil Aggestam, Shengyang Zhu, Jens Nielsen, Astrid Pieringer, Wolfgang Kropp and Wanming Zhai: Calibration and validation of the dynamic response of two slab track models using data from a full-scale test rig, *Engineering Structures,* vol 234, 2021, article 111980, 17 pp (also listed under projects VB13 and EU19)

Emil Aggestam: Slab track optimisation considering dynamic train–track interaction, Doctoral Dissertation, *Chalmers Mechanics and Maritime Sciences*, Gothenburg June 2021, 184 pp (Summary and five appended papers)

Emil Aggestam: Comparison of the dynamic response and environmental impact between traditional and innovative railway track systems, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2021, 28 pp (submitted for publication)

Emil Aggestam, Anders Ekberg and Jens Nielsen: Innovative requirements and evaluations for slab track structures, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2022, 16 pp (submitted for publication)

Emil Aggestam, Jens Nielsen, Karin Lundgren, Kamyab Zandi and Anders Ekberg: Optimisation of slab track design considering dynamic train–track interaction and environmental impact, *Engineering Structures*, vol 254, 2022, article 113749, 15 pp

TS20. WHEEL TREAD DAMAGE – IDENTIFICATION AND EFFECTS

Löpbaneskador på hjul – identifiering och konsekvenser

Project leader and supervisor	Professor Elena Kabo, Mechanics and Maritime Sciences / Division of Dynamics
Assistant supervisors	Professor Anders Ekberg, Professor Jens Nielsen and Docent Tore Vernersson, Mechanics and Maritime Sciences
Doctoral candidate	Mr Michele Maglio (from 2018-02-01; Lic Eng October 2020)
Period	2018-02-01 – 2021-06-30 (– 2023-01-31)
Chalmers budget (excluding university basic resources)	Stage 8: KSEK 400 (+ 301 in S2R) Stage 9: KSEK 1 200 (+ 1 838 in S2R) Stage 10: KSEK 1 310 (+ 510 in S2R)
Industrial interests in-kind budget	Stage 8: KSEK 0 + 0 + 0 + 0 Stage 9: KSEK 200 + 100 + 100 + 100 Stage 10: KSEK 50 + 50 + 50 + 50 *(Bombardier Transportation / Alstom + Faiveley Transport + Green Cargo + Lucchini Sweden)*

Wheel tread damage is accompanied by increased wheel–rail contact forces whose magnitudes depend on the type and shape of the geometric irregularity and on the characteristics of the dynamic vehicle–track system. High vertical loads due to tread defects imply an increased risk of wheel fatigue (and also damage to axles and bearings etc). To limit the risk of a catastrophic failure of the running gear (and the track), there are operational limits on allowed wheel impact loads. Based on field measurements and results from numerical simulations of dynamic vehicle–track interaction, project TS20 started by establishing wheel–rail contact forces and axle stresses resulting from different types of wheel tread conditions. Fatigue stress spectra were obtained for the running gear. The influence of tread defects and operational conditions, in particular train speed and track quality, on fatigue damage is being investigated.

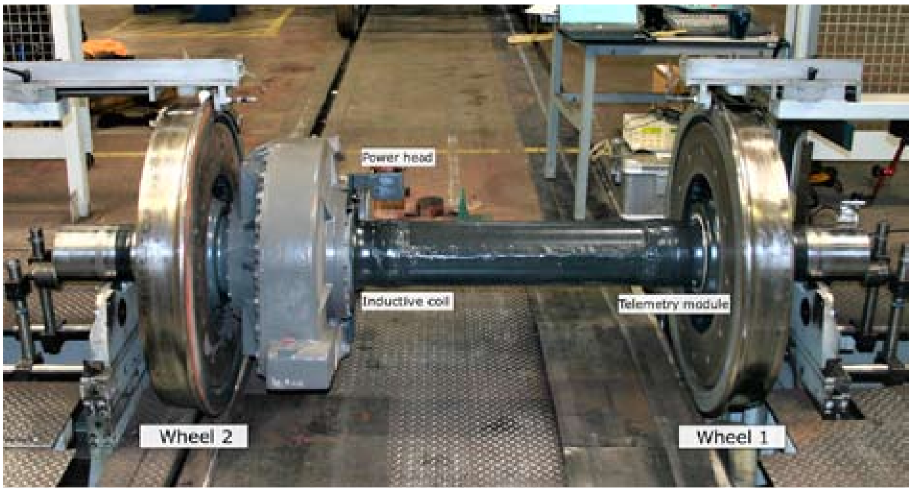
The in-house software WERAN (WhEel/RAil Noise), first developed in project VB10, has been extended for simulation of dynamic vehicle–track interaction. The software allows for computing wheel–rail contact forces and contact stresses in the time-domain. New implementations make it possible to consider the cross-coupling between the two wheels in a wheelset, as well as between the two rails in the track. By post-processing the calculated contact forces, stresses in the wheelset can be evaluated.

A field test was performed in collaboration with SJ and Trafikverket in April 2018. Wheel–rail contact loads generated by the passage of a wheelset with tread damage over a wayside wheel impact load detector were measured for different vehicle speeds, showing that peak impact loads increase linearly with the speed of the train within the tested range from 10 km/h up to 100 km/h. The damaged tread surfaces have been scanned and identified defects have been used as input to the simulation model. The maximum wheel–rail contact forces calculated in WERAN showed good agreement with those found in the field tests.

Finite element models of the wheelsets used in the field tests have been developed and employed in modal analyses in order to obtain frequency response functions. Moreover, stress frequency response functions have been extracted at locations of interest on the axles (i e, close to stress concentrations and to positions where strains have been monitored in the field tests). Frequency response functions of a ballasted track model have been obtained using a separate procedure developed and validated in project TS19.

PhD student Michele Maglio (right) together with (from the left) Professor Elena Kabo, Docent Tore Vernersson and Professor Jens Nielsen in project TS20. Samples (cross sections) of rails and a wheel are seen on the table. Michele Maglio is pointing to a part of a wheel running surface with severe RCF damage

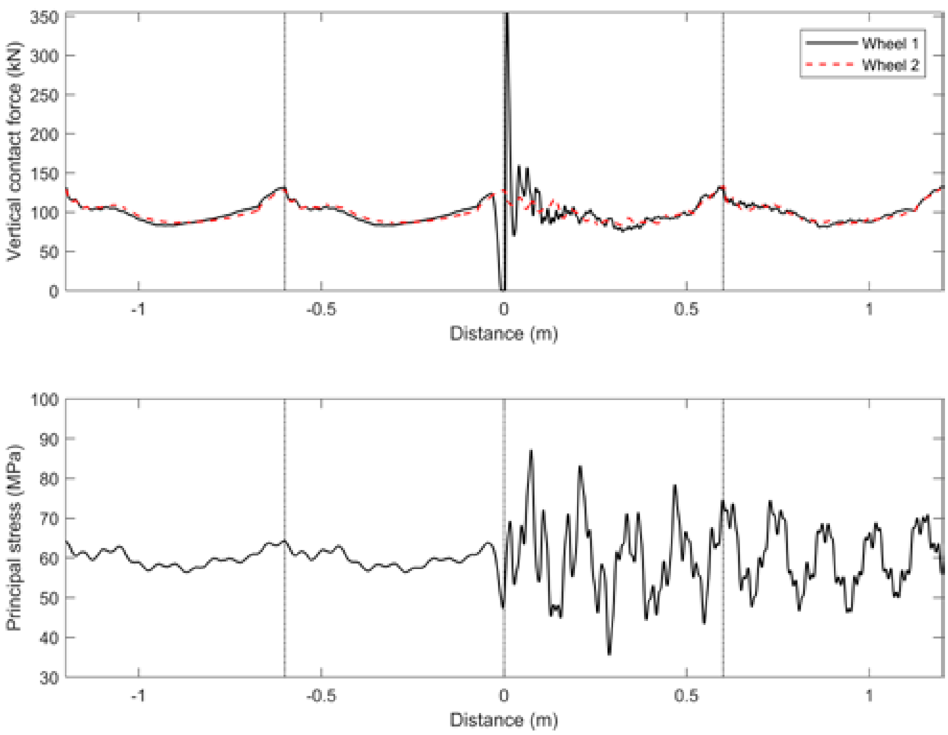
TS20. (cont'd)



The instrumented wheelset used during the field test in the SmartSet® part of project TS20

In collaboration with Lucchini RS and SJ, a leading axle of a double-decker X40 train in Sweden has been instrumented with Lucchini's Smartset® telemetry in order to acquire spectra of axle bending strains. These have been post-processed to obtain axle stress spectra for different stretches of the railway network during different periods of the year. CHARMEC has collaborated in the planning and installation of the telemetry system and has monitored the status of the two wheels mounted on the instrumented axle. Tread profiles and wheel out-of-roundness (OOR) at several rolling circles have been measured at regular intervals to study the evolution of wheel tread damage. This information is key to developing new knowledge on how tread damage influences load spectra for trains in revenue traffic.

Simulations of dynamic wheel-rail interaction have been performed in WERAN for different types of wheel OOR, different wheelset designs and different running conditions. Stresses at different locations in the axle have been derived to assess the influence of the distribution, shape and depth of tread damage at different vehicle speeds. A parametric study showed how the increase in wheel–rail contact forces and axle stresses depends on the combination of the shape and depth of the defect and the speed of the train. It has been shown that defects of larger size tend to have a significant influence on axle stresses, while stress levels generated by a small defect (with semi-axis lengths smaller than 10 mm) are comparable to stress magnitudes induced by the sleeper passing excitation. Moreover, simulations have demonstrated how vertical track irregularities cause



Calculated vertical wheel–rail contact force and principal stress at the fillet radius of the axle located near the wheel seat for a vehicle speed of 100 km/h in project TS20. A discrete tread defect with depth 2 mm, length 40 mm and width 60 mm is placed along the nominal rolling circle of Wheel 1

TS20. (cont'd)

higher axle stresses compared to the (fairly moderate) evolution of wheel OOR measured during the field tests on the SmartSet®-instrumented X40 train.

Field test data in terms of stress amplitudes measured by the SmartSet® telemetry have been post-processed by CHARMEC in order to quantify effects of wheel and track quality, train speed, wheelset maintenance, axle position within the trainset etc, on measured axle stresses. The stress data obtained from the field tests have been studied by means of statistical analyses. The obtained statistical stress distributions have been used as input for fatigue life analyses.

Michele Maglio presented his licentiate thesis (see below) at a seminar on 9 October 2020 where Professor Erland Johnson from RISE, Research Institutes of Sweden, introduced the discussion.

The joint reference group of projects TS20, MU22, MU30, MU34–38 and MU40 had members from Bombardier Transportation/Alstom, KTH, Lucchini Sweden, SJ, Trafikverket and voestalpine. From Stage 10, project MU41 is also included.

Elena Kabo, Anders Ekberg and Michele Maglio: Rolling contact fatigue assessment of repair rail welds, *Wear*, vols 436–437, 2019, article 203030, 8 pp (revised article from conference *CM2018*. Also listed under project MU22)

Michele Maglio, Matthias Asplund, Jens Nielsen, Tore Vernersson, Elena Kabo and Anders Ekberg: Digitalisation of condition monitoring data as input for fatigue evaluation of wheelsets, *Proceedings 19th International Wheelset Congress (IWC19)*, Venice (Italy) June 2019, 5 pp (also listed under project EU19)

Davide Della Valle: Railway wheel tread damage – detection and consequences of wheel-rail impact loading, MSc Thesis 2019:34, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2019, 72 pp and 2 annexes 6+27 pp (also listed under project EU19)

Michele Maglio, Astrid Pieringer, Jens Nielsen and Tore Vernersson: Wheel–rail impact loads and axle bending stress simulated for generic distributions and shapes of discrete wheel tread damage, *Journal of Sound and Vibration*, vol 502, 2021, article 116085, 19 pp (also listed under projects VB12 and EU19)

Michele Maglio, Tore Vernersson, Jens Nielsen, Astrid Pieringer, Pär Söderström, Daniele Regazzi and Steven Cervello: Railway wheel tread damage and axle bending stress – instrumented wheelset measurements and numerical simulations, *International Journal of Rail Transportation*, 2021, 23 pp, (also listed under project VB12), doi.org/10.1080/23248378.2021.1932621

Michele Maglio: Influence of wheel tread damage on wheelset and track loading – field tests and numerical simulations, Licentiate Thesis, *Chalmers Mechanics and Maritime Sciences*, Gothenburg October 2020, 102 pp (Summary and three appended papers. Also listed under project EU19)

An existing slab track. Photo: Slab Track Austria

TS21. MODEL-BASED CONDITION MONITORING OF S&C

Modellbaserad tillståndsövervakning av växlar och korsningar

Project leader and supervisor	Docent Björn Pålsson, Mechanics and Maritime Sciences/ Division of Dynamics
Assistant supervisors	Professor Jens Nielsen and Professor Håkan Johansson, Mechanics and Maritime Sciences
Doctoral candidate	Mr Marko Milosevic (from 2019-01-28; Lic Eng June 2021)
Period	2018-01-28 – 2021-06-30 (– 2024-01-27)
Chalmers budget (excluding university basic resources)	Stage 9: KSEK 800 (+ 1 273 in S2R) Stage 10: KSEK 2130 (+ 830 in S2R)
Industrial interests in-kind budget	Stage 9: KSEK 100 +100 Stage 10: KSEK 50 + 100 *(Abetong + voestalpine)*

3D geometry scan of a crossing rail

Crossing panel with accelerometer (yellow box).
Photo from Southern Mainline in Sweden

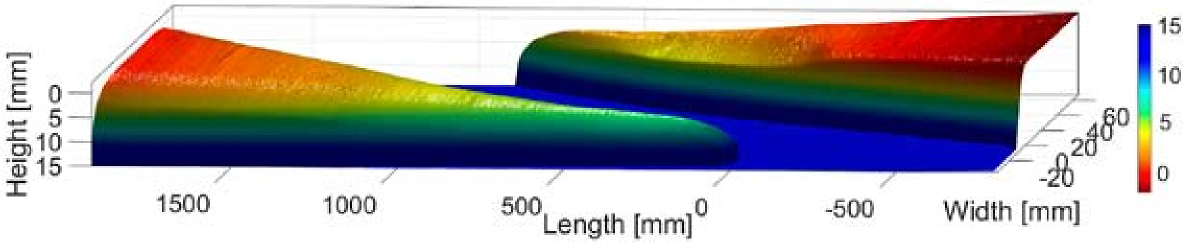
Railway switches and crossings (S&C, turnouts) connect different track sections and create a railway network by allowing for trains to change between tracks. This functionality comes at a cost as the load-inducing rail discontinuities in the switch and crossing panels cause much higher degradation rates for S&C than for regular plain line track. The high degradation rates create a potential business case for condition monitoring systems that can allow for improved maintenance decisions compared to what can be achieved from periodic inspection intervals using measurement vehicles or visual observation by engineers in track. The objective of project TS21 is therefore to develop a model-based numerical procedure that can identify the structural condition of switches and crossings (S&C) via embedded sensors. The goal is that the system should be accurate enough such that maintenance decisions can be taken based on output from this routine. The target system can be described as a Digital Twin representation of the physical system, where simulation models, condition monitoring data, and maintenance history can be combined to predict and identify the maintenance needs for S&C. To this end, several tailored processing tools for the analysis of accelerations from embedded sensors in crossing panels have been developed up to Marko Milosevic's licentiate examination in June 2021.

With the developed tools, a condition monitoring framework has been established. The framework includes the extraction of different crossing panel condition indicators for which the interpretation is supported by multibody simulations (MBS) of dynamic train–track interaction. The analysis procedure has shown robustness in processing a large dataset including 100 000 train passages. A particularly important development is a novel sleeper displacement reconstruction method based on frequency-domain integration from measured accelerations. Using the reconstructed displacements, the track response is being separated into quasi-static and dynamic domains based on deformation wavelength regions. This separation was found to be a promising strategy for independent observations of the ballast condition and the crossing rail geometry condition from a single measurement source.

In addition to sleeper acceleration measurements, field measurements have been performed in which crossing rail geometries were scanned. The scanned geometries have

PhD student Marko Milosevic (second from the left) surrounded by (from the left) Professor Jens Nielsen, Docent Björn Pålsson and Professor Håkan Johansson in project TS21

TS21. (cont'd)



3D scan of crossing nose (left) and wing rail (right)

been implemented into an MBS software with a structural representation of the crossing panel, where analyses have been performed to relate the concurrently measured accelerations and crossing rail geometries. To address the variation in operational conditions in the MBS environment, a sample of measured wheel profiles was accounted for in the analysis. This MBS study has demonstrated that there is a strong correlation between the crossing rail geometry condition, wheel–rail contact force, and crossing condition indicators computed from the dynamic track responses. The contrasting of measured and simulated track responses from six investigated crossing panels showed a good agreement. This observation supports the validity of the simulation-based condition assessment of crossing rail geometry. It has further been found that calibration of the track models to measured sleeper displacements dominated by the quasi-static track response improves the agreement between simulated and measured track response also in the dynamic track response domain being excited when wheels roll over the crossing.

Based on the work performed so far, a foundation has been laid for developing methods for automatic calibration of S&C MBS models and for subsequent damage evolution modelling based on operational online condition monitoring data. This development aims to address S&C service life in a digital environment and presents a key component for building a Digital Twin prototype for S&C condition monitoring. Marko Milosevic presented his licentiate thesis (see below) at a seminar on 4 June 2021 where Professor Anders Rønnquist from NTNU in Trondheim (Norway) introduced the discussion.

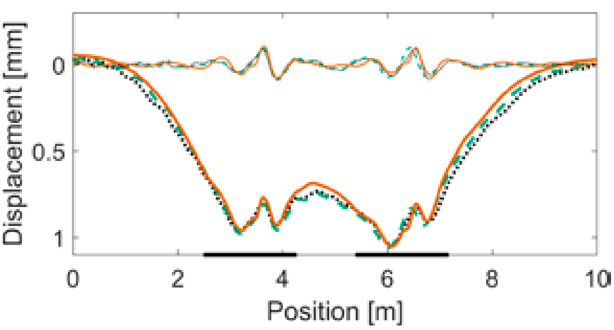
The work in project TS21 is continuously being presented and discussed during the biannual workshops with participants from University of Leoben (Austria), Virtual Vehicle (Austria), voestalpine and CHARMEC. Marko Milosevic participated at the ISMA2000 conference, see below.

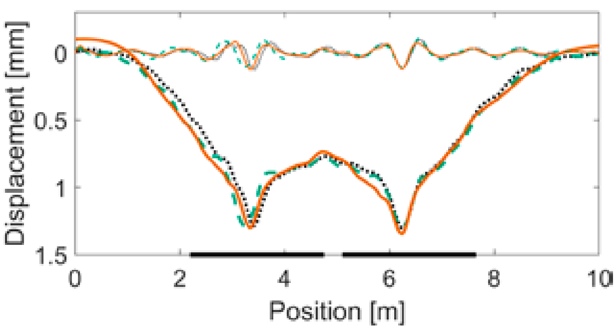
Marko Milosevic, Björn Pålsson, Arne Nissen, Håkan Johansson and Jens Nielsen: On tailored signal processing tools for operational condition monitoring of railway switches and crossings, *Proceedings 29th International Conference on Noise and Vibration Engineering (ISMA2020,* online*)*, Leuven (Belgium) September 2020, 15 pp

Marko Milosevic, Björn Pålsson, Arne Nissen, Jens Nielsen and Håkan Johansson: Reconstruction of sleeper displacements from measured accelerations for model-based condition monitoring of railway crossing panels, 2021, 21 pp (submitted for publication. Also listed under project EU19)

Marko Milosevic, Björn Pålsson, Arne Nissen, Jens Nielsen and Håkan Johansson: Condition monitoring of railway crossing geometry via measured and simulated track responses, 2021, 27 pp (to be submitted for publication. Also listed under project EU19)

Marko Milosevic: Towards model-based condition monitoring of railway switches and crossings, Licentiate Thesis, *Chalmers Mechanics and Maritime Sciences*, Gothenburg June 2021, 96 pp (Summary and two appended papers)





Calibration results in project TS21 showing measured and simulated sleeper displacements (full signals and band-passed to 1.0 – 0.2 m wavelengths) for an individual bogie passage over two crossing panels. Dotted and dashed lines are for measured sleeper displacements and the continuous line is for simulated sleeper displacement (thinner lines for band-pass filtered results). The scanned crossing geometries from each crossing panel are implemented in the simulation model. The two thick lines on the frame of the figures show the regions of the crossing rail scan

TS22. TRANSITION ZONE DESIGN FOR REDUCED TRACK SETTLEMENTS

Utformning av övergångszoner för minskade sättningar i spår

Project leader and supervisor	Professor Jens Nielsen, Mechanics and Maritime Sciences / Division of Dynamics
Assistant supervisors	Professor Magnus Ekh, Industrial and Materials Science, and Professor Jelke Dijkstra, Architecture and Civil Engineering
Doctoral candidate	Mr Kourosh Nasrollahi, MSc (from 2020-10-01)
Period	2020-10-01 – 2021-06-30 (– 2025-09-30)
Chalmers budget (excluding university basic resources)	Stage 9: kSEK 350 (+ 400 in S2R) Stage 10: kSEK 2485 (+ 965 in S2R)
Industrial interests in-kind budget	Stage 9: kSEK 64 + 0 Stage 10: kSEK 50 + 200 *(Abetong+ voestalpine)*

Transition zones between different track forms, including transitions between different superstructures, e g, slab track to ballasted track, and/or between substructures, e g, embankment to a bridge or tunnel, are studied. At such transitions, the discontinuity in track structure and gradient in track stiffness may lead to increased dynamic loads and an evolving irregularity in track geometry due to the accumulation of permanent track deformation (settlement), particularly on a ballasted track side. As a result, frequent and costly maintenance work to rectify the deteriorated geometry may be required. Project TS22 aims to generate models for the simulation of dynamic vehicle–track interaction leading to an optimization of transition zones. A model for the prediction of long-term track settlement will be developed and calibrated versus field measurements. The influence of hanging sleepers and of the difference in weight between the two track forms will be considered. Various mitigation measures and designs of the transition zone will be compared including the use of under sleeper pads, variation in rail pad stiffness, different sleeper designs and auxiliary rails.

The simulation procedure is being based on an iterative approach where a time-domain model of dynamic vehicle–track interaction in the short-term is integrated with a model of accumulated ballast settlement in the long-term. The track model is a non-linear finite element model accounting for gravity load, state-dependent foundation stiffness and hanging sleepers, while the empirical settlement equation is based on a viscoplastic material model formulation that will be calibrated against both experimental data and more advanced degradation models.

An extensive field measurement campaign will be carried out on Malmbanan (the Swedish Iron Ore Line) to assess the performance of a transition zone between ballasted track and slab track. Here the transition zone is instrumented for long-term condition monitoring of the evolving track stiffness and settlements. A finite element model of the applied slab track design has been developed and added to the CHARMEC library of different track forms. A model for the simulation of vertical dynamic interaction between a heavy-haul vehicle and the transition zone has been generated.

This cross-disciplinary project is carried out at Chalmers University as a collaboration between the division of Dynamics at the Department of Mechanics and Maritime Sciences, the division of Material and Computational Mechanics at the Department of Industrial and Materials Science, and the division of Geology and Geotechnics at the Department of Architecture and Civil Engineering. Project TS22 runs in parallel with work in the EU programme Shift2Rail.

Kourosh Nasrollahi, Jens Nielsen, Emil Aggestam, Jelke Dijkstra and Magnus Ekh: Prediction of differential track settlement in transition zones using a non-linear track model, *27th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2021,* online*)*, St Petersburg (Russia) August 2021, 10 pp

PhD student Kourosh Nasrollahi (second from the left) surrounded by (from the left) Professor Magnus Ekh, Professor Jens Nielsen and Professor Jelke Dijkstra in project TS22

VB12. HIGH-FREQUENCY WHEEL–RAIL INTERACTION

Samverkan tåg–spår vid höga frekvenser

Project leader	Dr Astrid Pieringer, Researcher (Swedish: forskare), Architecture and Civil Engineering / Division of Applied Acoustics
Co-worker	Professor Wolfgang Kropp, Architecture and Civil Engineering
Doctoral candidate	None (only senior researchers in this project)
Period	2012-01-01 – 2021-06-30 (– 2024-06-30)
Chalmers budget (excluding university basic resources)	Stage 7: see below Stage 8: see below Stage 9: see below Stage 10: see below
Industrial interests in-kind budget	Stage 7: kSEK 100 + 15 + 25 + 50 Stage 8: kSEK 100 + 15 + 0 + 0 Stage 9: kSEK 50 + 20 + 0 + 0 Stage 10: kSEK 100 + 30 + 0 + 0 *(Bombardier Transportation /Alstom + Interfleet Technology / SNC-Lavalin / Atkins Sverige + SL + Trafikverket)*

During Stages 7 and 8, this post-doc project was financed partly by the Department of Civil and Environmental Engineering (now ACE) and partly by the Chalmers Area of Advance Transport, profile Sustainable Vehicle Technologies. During Stage 9, it was partly financed by the Marie Skłodowska-Curie Individual Fellowship and Shift2Rail

For a photo of Astrid Pieringer and Wolfgang Kropp, see page 30

The interaction between wheel and rail is the predominant source of noise emission from railway operations in a wide range of conventional train speeds. On the one hand, this wheel–rail noise consists of rolling noise and impact noise caused by vertical interaction excited by roughness and discrete irregularities on the wheel and rail running surfaces, respectively. On the other hand, it consists of squeal noise generated by tangential interaction. In the previous doctoral project VB10, the model WERAN (WhEel/RAil Noise) was developed for the combined vertical and tangential wheel–rail interaction, which is valid in the frequency range relevant for noise generation. Project VB12 is a continuation of VB10 and focuses on different aspects of high-frequency wheel–rail interaction.

Acoustic monitoring of wheel and track properties. This monitoring is based on the idea that the sound or vibration due to the interaction between wheel and track in itself contains information about the wheel and track properties. To register this information, measurements can be carried out along the track or by specially equipped trains as in the case of the "Schallmesswagen" owned by DB Systemtechnik GmbH in Munich (Germany). In a co-operation project with them, financed by the Marie Skłodowska-Curie Individual Fellowship received by Astrid Pieringer, axle box vibrations registered by the "Schallmesswagen" (see photo below) were utilized to identify localized rail faults such as squats (see photo on page 43) and deteriorated insulating rail joints. WERAN was adapted to simulate the transfer path between roughness and localized rail faults in the contact to the axle box. Using this accurate model it was possible to identify acoustic signatures of different types of localized defects for arbitrary wheel–rail combinations with reasonable calculation effort. These signatures were then used for training a machine learning algorithm based on logistic regression. The model has been tested in a full-scale experiment on a track with well documented squats. The approach was found to work well and was able to identify the squats with a sufficiently high accuracy from signals of axle box acceleration. The results indicate that the proposed method is more than worthwhile to be further developed for use in field to detect squats in an automated way for more efficient track monitoring.

The approach has also been further developed towards a method for indirect rail roughness measurement from rolling stock. Based on an approach using the Least Mean Square (LMS) algorithm for source identification in the time domain, the vertical wheel–rail contact force is estimated from axle box acceleration. The approach has been tested on simulated data obtained from WERAN. Using the LMS algorithm, the time series of the contact force can be estimated from a simulated signal of axle box acceleration with good accuracy. In a second step, the combined wheel–

Noise measurement car "Schallmesswagen". Photo: DB Systemtechnik GmbH

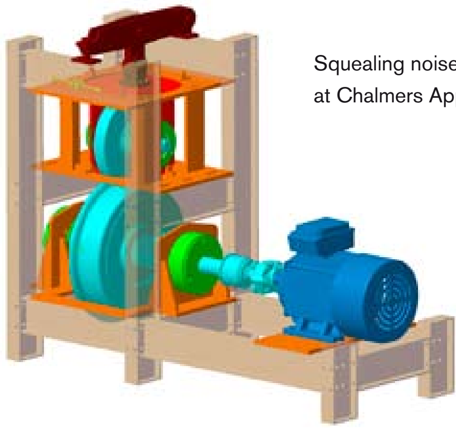
VB12. (cont'd)

rail roughness is obtained from the contact force based on a non-linear Hertzian contact model and a convolutional approach to determine the wheel and rail displacements. Separation of wheel roughness and rail roughness is possible by cycle averaging of the contact force. In the relevant wavelength range from 5 mm to 0.5 m, the rail roughness could be estimated with good accuracy for known track dynamics. Overall, deviations in third-octave bands between estimated and actual roughness were below 1 dB. Only for low rail roughness, higher deviations (but less than 2.5 dB) occurred around the pinned-pinned resonance frequency. Uncertainties in the track parameters affect the roughness estimation, where the most critical parameter is the rail pad stiffness. A deviation of 20 % in the rail pad stiffness leads to deviations in the rail roughness of up to 3.5 dB in single third-octave bands.

The work on indirect rail roughness measurement from rolling stock will be continued by investigating the potential to identify unknown track foundation parameters by model-based optimization, and by studying the influence of a variation of the lateral wheelset position on the roughness estimation.

The application of dither to mitigate curve squeal. WERAN has been applied to investigate the mechanisms behind self-excited vibrations leading to curve squeal. It also has been used to study the potential of dither for curve squeal mitigation. The application of dither means that an additional force signal (the dither signal) is added to the vibrational system to suppress self-excited vibrations. Any signal can be used as dither as long as its frequency content is above the squeal frequency and its amplitude is sufficiently strong. Time-domain simulations were applied to a setup in the squealing noise rig at Chalmers Applied Acoustics (see figure). Wheel and rail were represented by two flexible wheels. Constant friction was assumed. The analysis of this situation identified the coupling between lateral and vertical direction as the driving mechanism for building up self-excited vibrations. The lateral force leads to a vertical displacement. The change in vertical displacement also means a change in the vertical contact force that then modifies the lateral force. The results indicate, although the presence of modes in wheel and rail is needed, that instability can also occur without mode coupling.

It has been shown that the application of dither is able to hinder the build-up process of self-excited vibrations or to disturb already built-up vibrations to a degree where they collapse. The main condition for this is that the lateral amplitude due to the dither force is strong enough to reach the partial stick condition in the contact. In future work, the dither approach will be validated in the squealing noise rig.



Squealing noise rig
at Chalmers Applied Acoustics

Extension of WERAN. In co-operation with project TS20, the vertical module of WERAN has been extended to handle a complete wheelset on the track including the coupling between the two wheel–rail contacts via the wheelset axle and via the sleepers.

Astrid Pieringer and Matthias Stangl: AMONTRACK – ein EU gefördertes Projekt zur automatisierten Detektion von Einzelfehlern auf der Schienenfahrfläche, *Proceedings Fachtagung Bahnakustik – Infrastruktur, Fahrzeuge, Betrieb*, Planegg/Munich (Germany) November 2018, 9 pp

Wolfgang Kropp, Arthur Aglat, Jannik Theyssen and Astrid Pieringer: The application of dither for suppressing curve squeal, *Proceedings 23th International Congress on Acoustics (ICA 2019)*, Aachen (Germany) September 2019, 8 pp (also listed under project EU19)

Astrid Pieringer, Matthias Stangl, Jörg Rothhämel and Thorsten Tielkes: Acoustic monitoring of rail faults in the German railway network, *Proceedings 13th International Workshop on Railway Noise (IWRN13)*, Ghent (Belgium) September 2019, pp 242–250

Jens Nielsen, Astrid Pieringer, David Thompson and Peter Torstensson: Wheel–rail impact loads, noise and vibration – a review of excitation mechanisms, prediction methods and mitigation measures, *Proceedings 13th International Workshop on Railway Noise (IWRN13)*, Ghent (Belgium) September 2019, pp 3–40 (also listed under project TS8)

Michele Maglio, Astrid Pieringer, Jens Nielsen and Tore Vernersson: Wheel–rail impact loads and axle bending stress simulated for generic distributions and shapes of discrete wheel tread damage, *Journal of Sound and Vibration*, vol 502, article 116085, 2021, 19 pp (also listed under projects TS20 and EU19)

Michele Maglio, Tore Vernersson, Jens Nielsen, Astrid Pieringer, Pär Söderström, Daniele Regazzi and Steven Cervello: Railway wheel tread damage and axle bending stress – instrumented wheelset measurements and numerical simulations, *International Journal of Rail Transportation*, 2021, 23 pp (also listed under project TS20), doi.org/10.1080/23248378.2021.1932621

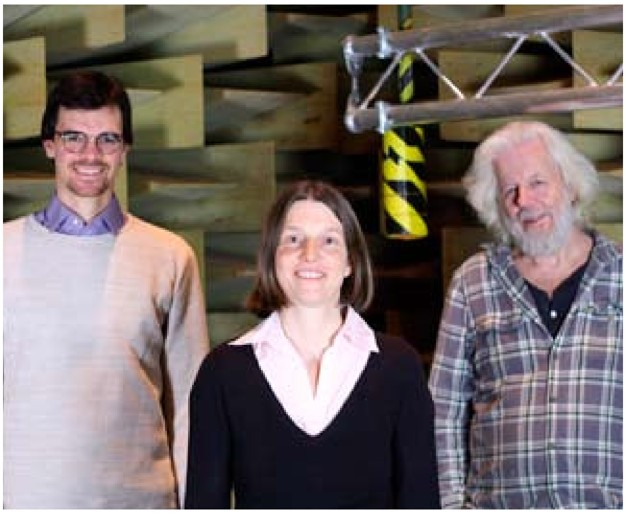
Wolfgang Kropp, Jannik Theyssen and Astrid Pieringer: The application of dither to mitigate curve squeal, *Journal of Sound and Vibration*, vol 514, article 116433, 17 pp, 2021 (also listed under project EU19)

Astrid Pieringer and Wolfgang Kropp: Model-based estimation of rail roughness from axle box acceleration, 2021 (submitted for publication. Also listed under projects EU19 and SP31)

VB13. PREDICTION AND MITIGATION OF NOISE FROM VEHICLES ON SLAB TRACKS

Prediktering och reduktion av buller från fordon på ballastfria spår

Project leaders and supervisors	Professor Wolfgang Kropp and Dr Astrid Pieringer, Researcher (Swedish: forskare), Architecture and Civil Engineering / Division of Applied Acoustics
Doctoral candidate	Mr Jannik Theyssen (from 2017-08-28; Lic Eng June 2020)
Period	2017-08-28 – 2021-06-30 (– 2022-08-27)
Chalmers budget (excluding university basic resources)	Stage 8: kSEK 833 Stage 9: kSEK 1 668 (+ 1 065 in S2R) Stage 10: kSEK 960 (+ 375 in S2R)
Industrial interests in-kind budget	Stage 8: kSEK 0 + 0 Stage 9: kSEK 150 + 100 Stage 10: kSEK 50 + 50 *(Abetong + Bombardier Transportation /Alstom)*



From the left: PhD student Jannik Theyssen, Dr Astrid Pieringer and Professor Wolfgang Kropp in project VB13. The photo is taken in the unechoic chamber at the Division of Applied Acoustics

Rolling noise from high-speed trains may call for costly mitigation measures along the tracks and it is thus important to be able to predict this noise with high accuracy already in the planning phase. As a prediction tool, typically Nord2000 is used in Scandinavia but also the European prediction model CNOSSOS might be applied here. However, these models are entirely dependent on realistic input for source characterization. Today very little is available in this area for rolling noise on slab tracks. At the same time, it is known that rolling noise on slab tracks can be noticeably higher than on traditional ballasted tracks. The overall objective of project VB13 is thus to develop a method for accurate prediction of high-speed rail rolling noise on slab tracks and of the impact of noise control measures along these tracks. Cost-effective and sustainable means for noise reduction can then be found. The project is carried out in co-operation with project TS19 "Design criteria for slab track structures", see page 20.

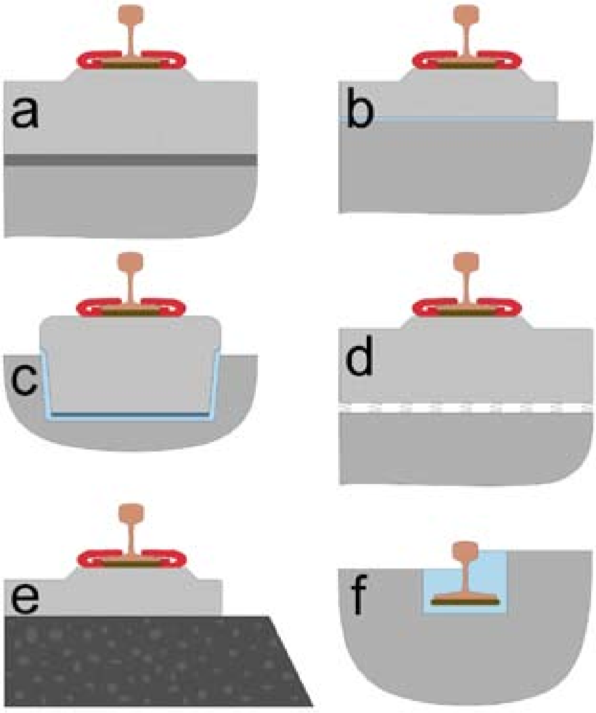
Modelling of rolling noise generation. The main components involved in the generation of rolling noise are the wheels, the rails and the sleepers or the slab track surface. Both wheel and track are excited by the contact forces from the rolling wheels due to the roughness of their contacting surfaces. In project VB10, a time-domain approach for the prediction of contact forces due to roughness excitation during rolling has been developed. A time-domain formulation for solving the non-linear contact between wheel and rail has been established where the dynamic responses of wheel and track are taken into account in the form of precalculated impulse response functions. This offers a modular system where models of different complexity can be utilized.

In project VB13 this approach has been complemented with models for the dynamic response from the wheel and the dynamic behaviour of different track designs. In addition, models for predicting sound radiation from wheel and track have been added to the prediction tool. Thus a complete model is obtained for the prediction of sound generation during rolling which allows for studying different measures for noise reduction. In the following the extensions made in project VB13 are discussed briefly.

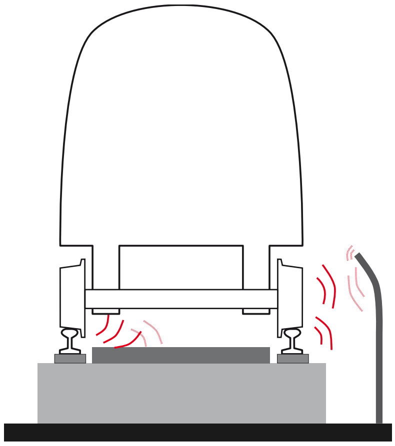
Track model. A model for the dynamic response of the rail based on Waveguide Finite Elements (WFE) has been established. The WFE can be used for modelling a rail that is continuously coupled to the track. In addition, solutions have been formulated to couple the rail to discrete supports in the form of slab track, or sleepers, including rail pads and under sleeper pads. This allows for calculation of the rail's dynamic response in the relevant frequency range for a large variety of track designs. The rail can be coupled to any stiffness, including frequency-dependent or even location-dependent stiffness. The discrete elements also include monobloc sleepers modelled as Timoshenko beams. The figure below shows typical track designs that can be modelled with this approach. The extension has been validated for both slab tracks and ballasted tracks through a comparison to receptance measurements on a full-scale slab track test rig in Chengdu (China), where Jannik Theyssen and Emil Aggestam took part, see again page 20.

Sound radiation from wheel and track. One of the major steps in project VB13 is the establishment of a complete set of models to describe the sound radiation from wheels and tracks in the presence of reflecting surfaces. It exploits the computationally efficient Wavenumber Boundary

VB13. (cont'd)



Typical track designs that can be modelled in project VB13: (a) compact slab track, (b) track with sleepers on a continuous asphalt or concrete support, (c) booted individual sleepers, (d) floating slab track, (e) ballasted track and (f) embedded rails


Demonstration of the capacity of the model in project VB13

Element Method (WBEM) which is based on wavenumber decomposition and thus is in line with the models for the dynamic response of the involved structures. This allows for a very efficient modelling where transfer functions can be calculated from exciting forces to stationary microphone positions along the track or to microphone positions moving with the vehicle. The model also allows the inclusion of absorption by defining the acoustic impedance of surfaces supposed to function as absorbers. The capacity of the model as in its present state is shown in the figure. The model components have been compared to, and validated against, analytical models and smaller laboratory measurements with idealised structures.

Take-aways from the models. The developed software has been used to evaluate the influence of slab track parameters on the radiated sound power. Five main take-aways from the work are: (1) of the investigated slab track parameters (thickness, rail pad stiffness, rail pad damping), rail pad stiffness has the largest influence, (2) slab surface vibration does not contribute significantly to the total sound power, (3) continuous support of the rail significantly decreases the radiated sound power, (4) the slab surface does not influence the radiation efficiency of the wheel; however, as expected, it changes the angles under which sound is radiated, and (5) the superstructure of the slab track, including concrete panels and soil layers, can be approximated as an infinitely long structure and as such modelled using the WFE method. The model will be further used to investigate the influence of different designs such as under sleeper pads and the presence of absorbing surfaces. Finally, a demonstration and validation of the complete model based on field measurement is being planned.

Jannik Theyssen presented his licentiate thesis (see below) at a seminar on 9 June 2020 where Dr-Ing habil Stefan Lutzenberger from Müller-BBM Rail Technologies, Planegg / Munich (Germany), introduced the discussion. The joint reference group of projects TS19 and VB13 had members from Abetong, Bombardier Transportation / Alstom (Switzerland) and Trafikverket.

Jannik Theyssen, Astrid Pieringer and Wolfgang Kropp: The influence of track parameters on the sound radiation from slab tracks, *Proceedings 13th International Workshop on Railway Noise (IWRN13)*, Ghent (Belgium) September 2019, pp 3–40 (also listed under project EU19)

François Fabre, Jannik Theyssen, Astrid Pieringer and Wolfgang Kropp: Sound radiation from railway wheels including ground reflections – a half-space formulation for the Fourier boundary element method, *Journal of Sound and Vibration*, vol 493, 2021, article 115822, 17 pp

Jannik Theyssen, Emil Aggestam, Shengyang Zhu, Jens Nielsen, Astrid Pieringer, Wolfgang Kropp and Wanming Zhai: Calibration and validation of the dynamic response of two slab track models using data from a full-scale test rig, *Engineering Structures*, vol 234, 2021, article 111980, 17 pp (also listed under projects TS19 and EU19)

Jannik Theyssen: Modelling the acoustic performance of slab tracks, Licentiate Thesis, *Chalmers Architecture and Civil Engineering*, Gothenburg June 2020, 113 pp (Summary and three appended papers)

MU22. IMPROVED CRITERION FOR SURFACE INITIATED RCF

Förbättrat kriterium för ytinitierad rullkontaktutmattning

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	Professor Elena Kabo and Professor Roger Lundén, Mechanics and Maritime Sciences
Doctoral candidate	None (only senior researchers in this project)
Period	2007-07-01 – 2021-06-30 (–2024-06-03)
Chalmers budget (excluding university basic resources)	Stage 5: kSEK 700 Stage 6: kSEK 200 Stage 7: kSEK 1 300 Stage 8: kSEK 1 000 Stage 9: kSEK 300 Stage 10: kSEK 400
Industrial interests in-kind budget	Stage 5: kSEK 100 + 200 + 100 Stage 6: kSEK 50 + 100 + 50 Stage 7: kSEK 100 + 100 + 50 Stage 8: kSEK 100 + 100 + 50 Stage 9: kSEK 120 + 100 + 50 Stage 10: kSEK 100 + 50 + 50 *(Bombardier Transportation / Alstom + Lucchini Sweden + SweMaint)*

From the left: Professor Elena Kabo, Professor Anders Ekberg and (sitting) Professor Roger Lunden in project MU22. Photo taken in 2018

Several CHARMEC projects have been (and are) related to material and structural deterioration. The present project MU22 aims at developing and improving analyses and predictive abilities for railway deterioration phenomena with a focus on rolling contact fatigue (RCF). It also aims at facilitating operational implementation of derived knowledge and predictive capabilities etc. Examples of applications are operational monitoring and mitigation of (RCF) deterioration, and inclusion of (RCF) deterioration in LCC and RAMS analyses, see project TS18. Project MU22 also supports other CHARMEC projects dealing with deterioration and provides expertise to projects where material and structural deterioration is of interest but not a core topic. The activity includes interaction with research and industry partners (within and outside CHARMEC) to uphold and develop a world leading competence in the field of material and structural deterioration with a focus on RCF of railway wheels and rails. The results arrived at contributed to CHARMEC's winning of the 2019 Chalmers Impact Award (see page 81) for our contributions dealing with methods to predict crack formation in railway wheels and with introducing harmonized load limits for railway transportation in Europe.

Several meetings have been held with our partners to plan, evaluate and disseminate CHARMEC's research including a presentation to Trafikverket and others of the UIC IRS 70729 where CHARMEC has contributed, see project SP28. Descriptions for Trafikverket's Areas of Excellence Wheelsets and brakes and Track, see page 87, have been produced and pertinent research agreements with Trafikverket have been drafted, submitted and approved. Also three project proposals to Chalmers Area of Advance Transport have been developed and granted.

Anders Ekberg and Roger Lundén have been involved in discussions on load carrying capacity of tracks with Green Cargo and Trafikverket. This work resulted in a new approach to establish (the relative) geotechnical impact of vehicles, which was developed, implemented and employed in operation for Trafikverket's vehicle categorization scheme. Anders Ekberg, Mohammad Salahi Nezhad (MU38) and Daniel Gren (MU35) together with staff from Trafikverket identified and selected damaged rail samples on the Western Main Line close to Flen on 2020-02-27. The samples were studied and evaluated in project MU35.

Nicola Zani from University of Brescia in Italy was a guest researcher at CHARMEC during the period 2 March to 27 May 2020, see project MU39. Anders Ekberg and Jens Nielsen have been active in several meetings regarding cracks in S&C sleepers with Abetong and Trafikverket. Anders Ekberg participated as international expert in the yearly co-ordination meeting of the British research initiative Track to the future (https://t2f.org.uk/) on 19–20 July 2018. Here several projects bring a good synergy to CHARMEC's research.

Elena Kabo was a member of the technical committee for the 19th International Wheelset Congress (IWC19) in Venice (Italy) on 16–20 June 2019. She participated in tele-meetings and a joint meeting of the technical and organizing committees of IWC in Berlin on 2018-09-20 and she chaired a plenary session in Venice. CHARMEC's senior researchers reviewed 41 of the 121 two-page abstracts

MU22. (cont'd)

submitted to IWC19. Anders Ekberg made a presentation together with Stuart Grassie at the IHHA2019 in Narvik (Norway) and also chaired a session.

Roger Deuce and Anders Ekberg gave an overview of CHARMEC's research on "Track impact force generation from wheel tread irregularities" at an RSSB meeting in London on 2020-02-26. Anders Ekberg presented research on "Reliable and efficient railway" at the Research2Business forum of IVA (Royal Swedish Academy of Engineering Sciences) on 2020-09-02. This presentation focused on methods to prevent cracking. Anders Ekberg participated in the Railway Gazette Rail Panel "Developing smart rail infrastructure" on 2020-09-23 (a video from this event is available at https://rgtv.wavecast.io/interactive-broadcast-week/session-3).

On 2020-12-02, Anders Ekberg and Elena Kabo made a presentation on "The conditions under which RCF progresses to transverse defects" and participated in an ICRI (International Collaborative Research Initiative) Broken rail workshop organized by Eric Magel of NRC (National Research Council Canada). Some 45 specialists from all over the world took part in this online event. Among other presenters were Richard Stock (Linsinger, Austria) and Peter Mutton (Monash University, Australia). On 2021-02-11, Anders Ekberg made a presentation "Assessing, monitoring and predicting health of track and vehicles" in a Nordic Heavy Haul seminar on development of the Iron Ore Line in Sweden and Norway. Anders Ekberg, Björn Paulsson and Elena Kabo supervised a MSc thesis on ballast entrapment in switches and have drafted a related project proposal on switch control detection devices (TKK), see project SP33 on page 72. Anders Ekberg and Elena Kabo together with Stuart Grassie (railmeasurement.com) supervised a BSc thesis on early crack propagation in rail, see below. Anders Ekberg held a PhD course at Chalmers on "Advanced Fatigue Design" during the autumn of 2018. The course contained lectures on multiaxial and contact fatigue, fracture mechanics including short crack growth, thermal effects and overviews of gigacycle fatigue, vibration fatigue etc. Anders Ekberg gave a twelve-hour online course on 23–25 June 2020 on "Selected topics in railway mechanics with focus on deterioration" with 73 participants from industry and academia. Much of the content in this course will be included in the new railway technology course. He also repeated the PhD course on "Advanced Fatigue Design" between May and August 2020 with nine participants.

Elena Kabo was a member of the grading committee at Lund University on 2018-12-04 when Gustav Lindberg defended his PhD thesis "On the growth of bone through stress driven diffusion and bone generation processes". Anders Ekberg was a member of the grading committee at TU Delft (The Netherlands) on 2018-12-19 when Yuewei Ma defended his PhD thesis "Wheel-rail interaction – enhanced explicit finite element modelling, verification and validation". Anders Ekberg was also a member of the grading committee for Hamid Khajehei who defended his PhD thesis "Data-driven models for railway track geometry maintenance" at Luleå Technical University on 2021-06-18.

Example of damage as studied in project MU22; ice and snow are trapped in RCF cracks initiated on the running surface of a wheel

For the joint reference group, see under project TS20.

Elena Kabo, Anders Ekberg and Michele Maglio: Rolling contact fatigue assessment of repair rail welds, *Wear*, vols 436–437, 2019, article 203030, 8 pp (revised article from conference *CM2018*. Also listed under project TS20)

Erika Steyn: Rail surface treatment: Grinding and milling – competing or complementary technologies, MSc Thesis 2019:20, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2019, 58 pp, hdl.handle.net/20.500.12380/300204

Roger Deuce, Anders Ekberg and Elena Kabo: Mechanical deterioration of wheels and rails under winter conditions – mechanisms and consequences, *IMechE Journal of Rail and Rapid Transit*, vol 233, issue 6, 2019, pp 640–648 doi.org/10.1177/0954409718802437

Anders Ekberg and Björn Pålsson: Multiscale modelling of train–track interaction phenomena with focus on contact mechanics, *Wear*, vols 430–431, 2019, pp 393–400 (revised article from conference *CM2018*)

Anders Ekberg and Stuart Grassie: Surface damage of wheels and rails – similarities, differences and effective mitigation strategies, *Proceedings International Heavy Haul Association STS Conference (IHHA2019)*, Narvik (Norway) June 2019, pp 801–809

Robin Andersson, Elena Kabo and Anders Ekberg: Numerical assessment of the loading of rolling contact fatigue cracks close to rail surface irregularities, *Fatigue & Fracture of Engineering Materials & Structures*, vol 43, issue 5, 2020, pp 947–954 (also listed under project EU19. This article from MU31 was published after the project was finished)

Benjamin Pettersson, Wilhelm Sjödin and Monika Stoyanova: Analysis of early crack propagation in rail, BSc Thesis 2020:01, *Chalmers Mechanics and Maritime Sciences*, 26 pp, hdl.handle.net/20.500.12380/301174

Anders Ekberg and Elena Kabo: Risk of fatigue of train car chassis due to pressure waves between meeting trains, Research Report 2020:01, *Chalmers Mechanics and Maritime Sciences*, 15 pp (also listed under project SP30)

MU28. MECHANICAL PERFORMANCE OF WHEEL AND RAIL MATERIALS

Mekaniska prestanda hos hjul- och rälmaterial

In October 2018, the MU28 project was concluded with Dimitrios Nikas' successful defence in public of his doctoral dissertation "Influence of combined thermal and mechanical loadings on pearlitic steel microstructure in railway wheels and rails", see the previous Triennial Report. Professor Johan Ahlström, Professor Christer Persson and Professor Magnus Ekh were his supervisors. The faculty-appointed external examiner of the dissertation was Professor Reinhard Pippan from University of Leoben in Austria.

In project MU28, material properties under realistic conditions were examined by use of uniaxial and biaxial servo-hydraulic test frames for a range of temperatures. Both virgin material and the anisotropic surface layer of used material have been investigated. The overall aim was to arrive at a better understanding of material behaviour under service conditions and to enable implementation and calibration of realistic simulation models describing this behaviour.

Dimitrios Nikas continued his employment until 31 May 2019. During the extension, he conducted a literature study and authored, together with Anders Ekberg, the report "Potentials & barriers for S&C materials development", see page 61. This work was performed within projects EU17 In2Track and EU19 In2Track2.

PhD student Dimitrios Nikas (doctorate earned in October 2018) in project MU28. In the biaxial rig, a test bar is exposed to torsional prestraining. Photo taken in 2016

Dimitrios Nikas and Johan Ahlström: High temperature biaxial low cycle fatigue behaviour of railway wheel steel, *Proceedings 12th International Conference of Multiaxial Fatigue and Fracture (ICMFF12)*, Bordeaux (France) June 2019, *MATEC Web of Conferences*, vol 300, 2019, article 07001, 8 pp (also listed under projects MU30 and EU19)

Ali Esmaeili, Johan Ahlström, Magnus Ekh, Dimitrios Nikas and Tore Vernersson: Modelling of temperature and strain rate dependent behaviour of pearlitic steel in block braked railway wheels, *Railway Engineering Science*, vol 29, 2021, pp 362–378 (also listed under project MU32)

MU29. DAMAGE IN WHEEL AND RAIL MATERIALS

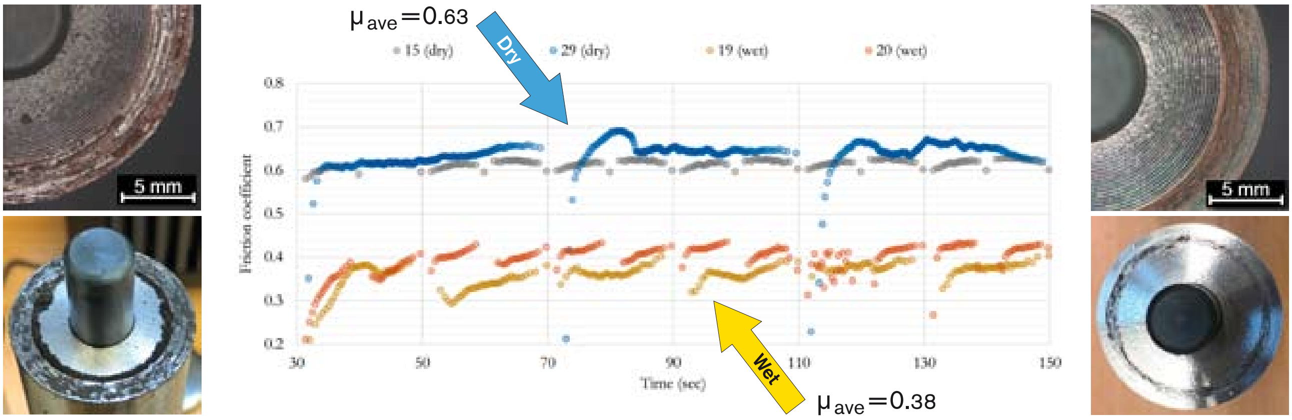
Skador i hjul- och rälmaterial

Project leader and supervisor	Professor Johan Ahlström, Industrial and Materials Science / Division of Engineering Materials
Assistant supervisor	Professor Christer Persson, Industrial and Materials Science
Doctoral candidate	Ms Casey Jessop (from 2014-02-10; Lic Eng March 2017; PhD June 2019)
Period	2014-02-10 – 2019-06-30
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 1 570 Stage 8: kSEK 2 400 (+ 678 in S2R) Stage 9: kSEK 477 (+ 889 in S2R)
Industrial interests in-kind budget	Stage 7: kSEK 100+50+15+50+200 Stage 8: kSEK 100 + 50 + 15 + 0+200 Stage 9: kSEK 50 + 50 + 15 + 0+50 *(Bombardier Transportation / Alstom + Lucchini Sweden + SNC-Lavalin / Atkins Sverige + Trafikverket + voestalpine)*

Casey Jessop (doctorate earned in June 2019), Yubin Zhang and Dorte Juul Jensen during a collaboration meeting in Copenhagen when preparing for synchrotron experiments at APS (Argonne Photon Source) in Illinois (USA). Photo: Johan Ahlström

For a photo of Johan Ahlström, see page 42, and for a photo of Christer Persson, see page 32 in the previous Triennial Report

MU29. (cont'd)



Friction experiments in project MU29 clearly showed the effect of climatic conditions such as wet surfaces

Early in project MU29, a high-power X-ray radiography study was performed on a rail section with a squat taken from field, see page 43. The aim was to observe the network of cracks associated to the squat and to investigate the ability of radiography and image analysis to detect crack extension and crack geometry under field-like conditions, i e, with access from only the sides and the top of the rail. Combining the exposures from a range of angles, a method was developed to render a 3D representation of the complete and complex crack network.

Further characterization studies on the squat crack network were made using microscopy as well as X-ray tomography to measure global geometry and local topology. Damage initiation experiments were carried out using our biaxial testing machine on test bars without and with initial thermal damage in the form of a white etching layer (WEL) spot. The test bars were characterized using optical, stereo and scanning electron microscopy (SEM). Residual stresses around the WEL spots were measured using X-ray diffraction and crack networks were examined using X-ray tomography in collaboration with Denmark Technical University (DTU). See also CHARMEC's Triennial Reports for Stages 7 and 8.

Friction experiments to investigate crack face friction between two R260 rail steel surfaces in different combinations of compression and torsional loading were performed under wet and dry conditions. Main results include the build-up of a surface pattern much alike the topography found in squat cracks, and a direction dependence of friction. As expected, the wet condition resulted in lower friction but, more surprisingly, a drastically decreased wear rate.

During spring 2018, Casey Jessop's work was supported by an InterReg project, to enable further tomography of void and crack formation and to get started with synchrotron studies in collaboration with DTU researchers. The resulting crystallographic orientation maps from synchrotron X-ray diffraction experiments were compared to Electron Backscatter Diffraction (EBSD) experiments made in project MU28 on the same R8T wheel steel samples annealed at different temperatures. It was found that the higher angular resolution of the synchrotron experiments resulted in more accurate local misorientation measurements. The misorientation decreases in ferrite grains with increasing annealing temperature. SEM microscopy was applied to samples with similar heat treatments to see the degree of spheroidization as a function of annealing temperature. Furthermore, information on the elastic strain within specific ferrite grains could be obtained using Differential-Aperture X-ray Microscopy (DAXM), which is not possible using other methods, such as EBSD. The elastic strains were found to be released with annealing at higher temperatures, and were nearly zero for the sample annealed at 500°C, see also under project MU30.

Casey Jessop successfully defended her doctoral dissertation (see below) on 13 June 2019 with Professor Sabine Denis from University Lorraine in France acting as the faculty-appointed external examiner.

The joint reference group of projects MU28, MU29, MU30, MU32 and MU34 had members from Bombardier Germany, Lucchini Sweden, SJ, Trafikverket and voestalpine.

Casey Jessop and Johan Ahlström: Friction between pearlitic steel surfaces, *Wear*, vols 432–433, 2019, article 102910, 9 pp (revised article from conference *CM2018*. Also listed under projects MU30 and EU19)

Casey Jessop, Johan Ahlström, Christer Persson and Yubin Zhang: Damage evolution around white etching layer during uniaxial loading (Technical note), *Fatigue & Fracture of Engineering Materials & Structures*, vol 43, issue 1, 2019, pp 201–208 (also listed under project MU30)

Casey Jessop: Damage and defects in railway materials – influence of mechanical and thermal damage on crack initiation and propagation, Doctoral Dissertation, *Chalmers Industrial and Materials Science*, Gothenburg June 2019, 95 pp (Summary and five appended papers).

MU30. MODELLING OF PROPERTIES AND DAMAGE IN WHEEL AND RAIL MATERIALS

Modellering av egenskaper och skador i hjul- och rälmaterial

Project leader and supervisor	Professor Johan Ahlström, Industrial and Materials Science / Division of Engineering Materials
Doctoral candidate	None (only senior researcher in this project)
Period	2013-04-18 – 2021-06-30 (– 2024-06-30)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 290 Stage 8: KSEK 1 275 (+ 229 in S2R) Stage 9: KSEK 450 (+ 1 682 in S2R) Stage 10: KSEK 600 + 300 (+ 1 800 in S2R)
Industrial interests in-kind budget	Stage 7: KSEK 50 + 50 + 15 + 50 + 200 Stage 8: KSEK 50 + 50 + 15 + 0 + 200 Stage 9: KSEK 50 + 50 + 15 + 0 + 150 Stage 10: KSEK 50 + 50 + 20+ 0 + 150 *(Bombardier Transportation / Alstom + Lucchini Sweden + SNC-Lavalin / Atkins Sverige + Trafikverket + voestalpine)*

For a photo of Johan Ahlström, see page 42

The main purpose of this senior research project is to help synthesize and interpret results from previous and current experimental projects and to guide the implementation of these results into material models of required complexity that captures important phenomena. Accurate yet efficient material models are crucial for simulation of material deformation and of crack formation and growth.

The research work on thermal damage in the wheel/rail surface layers because of repeated slipping due to, for example, malfunctioning WSP devices is a field where previous results can be implemented in new and improved models. Here localized discontinuities in material strength and large stress gradients are supposed to form possible initiation sites for RCF cluster cracks and squat-type cracks. Within Stage 9, collaborations with Ali Esmaeili (MU32) and Björn Andersson (MU37) included improving the full model of phase transformation and thermal damage using more advanced material constitutive models based on previous experimental work.

Collaboration with Denmark Technical University (DTU) has continued with studies of material taken from crossing noses of austenitic manganese steel (Mn13) and from pearlitic R350HT rail steel. Biaxial fatigue experiments were done at Chalmers and the fatigued material was analysed by use of Transmission Electron Microscopy (TEM) at DTU Risø. The co-operation with DTU has improved our possibilities for in-depth characterization of deformed surface layers of rails using X-ray tomography and TEM.

Another field where large steps are being taken to understand the material behaviour under combined mechanical and thermal loading is synchrotron studies in collaboration with researchers at both DTU and the European Synchrotron Radiation Facility (ESRF) in Grenoble (France). First, a Dark Field X-ray Microscopy (DFXM) study on wheel material ER8T concluded that pro-eutectoid ferrite grains can be identified and analysed concerning their residual stress level and strain gradients. The accuracy of DFXM is extremely high with angular, spatial, and strain resolution of 0.005°, sub-100 nm and 5×10^{-5}, respectively. Also, in an ongoing study, wheel material ER7T that has been exposed to low cycle fatigue loading (cyclic plasticity) is heat treated at temperatures 300-600 °C and analysed with the same technique. The ability of DFXM to measure with extremely high resolution, complemented with the EBSD technique, see project MU29, for overview of the grain structure (see figure in project MU36) is key for understanding how stresses relax and material behaviour changes on thermal loading.

During Stage 9, the doctoral students Dimitrios Nikas, Ali Esmaeili, Casey Jessop, Knut Andreas Meyer and Somrita Dhar (DTU) have graduated. The integration between the two research fields ”materials science” and ”applied mechanics” has been successful through close collaboration between their projects.

For the joint reference group, see under project TS20.

Casey Jessop and Johan Ahlström: Friction between pearlitic steel surfaces, *Wear*, vols 432–433, 2019, article 102910, 9 pp (revised article from conference *CM2018*. Also listed under projects MU29 and EU19)

Casey Jessop, Johan Ahlström, Christer Persson and Yubin Zhang: Damage evolution around white etching layer during uniaxial loading (Technical note), *Fatigue & Fracture of Engineering Materials & Structures*, vol 43, issue 1, 2019, pp 201–208 (also listed under project MU29)

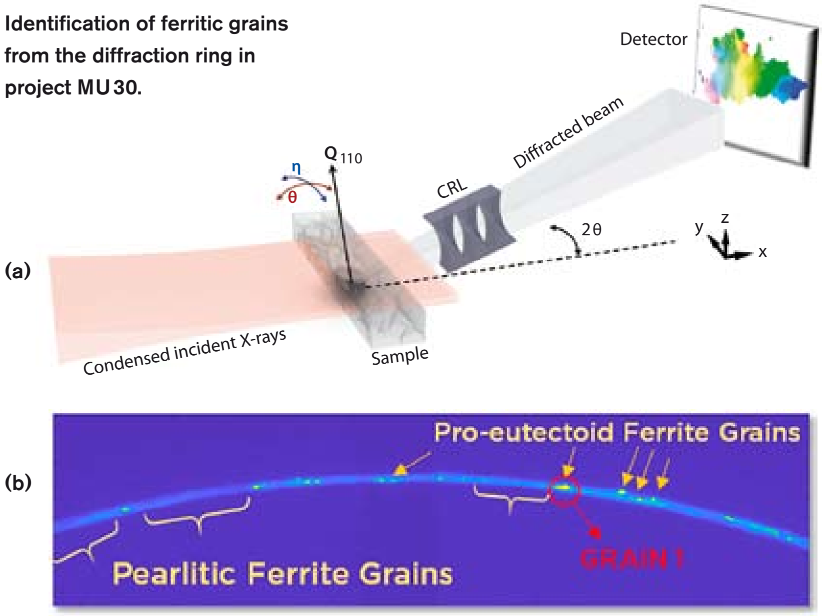
Dimitrios Nikas and Johan Ahlström: High temperature bi-axial low cycle fatigue behaviour of railway wheel steel, *Proceedings 12th International Conference of Multiaxial Fatigue and Fracture (ICMFF12)*, Bordeaux (France) June 2019, *MATEC Web of Conferences*, vol 300, 2019, article 07001, 8 pp (also listed under projects MU28 and EU19)

Johan Ahlström and Xiaodan Zhang: Effect of strain gradient on the microstructure and mechanical properties of pearlitic steel, *Proceedings 40th Risø International Symposium on Materials Science and Engineering*, Risø / Roskilde (Denmark) September 2019, *IOP Conference Series: Materials Science and Engineering*, vol 580, article 012027, 6 pp

Somrita Dhar, Johan Ahlström, Xiaodan Zhang, Hilmar Danielsen and Dorte Juul Jensen: Multi-axial fatigue of head-hardened pearlitic and austenitic manganese railway steels – a comparative study, *Metallurgical and Materials Transactions A*, vol 51, 2020, pp 5639–5652 (also listed under project EU19) doi.org/10.1007/s11661-020-05941-8

MU30. (cont'd)

Identification of ferritic grains from the diffraction ring in project MU 30.



(a) Schematic of the DFXM experimental setup. The incident beam was focused horizontally to illuminate slices of the diffracting grain (shown in dark). The angles θ, η, and 2θ correspond to the tilt angles around the $\vec{Q}_{110}$ scattering vector of the grain of interest. An objective CRL was used to create a magnified image of the grain at about 5 meters away from the sample

(b) A ~30° portion of 110 diffraction ring showing powder diffraction-like regions (pearlitic ferrite grains with high mosaicity) and bright spots (pro-eutectoid ferrite with narrow angular spread). Brighter colors show higher detected intensity

Picture composed by Can Yildirim at ESRF and reproduced from Scripta Materialia, vol 197, 2021 (with permission from Elsevier)

Ali Esmaeili, Johan Ahlström, Björn Andersson and Magnus Ekh: Modelling of cyclic plasticity and phase transformations during repeated local heating events in rail and wheel steels, *International Journal of Fatigue*, vol 151, 2021, article 106361, 15 pp (also listed under projects MU32, MU37 and EU19)

Can Yildirim, Casey Jessop, Johan Ahlström, Carsten Detlefs and Yubin Zhang: 3D mapping of orientation variation and local residual stress within individual grains of pearlitic steel using synchrotron dark field X-ray microscopy, *Scripta Materialia*, vol 197, 2021, article 113783, 5 pp (also listed under project EU19)

Knut Andreas Meyer, Daniel Gren, Johan Ahlström and Anders Ekberg: A method for in-field railhead crack detection using digital image correlation, *International Journal of Rail Transportation*, 2022, 20 pp (also listed under projects MU34 and MU35)
doi.org/10.1080/23248378.2021.2021455

The new 3D micro-DIC (Digital Image Correlation) equipment, as used in projects MU30, MU34 and MU35 at Chalmers Department of Industrial and Materials Science, Divison of Engineering Materials, is here set-up in front of a mechanical test frame. Main components are a stereo-microscope with a special lens attachment and two cameras to register pictures from a central part of a test bar. Before the test, the equipment is calibrated and the test bar is provided with a characteristic pattern, for example, by spray painting with 50 % coverage.
During the test, image-pairs are recorded either at regular intervals (tensile testing) or synchronized with, for example, the peak load (fatigue testing). After the test, the image-pairs from different time instances are compared by digital image analysis, and use of the two images in each pair then makes 3D analyses possible. The picture series are used to identify how different points on the test bar surface have moved in space, and thus the local strain field can be determined.
The equipment will be employed in mechanical testing as a non-contacting strain sensor measuring how strain fields change when fatigue cracks propagate

MU32. MODELLING OF THERMOMECHANICALLY LOADED RAIL AND WHEEL STEELS

Modellering av termomekaniskt belastade stål i räler och hjul

The MU32 project was concluded with Ali Esmaeili's successful defence in public of his doctoral dissertation in January 2019. Professor Magnus Ekh, Professor Johan Ahlström and Docent Tore Vernersson were his supervisors. The faculty-appointed external examiner of the dissertation was Dr David Fletcher from the Department of Mechanical Engineering at the University of Sheffield in the UK. The title of the dissertation is "Modelling of cyclic and viscous behaviour of thermomechanically loaded pearlitic steels – application to tread braked railway wheels", see the previous Triennial Report.

Rail and wheel materials are subjected to very high stresses and, in some cases, also to elevated temperatures. The rolling contact loading results in a multiaxial stress state with a combination of compression and shear. The temperature may increase due to frictional heat generated between wheel and rail or between wheel and brake blocks at tread braking. This further increases the complexity of the loading situation. The main goal of project MU32 was to improve modelling of the cyclic behaviour of wheel and rail materials subjected to combined mechanical and thermal loadings. The project was conducted in close collaboration with project MU28 where tests were performed by Dimitrios Nikas on pearlitic steels at elevated temperatures for uniaxial as well as compression–torsional loading. The resulting knowledge on how the material behaves in realistic loading situations was used in the current project to formulate, calibrate and validate material models. These models were then used as part of a collaboration with Mandeep Singh Walia in project SD10 to develop a simulation methodology to analyse the influence of operational parameters on the fatigue life of wheel treads..

A cyclic viscoplastic model was calibrated against slow-cyclic strain-controlled tests with hold-time and ratchetting tests with rapid cycles as well as against cyclic biaxial tests. The viscoplasticity model was then employed in the simulation methodology to predict the fatigue life of wheel treads.

Wheel skidding typically occurs during braking when a wheelset is accidentally locked and the wheels slide (skid) on the rail. The local heating can cause phase transformations in the surface layer of the wheel rim and thereby residual stresses. These stresses combined with the rolling contact loading may lead to initiation of cracks. A cyclic plasticity model incorporating phase transformations was developed and used in thermomechanical FE simulations of wheel skidding followed by rolling contact loading. The stress field in the surface layer has been analysed to find explanations on why and where cracks might start.

For the joint reference group, see under project TS20.

Ali Esmaeili, Johan Ahlström, Magnus Ekh, Dimitrios Nikas and Tore Vernersson: Modelling of temperature and strain rate dependent behaviour of pearlitic steel in block braked railway wheels, *Railway Engineering Science*, vol 29, 2021, pp 362 – 378 (also listed under project MU28)

Ali Esmaeili, Johan Ahlström, Björn Andersson and Magnus Ekh: Modelling of cyclic plasticity and phase transformations during repeated local heating events in rail and wheel steels, *International Journal of Fatigue*, vol 151, 2021, article 106361, 15 pp (also listed under projects MU30, MU37 and EU19)

Professor Johan Ahlström, Doctor David Fletcher (external examiner), Doctor Ali Esmaeili, Professor Magnus Ekh and Docent Tore Vernersson after the doctoral examination in project MU32 on 10 January 2019

MU33. NUMERICAL SIMULATION OF ROLLING CONTACT FATIGUE CRACK GROWTH IN RAILS

Simulering av spricktillväxt i räl under rullkontaktutmattning

In January 2019, the MU33 project was concluded with Dimosthenis Floros' successful defence in public of his doctoral dissertation "Finite element procedures for crack path prediction in multi-axial fatigue", see the previous Triennial Report. Professor Fredrik Larsson and Professor Anders Ekberg were his supervisors. The faculty-appointed external examiner of the dissertation was Professor Bo Alfredsson from the Department of Solid Mechanics at the Royal Institute of Technology (KTH) in Stockholm.

Among deterioration phenomena in rails, surface-initiated rolling contact fatigue (RCF) cracks are considered as one of the most crucial in terms of cost, reliability and safety. The study of such cracks is complicated since conventional methods of fracture analysis (linear elastic fracture mechanics, LEFM) are not suitable as the cracks form, typically, in the surface layer of rail steel where large inelastic deformations develop. Also, the strongly non-monotonic loading of the cracks, brought on by the passing wheels, complicates the analysis.

Understanding how cracks of this kind form and propagate will provide guidance for effective maintenance of rails and wheels, friction management (e g, lubrication), required intervals for profile management (e g, grinding and milling), and assessment of the influence of the profile management. The present project set out from results obtained in previous projects when establishing reliable criteria for crack propagation. In projects MU17 and MU20, RCF cracks were analysed within the concept of material forces. This concept has here been further developed by accounting for gradient-enhanced plasticity models. A framework for continuum modelling and the pertinent numerical procedures has been developed. It has been shown that the novel formulation overcomes the mesh-dependency issues otherwise pertinent to material force evaluation for (standard) local plasticity models.

The main focus of the present work concerned the suitability of different fatigue crack models. In an introductory study, numerical simulations of crack growth in a cracked tubular specimen showed the key role of plastic deformation in suppressing crack growth from cyclic tension in the presence of static torsion. These results agree well with experimental findings reported in the literature.

A methodology was developed to assess the suitability of different fatigue crack models with respect to the estimation of crack-growth direction (and kinking) under non-monotonic loading. Physical experiments from the literature have been simulated in a finite element framework developed by us, allowing for evaluation of the different criteria under various loading conditions. In order to estimate the suitability of these criteria under relevant RCF conditions pertinent to railway traffic, twin disc experiments have been considered. As a result of this study, an accumulative criterion for crack growth propagation under arbitrary load cycles was proposed. See also CHARMEC's Triennial Reports for Stages 7 and 8.

Dimosthenis Floros continued his employment until 2019-05-31. The results accounted for in his doctoral thesis were then extended and a further analysis was made of operational conditions involving local contact, rail bending and thermal loading of rails. This work was performed within project EU19 In2Track2.

Professor Fredrik Larsson, Doctor Dimosthenis Floros, Professor Bo Alfredsson and Professor Anders Ekberg at the doctoral examination in project MU33 on 18 January 2019

Dimosthenis Floros, Anders Ekberg and Fredrik Larsson: Evaluation of crack growth direction criteria on mixed-mode fatigue crack growth experiments, *International Journal of Fatigue*, vol 129, 2019, article 105075, 14 pp (also listed under project EU19)

Dimosthenis Floros, Anders Ekberg and Fredrik Larsson: Evaluation of mixed-mode crack growth direction criteria under rolling contact conditions, *Wear*, vols 448–449, 2020, article 203184, 10 pp (revised article from conference *CM2018*. Also listed under project EU19)

Head checks along inner edge of a rail. Photo: Anders Ekberg

MU34. INFLUENCE OF ANISOTROPY ON DETERIORATION OF RAIL MATERIALS

Inverkan av anisotropi på nedbrytning av rälmaterial

Project leader and supervisor	Professor Magnus Ekh, Industrial and Materials Science / Division of Material and Computational Mechanics
Assistant supervisor	Professor Johan Ahlström, Industrial and Materials Science
Doctoral candidate	Mr Knut Andreas Meyer (from 2015-05-18; Lic Eng October 2017; PhD October 2019)
Period	2015-05-18–2021-06-30 (–2021-08-31)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 150 Stage 8: KSEK 2 500 (+ 1 181 in S2R) Stage 9: KSEK 465 (+ 2 752 in S2R)
Industrial interests in-kind budget	Stage 7: KSEK 25 + 50 + 110 Stage 8: KSEK 0 + 0 + 110 Stage 9: KSEK 0 + 0 + 360 *(SL + Trafikverket + voestalpine)*

Rolling Contact Fatigue (RCF) crack initiation is often connected to the accumulation of plastic deformation in the surface layer of rails and wheels. The behaviour and strength of this highly deformed layer are thus key properties of rail and wheel materials. The work in project MU34 concerned both experimental and numerical modelling methods.

A method for producing a material in an axial-torsion testing machine with properties similar to those in the near-surface region of rails has been developed. Virgin R260 low cycle fatigue test bars were predeformed by twisting under axial compressive loads. The resulting microstructure and hardness were compared to measurements from field samples supplied by Trafikverket. The resulting material closely resembles what is found in used R260 rails at a depth between 50 and 100 μm into the railhead.

An advantage with the present predeformation method is that it produces material samples suitable for further mechanical testing. Different degrees of deformation are achieved by applying from one up to a maximum of six predeformation cycles. The twist of the specimen in each predeformation cycle is 90 degrees. The predeformed test bars are then re-turned and drilled out to form thin-walled test bars. They have been used to characterize the yielding behaviour at different depths in the rail. As expected, it was found that the size of the yield surface and the degree of anisotropy both increase with the amount of predeformation. However, the largest changes occur already after the first out of six predeformation cycles, indicating that the yield surface is anisotropic several millimetres into the railhead.

To model the anisotropic yield surfaces and their evolution observed in the experiments, distortional hardening models available in literature were evaluated. After calibration of the models it was found that they fit the experimental results rather well, but could not satisfactorily predict other results. Furthermore, their numerical stability was rather poor making them unsuitable for being used in simulations of rail–wheel contact.

Motivated by the discovered model deficiencies, an improved model formulation was developed during a research stay at TU Dortmund University in Germany. The new model is simpler and it can fit the experimental results

Professor Johan Ahlström, Doctor Knut Andreas Meyer, Professor Odd Sture Hopperstad and Professor Magnus Ekh after the doctoral examination in project MU34 on 4 October 2019

MU34. (cont'd)

better than the previously used models. It is also numerically stable making it suitable for being used in FE simulations of rolling contact.

One key usage of the developed material models is to analyse rail deterioration during rolling contact loading. In a joint work with researchers at University of Leoben in Austria, the predicted plastic deformations in a rail from two models were compared after 1400 loading cycles. We found that a good accuracy of the material model is of utmost importance.

To reduce the computer time a new methodology for rolling contact simulations was proposed based on a periodic boundary condition and a model order reduction. This gave a reduction of the computational time with a factor larger than 25. By using the methodology, a comparison was made between predicted stresses and strains in the rail from an isotropic model and from the recently developed anisotropic model. Large differences in the stresses and strains from these models were observed which again motivates the need to use an accurate material model.

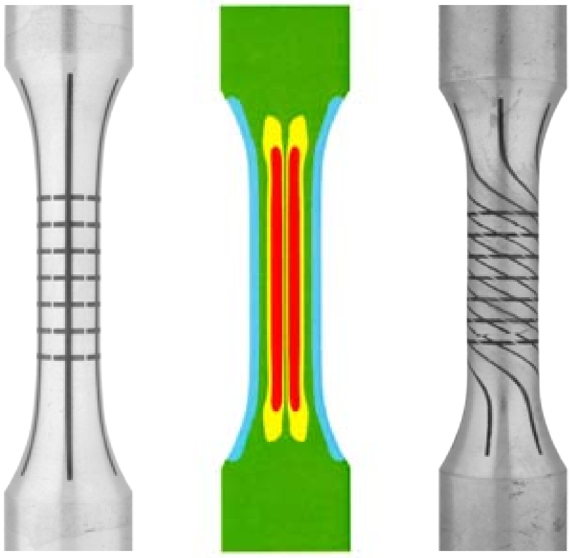
Multiaxial cyclic experiments on predeformed thin-walled cylindrical test bars have also been conducted. The purpose was to further analyse and increase the understanding of the cyclic behaviour of the anisotropic surface layer in rails. The multiaxiality of loading used in the cyclic experiments has been of both proportional and various non-proportional types.

Finally, a spinoff project within the In2Track2 project EU19 has been conducted. Here the idea is to use Digital Image Correlation (DIC, see photo on page 37) in combination with rail bending from the train load to detect cracks. A key advantage with the proposed method is that individual cracks can be explicitly described. Numerical results show that the crack depth can be determined. This information can be used both to determine how dangerous a crack is and to find how much of the material that should be removed during maintenance.

Project MU34 has been presented and discussed during biannual workshops with participants from University of Leoben, voestalpine and CHARMEC. Knut Andreas Meyer successfully defended his doctoral thesis (see below) on 4 October 2019 with Professor Odd Sture Hopperstad from Norwegian University of Science and Technology in Trondheim as the faculty-appointed external examiner.

Knut Andreas Meyer continued his employment until 2021-08-31. From 2020-09-01 he was employed as a postdoc and continued his work in projects EU19 In2Track2 and EU21 In2Track3.

For the joint reference group, see under project TS20.



Test bar in project MU34 being undeformed (left), having simulated residual shear stresses (centre) and being deformed (right)

Knut Andreas Meyer, Magnus Ekh and Johan Ahlström: Material model calibration against axial-torsion-pressure experiments accounting for the non-uniform stress distribution, *Finite Elements in Analysis and Design*, vol 163, 2019, pp 1–13 (also listed under project EU19)

Knut Andreas Meyer, Magnus Ekh and Johan Ahlström: Anisotropic yield surfaces after large shear deformations in pearlitic steel, *European Journal of Mechanics–A/Solids*, vol 82, 2019, article 103977, 21 pp (also listed under project EU19)
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Martin Pletz, Knut Andreas Meyer, David Künstner, Stephan Scheriau and Werner Daves: Cyclic plastic deformation of rails in rolling/sliding contact – quasistatic FE calculations using different plasticity models, *Wear*, vols 436–437, 2019, article 202992, 10 pp (revised article from conference *CM2018*)

Knut Andreas Meyer: Modeling and experimental characterization of large biaxial strains and induced anisotropy in pearlitic rail steel, Doctoral Dissertation, *Chalmers Industrial and Materials Science*, Gothenburg October 2019, 171 pp (Summary and six appended papers)

Knut Andreas Meyer: Evaluation of material models describing the evolution of plastic anisotropy in pearlitic steel, *International Journal of Solids and Structures*, vols 200–201, 2020, pp 266–285 (also listed under project EU19)

Knut Andreas Meyer, Daniel Gren, Johan Ahlström and Anders Ekberg: A method for in-field railhead crack detection using digital image correlation, *International Journal of Rail Transportation*, 2022, 20 pp (also listed under projects MU30 and MU35)
doi.org/10.1080/23248378.2021.2021455

Knut Andreas Meyer and Andreas Menzel: A distortional hardening model for finite plasticity, *International Journal of Solids and Structures*, vol 232, 2021, article 111055, 20 pp

Knut Andreas Meyer, Rostyslav Skrypnyk and Martin Pletz: Efficient 3D finite element modeling of cyclic elasto-plastic rolling contact, *Tribology International*, vol 161, 2021, article 107053, 12 pp

MU35. CHARACTERIZATION OF CRACK INITIATION AND PROPAGATION IN ANISOTROPIC MATERIAL

Karakterisering av sprickinitiering
och propagering i anisotropt material

Project leader and supervisor	Professor Johan Ahlström, Industrial and Materials Science / Division of Engineering Materials
Assistant supervisor	Professor Magnus Ekh, Industrial and Materials Science
Doctoral candidate	Mr Daniel Gren, MSc (from 2019-06-10)
Period	2019-06-10 – 2021-06-30 (– 2024-06-09)
Chalmers budget (excluding university basic resources)	Stage 9: KSEK 1 000 (+ 1 237 in S2R) Stage 10: KSEK 2 435 + 450 (+ 950 in S2R)
Industrial interests in-kind budget	Stage 9: KSEK 0 + 0 + 200 Stage 10: KSEK 50 + 30 + 200 *(Bombardier Transportation/ Alstom + Green Cargo + voestalpine)*

PhD student Daniel Gren (to the right) and his supervisor Professor Johan Ahlström in front of the MTS 809 axial-torsion test rig used in project MU35

The material properties close to the contact surfaces of pearlitic railway rails and wheels are not definitive after manufacturing but are developing in operation under the rolling contact loading. The accumulating cold deformation taking place leads to work hardening and alignment of the microstructure and produces a compressive residual stress in the surface layer. The microstructure developed here is similar to the one formed in drawn pearlitic steel wires. These have a tensile strength reaching over 6 GPa which is the highest existing in steel today. One presumes that this unrivalled strength is due to the aligned microstructure, which diverts microcracks to directions parallel to the loading direction of the wire. However, below the immediate rail–wheel contact, this aligned microstructure is not well suited for the loadings imposed but instead leads to cracks that form and propagate down into the rail or wheel. Understanding the strength, toughness and fatigue properties of anisotropic material is thus necessary for efficient actions against rolling contact fatigue (RCF), aiming at promoting longer life and lower life cycle costs and at furnishing a background to numerical models useful for accurate predictions.

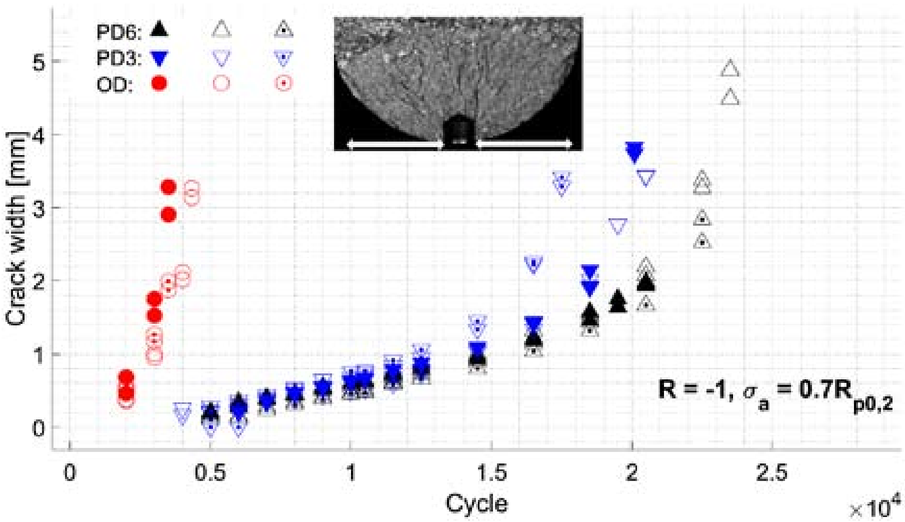
The aim of project MU35 is better to understand the anisotropy developing in service in the surface layers of rails and wheels and to display the effects the anisotropy will have on the overall properties of these components. It is known that both mechanical properties and fracture characteristics are drastically changed as the anisotropy of the material increases. Attempts to create a more favourable anisotropy will be included in the present work.

A method to predeform specimens using our axial-torsion test equipment has been developed in project MU34 such that a specimen's properties become similar to what is found in field samples. Here, this predeformation methodology has been used to produce anisotropic pearlitic rail material. The present experiments with fatigue crack initiation and propagation in anisotropic microstructures will lead to a better understanding of crack paths, to an improved background for modelling work, and to increased possibilities for prediction of safety limits and maintenance actions. Samples from field will be characterized for comparison, and interaction with other CHARMEC projects as well as with EU projects is foreseen.

A methodology for uniaxial crack propagation experiments with biaxially deformed pearlitic steel bars (grade R260) has been developed. It includes predeformation, shear strain measurement, polishing, hole drilling, developing a control program for mechanical testing and also crack measurement with optical and stereo microscopes. Furthermore, a MATLAB program for estimating the real crack length (curvature correction) using edge detection has been developed. The study is ongoing and has shown good repeatability between identical tests and well-defined crack growth rates. However, the influence of anisotropy is often difficult to distinguish and isolate from the influence of work hardening, a fact that needs to be sorted out for coming work.

The work has also included support of a study done in project MU34 where railhead surface cracks were identified from photographs taken under different levels of rail

MU35. (cont'd)



Measured crack growth under fatigue loading for different levels of predeformation of specimens in project MU35. PD6 and PD3 were predeformed to 140 % and 70 % surface shear strain, respectively, and OD was non-deformed. Crack width was measured separately for left and right side, giving two markers at the same cycle number. Three duplicate tests were done in each case, as indicated by three different markers for each predeformation level. The insert shows the appearance of a fracture surface and defines the crack widths measured

bending using Digital Image Correlation (DIC, see photo on page 37). Verification of the results included mapping of the crack network by means of serial sectioning. This means that the railhead was ground in steps to enable studies of regularly spaced internal planes by optical microscopy. The crack network was identified using image analysis of planes with 0.25 mm spacing starting from the gauge corner and down to a depth of 9 mm. It was found that the deepest cracks could be identified in the DIC images. Thus the proposed photographic method should have a potential for improving rail condition monitoring in field.

A specific task for Trafikverket included studies of samples of used pearlitic rails taken from the field. Parts of their head with different severity of damage were metallographically prepared by sectioning, grinding and polishing and thereafter examined using hardness testing and optical microscopy. Positions, lengths, depths and angles of cracks were recorded, and patterns were looked for. A weak correlation between surface length and depth of a crack was found, but it was not judged to be strong enough to be used for maintenance planning after observations of surface crack lengths only.

For the joint reference group, see under project TS20.

Daniel Gren: Utvärdering av rälskador (Assessment of rail damage; in Swedish), Internal report for the Swedish Transport Administration, *Chalmers Industrial and Materials Science*, Gothenburg September 2020, 33 pp

Knut Andreas Meyer, Daniel Gren, Johan Ahlström and Anders Ekberg: A method for in-field railhead crack detection using digital image correlation, *International Journal of Rail Transportation*, 2022, 20 pp (also listed under projects MU30 and MU34) doi.org/10.1080/23248378.2021.2021455

Example of a severe squat. Photo: DB Systemtechnik GmbH

Head check crack propagating to full rail failure on Malmbanan (Iron Ore Line) in northern Sweden

MU36. MATERIAL CHARACTERISTICS IN WELDING AND OTHER LOCAL HEATING EVENTS

Materialkarakteristik vid svetsning och annan lokal upphettning

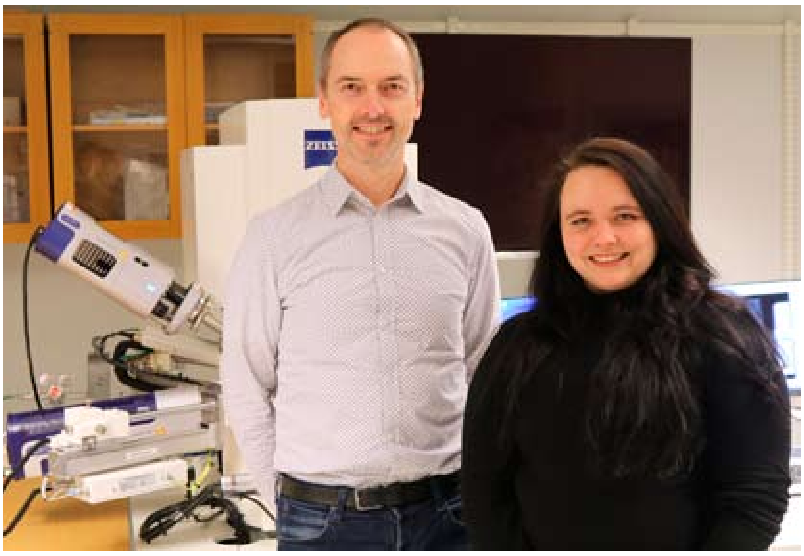
Project leader and supervisor	Professor Johan Ahlström, Industrial and Materials Science / Division of Engineering Materials
Assistant supervisor	Professor Magnus Ekh, Industrial and Materials Science
Doctoral candidat	Ms Erika Steyn, MSc (from 2019-06-10)
Period	2019-06-10 – 2021-06-30 (–2024-06-09)
Chalmers budget (excluding university basic resources)	Stage 9: kSEK 1 000 (+ 1 073 in S2R) Stage 10: kSEK 2 435 + 450 (+ 950 in S2R)
Industrial interests in-kind budget	Stage 9: kSEK 0 + 0 + 0 +200 Stage 10: kSEK 50 + 30 + 100 + 100 *(Bombardier Transportation/Alstom + Green Cargo + Lucchini + voestalpine)*

The strong effect of heat treatment on the microstructure and properties of steel makes it possible to tailor steel properties, and even to introduce beneficial gradients in properties and residual stresses. But as much as this is a benefit during manufacturing of steel products, it may be detrimental if and when the products are exposed to high temperatures during their service life.

Welding as well as grinding processes induce short-term local heating of the material. Short-term local friction heating can also occur when a railway vehicle's wheelset skids along the rail, for example, because of a malfunctioning brake or traction system or because of climatic conditions. Here the subsequent temperature elevation (usually up to 800-1000 °C) in pearlitic rail and wheel steels leads to loss of beneficial residual stresses and to material degradation and phase transformations. The temperature-dependent differences in thermal expansion, density and mechanical properties of the material phases result in residual stresses and in a localization of strains upon subsequent rolling contact loading, which can lead to crack initiation in rail and wheel surfaces.

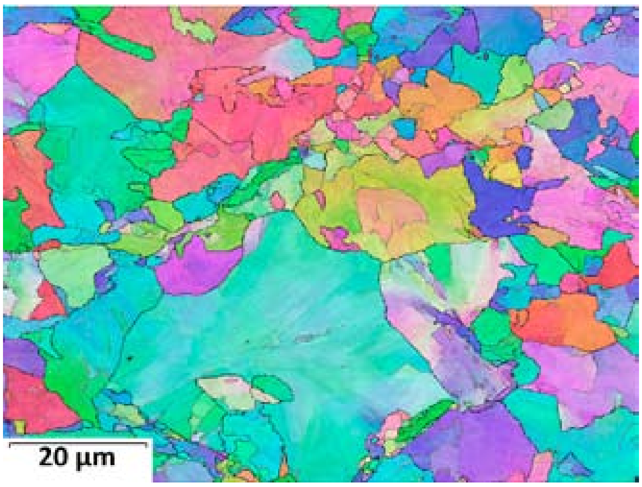
There are many parallels between the base material behaviour upon welding and the thermal damage from frictional heating, and the two areas will benefit from combined studies. The effect of local heating, whether induced by welding or friction, is a degraded or changed material structure with a subsequent gradient in mechanical properties and residual stresses. New methods for repair welding, including additive manufacturing (AM) and surface treatment, are developing and they could drastically improve the mechanical performance of the rail running surface. Especially switches and crossings and also rails in tight curves could benefit from such new techniques in a life cycle cost (LCC) perspective. However, for new technologies to be developed and successfully implemented in field after rigorous safety assessments, a solid scientific foundation is needed. This is also important for existing welding methods carried out in track, where the effect of process parameter variations may be large.

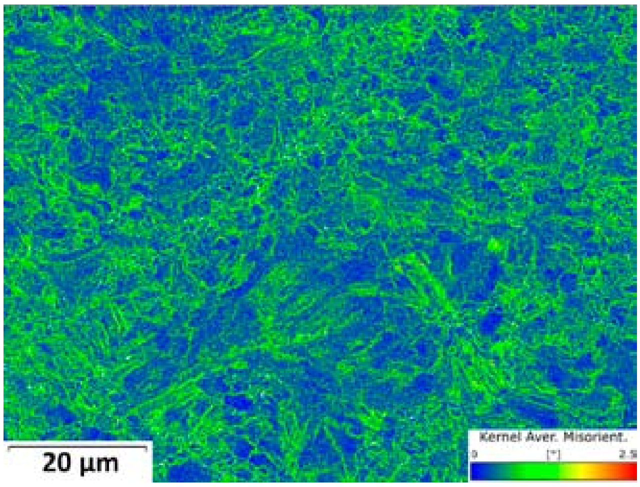
CHARMEC researchers have previously studied thermal processes, affecting the properties of rail and wheel steels, connected to rail welding (projects MU8, EU15 WRIST), laser cladding (projects MU7, EU7 INFRASTAR, MU15) and thermal damage induced by contact friction heating (projects MU2, 3, 23, 29, 30, 31, 32). Pearlitic steels have been characterized after exposure to plastic straining and elevated temperature, and to some extent high constant temperature properties of wheel material have been determined. Project MU36 aims at expanding the knowledge of material behaviour under combined thermal and mechanical loadings. Collaboration between the present experimentally oriented project and project MU37, which has focus on modelling and simulation, could lead to accurate and predictive methods supporting technology development and a decreased LCC.



PhD student Erika Steyn and her supervisor Professor Johan Ahlström in front of the new ZEISS 450 Scanning Electron Microscope (SEM) which is used in project MU36 for measuring crystal misorientation in fatigue tested samples

MU36. (cont'd)



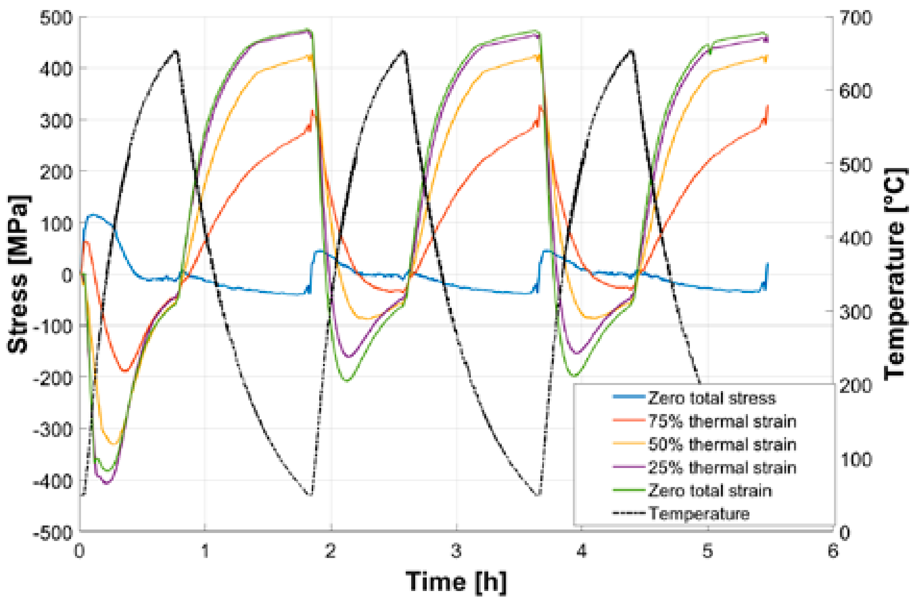


Microstructural mapping of ER7T material after LCF ($\Delta\varepsilon/2=1.0$ %) at room temperature.
Left: Orientation contrast and grain boundary plot. Right: Kernel Average Misorientation (KAM) map

In the current project MU36, ThermoMechanical Fatigue (TMF) and weld simulation, i e, experiments exposing test bars to welding-like stress-temperature cycling, are performed in our biaxial test rig which is equipped with an induction coil for rapid heating of the sample. The self-cooling taking place is sufficient for simulating block braking and other large heat input processes. More specifically, cyclic thermal loading with restricted thermal expansion was imposed to support model development for simulating block braking as studied in project SD11. Here thermal dilatation was restricted to 0, 25, 50, 75 and 100 % in the tests, leading to different amounts of plastic and viscoplastic straining. The temperature cycle used so far follows the most severe one experienced by the material in the wheel rim and wheel web, respectively. Development of a more generalized and parameterized temperature cycle is ongoing which will support evaluation of the effect on material degradation (spheroidization) during the braking cycles. As observed in the figure below, an increase of the restriction of thermal dilatation results in a higher stress response.

Microstructure characterization to promote the understanding of degradation processes can be made using different types of electron microscopy and X-ray diffraction. An ongoing study concerns the relaxation of residual stresses in samples that have been cyclically deformed and thereafter heat treated at different temperatures. The figure above shows an example of the Electron Backscatter Diffraction technique used to visualize the orientation distribution and residual strains over a large cross section. Complementary synchrotron experiments are done to allow for measurements on local level, within single grains, which better explains the mechanism of stress relaxation.

For the joint reference group, see under project TS20.



Measured stress response to restriction of thermal dilatation over three braking cycles of 110 minutes each. The five wheel rim samples were subjected to different mechanical strain levels as given in percent of the free expansion thermal strain

MU37. NUMERICAL SIMULATIONS OF WELDING AND OTHER HIGH-TEMPERATURE PROCESSES

Numerisk simulering av svetsning och andra högtemperaturprocesser

Project leader and supervisor	Professor Magnus Ekh, Industrial and Materials Science / Division of Material and Computational Mechanics
Assistant supervisors	Professor Johan Ahlström and Professor Lennart Josefson, Industrial and Materials Science
Doctoral candidate	Mr Björn Andersson (from 2019-03-18; Lic Eng December 2021)
Period	2019-03-18 – 2021-06-30 (– 2024-03-17)
Chalmers budget (excluding university basic resources)	Stage 9: kSEK 1 000 (+ 1 116 in S2R) Stage 10: kSEK 2 245 (+ 875 in S2R)
Industrial interests in-kind budget	Stage 9: kSEK 0 + 0 + 200 Stage 10: kSEK 50 + 30 + 200 *(Bombardier Transportation / Alstom + Green Cargo + voestalpine)*

Rail and wheel materials are subjected to very high stresses and, in some cases, also to elevated temperatures, and the rolling contact loading results in a multiaxial stress state with a combination of compression and shear. If the temperature in the steel is increased sufficiently and followed by rapid cooling, then austenite and martensite may develop which can be detrimental for the steel properties. Earlier research within CHARMEC has been devoted to models for these phase transformations. However, there is a need to further develop the modelling, e g, regarding the coupling between the phase transformations and the temperature-dependent cyclic mechanical behaviour of the phases in the material. The purpose is to increase the quality in the simulations of residual stresses after the phase transformations and to clarify how the stresses are affected by repeated mechanical contact loading. The developed models will be used to address applications such as short heating events (e g, braking situations) and welding and grinding of rails.

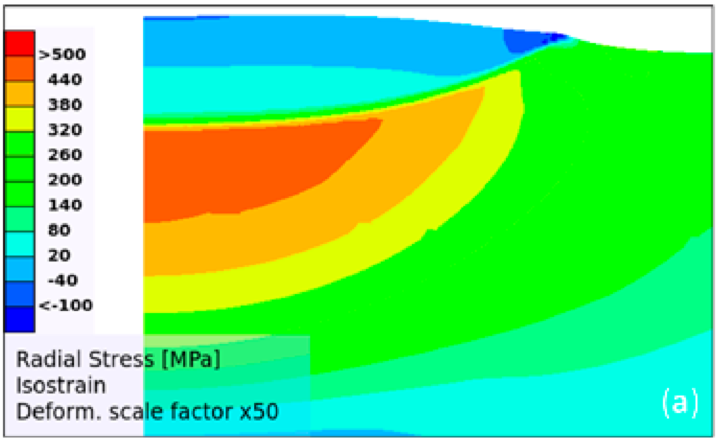
Poor adhesion during braking and traction processes may result in sliding of the wheel on the rail surface. The reason can be a defective, frozen or incorrectly tuned brake, as well as a low wheel–rail adhesion caused by environmental conditions (rain, snow, leaves etc). The sliding may lead to a localized region with instantly high temperature due to the generation of heat from friction between the wheel and the rail. The temperature is sometimes high enough to cause phase transformation to austenite in a thin surface layer. When the wheel unlocks, the wheel often cools down sufficiently fast to cause martensitic White Etching Layer (WEL) formation. For many years, WELs have been known as potential initiators of fatigue cracks in railway rail (e g, studs) and wheel steels (e g, crack clusters).

There is a need to develop models for the material behaviour due to thermal and cyclic mechanical loading combined with possible phase transformations. Such models can be used to predict plastic deformations and how residual stresses develop. Results from such predictions form the basis for fatigue crack indicators. These models will in this project, besides simulations of heat events in wheel-rail contact regions, be used for simulations of welding and grinding of rails.

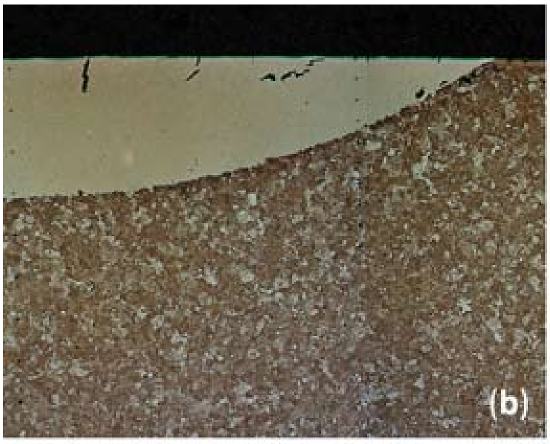
A phase transformation model for pearlitic steel has been developed during earlier CHARMEC projects. This model accounts for the phases (and microstructures) pearlite, austenite, martensite and tempered martensite.

PhD student Björn Andersson (front) together with (from the left) Professor Magnus Ekh, Professor Johan Ahlström and Professor Lennart Josefson in project MU37

MU37. (cont'd)



(a) Stress field results from simulation of the heating event



(b) Martensitic spot (WEL) on a pearlitic steel railhead induced by laser heating

A cyclic plasticity model incorporating the phase transformation model was developed in project MU32 and has been further refined in the present project. This model has now been used in thermomechanical finite element simulations of wheel skidding followed by rolling contact loading. The development of the stress field has been analysed to find explanations of why and where cracks might initiate.

In the cyclic plasticity model with phase transformations, it is necessary to homogenize the response from the phases that are present to get the overall behaviour of the multi-phase material. This can be done in different ways. A study has been conducted to investigate the influence of different choices: isostrain, isostress and a self-consistent approach. Results show that the choice has a clear influence on results for the residual stresses after a thermal loading that causes martensite formation on a rail surface. The results have also been compared to experimental data. In this study the cyclic plasticity model with phase transformations has also been extended to account for transformation-induced plasticity.

A tool for finite element simulations in ABAQUS for welding has been developed to simulate an arc welding process where a filler metal is fused and added to the material. With this tool and the improved material modelling components described above, repair welding of rails is being simulated, and also the subsequent redistribution of residual welding stresses during operation. This will enhance the prediction of the fatigue life of the repaired rail.

Project MU37 is running in parallel with an experimental project (MU36) and test results will be used to formulate and verify/validate simulation models. CHARMEC researchers have previously studied thermal processes, both connected to rail welding (MU8, EU15 WRIST), laser cladding (MU7, EU7 INFRASTAR, MU15) and thermal damage induced by contact friction heating (MU2, 3, 23, 29, 30, 32).

For the joint reference group, see under project TS20.

Ali Esmaeili, Björn Andersson, Johan Ahlström and Magnus Ekh: Modelling of cyclic plasticity and phase transformations during repeated local heating events in pearlitic steels (presented at *6th International Conference on Material Modelling (ICMM6)* in Lund (Sweden) June 2019 (Summary and Power Point presentation. Also listed under project SP30)

Ali Esmaeili, Johan Ahlström, Björn Andersson and Magnus Ekh: Modelling of cyclic plasticity and phase transformations during repeated local heating events in rail and wheel steels, *International Journal of Fatigue*, vol 151, 2021, article 106361, 15 pp (also listed under projects MU30, MU32 and EU19)

Chalmers Johanneberg campus

MU38. GROWTH OF ROLLING CONTACT FATIGUE CRACKS

Tillväxt av sprickor vid rullkontaktutmattning

Project leader and supervisor	Professor Fredrik Larsson, Industrial and Materials Science / Division of Material and Computational Mechanics
Assistant supervisors	Professor Anders Ekberg and Professor Elena Kabo, Mechanics and Maritime Sciences
Doctoral candidate	Mr Mohammad Salahi Nezhad, MSc (from 2019-09-01)
Period	2019-09-01 – 2021-06-30 (– 2024-08-31)
Chalmers budget (excluding university basic resources)	Stage 9: kSEK 800 (+ 963 in S2R) Stage 10: kSEK 2485 (+ 965 in S2R)
Industrial interests in-kind budget	Stage 9: kSEK 50 +50 + 0 + 50 + 200 Stage 10: kSEK 50 + 50 + 20 + 50 +200 *(Bombardier Transportation / Alstom + Lucchini Sweden + SNC-Lavalin / Atkins Sverige + SweMaint + voestalpine)*

Fatigue crack growth, and especially rolling contact fatigue (RCF) crack growth, is the major deterioration factor and one of the foremost cost drivers in railway operations. Therefore, extensive research and development efforts have been put into predicting and combating RCF. How different operational factors affect RCF initiation is yet to a large extent unknown. Also, quantification of the magnitude of the influence of different parameters is insufficient. The overall risk of RCF initiation can well enough be predicted but predictions of the time to initiation and failure are afflicted with large uncertainties. In particular, there are large uncertainties in the prediction of crack growth in terms of direction of the growth and the rate of propagation.

PhD student Mohammad Salahi Nezhad (second from the right) surrounded by (from the left) Professor Anders Ekberg, Professor Elena Kabo and Professor Fredrik Larsson in project MU38

The aim of project MU38 is to investigate and develop methods to predict crack progression in railway wheels and rails. This includes detailed analyses as well as coarser engineering approaches. More specifically, basic models for predicting the growth of individual cracks during cyclic loading corresponding to passing traffic will be developed based on finite element simulations. These models can then be used to evaluate the influence of different operational parameters on the direction and rate of crack growth. Ultimately, once calibrated, they can be used to aid in predicting the rate of deterioration in field and how this rate will be influenced by altered operational conditions. The latter will, however, require additional work regarding the (large) number of influencing factors not accounted for in the modelling setup.

The present research sets out and continues from the results obtained in project MU33, where models for crack path predictions were developed and verified against experimental findings. In particular, results from the models were compared to experimental findings from twin-disc experiments, which are highly relevant for the wheel–rail contact situation in railway traffic.

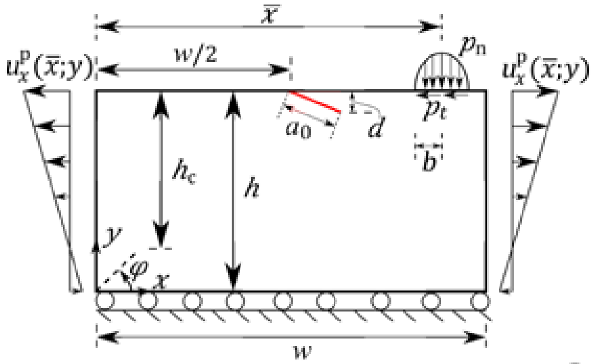
So far, the current project has involved adopting the crack growth criteria from project MU33 to loading scenarios pertinent to railway traffic. A procedure for advancing the modelled crack in a finite element model of the rail has been developed. For a set of load combinations, the crack paths have been simulated as illustrated in the figure. Here, the combined effect of local contact on the railhead (containing a pre-existing crack) and global rail stretching and bending is being studied using the finite element method, and the resulting crack paths are being simulated for different ratios between contact pressure and rail bending moment.

Results from the detailed analyses can be compared to coarser engineering predictions and increase the quantitative capabilities of the latter. The ultimate goal is to utilize operational data from track damage progression to further enhance/calibrate/validate numerical analyses.

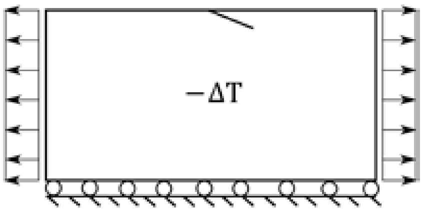
For the joint reference group, see under project TS20.

Mohammad Salahi Nezhad, Dimosthenis Floros, Fredrik Larsson, Anders Ekberg and Elena Kabo: Numerical predictions of crack growth direction in a railhead under contact, bending and thermal loads, *Engineering Fracture Mechanics*, vol 261, 2022, article 108218, 11 pp

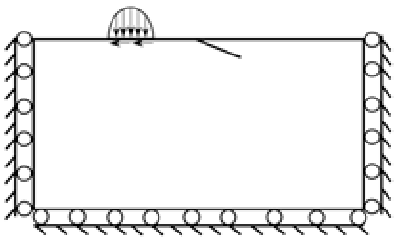
MU38. (cont'd)



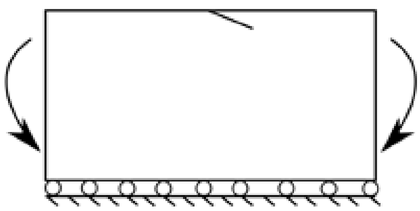
Model of part of a rail subjected to three loads due to passing traffic, and having an initial crack of length a_0.
Here $w=300$ mm, $h=100$ mm, $a_0=4.3$ mm and $d=2.0$ mm. Crack face friction not considered



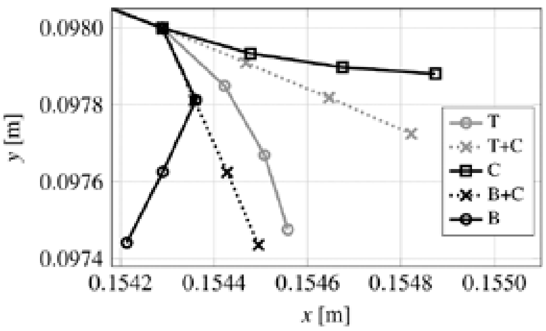
Load a: Lowered temperature



Load b: Contact from rolling wheel



Load c: Rail bending



Results from numerical simulations of the path of the propagating crack for each of the three different loads, and for two combinations

T = Temperature load
C = Contact load
B = Bending load

Extreme freight transport is achieved by iron ore wagons going from Kiruna to Luleå in Sweden and Narvik in Norway. Wagons of 20-tonne empty and 120-tonne loaded weight are carried by two bogies and eight wheels. The load 15 tonnes per wheel means a nominal elliptic wheel–rail contact area of 12 by 17 mm and a maximum contact pressure of 1400 MPa; dynamic contributions not included

MU39. NUMERICAL MODELLING OF MATERIAL DETERIORATION IN RAILWAY APPLICATIONS

Numerisk modellering av nedbrytning av material i järnvägstillämpningar

Project leaders	Professor Magnus Ekh and Professor Fredrik Larsson, Industrial and Materials Science / Division of Material and Computational Mechanics
Doctoral candidate	None (only senior researchers in this project)
Period	2018-06-01 – 2021-06-30 (– 2024-06-30)
Chalmers budget (excluding university basic resources)	Stage 9: KSEK 200 (+ 1 492 in S2R) Stage 10: KSEK 250 (+ 800 in S2R)
Industrial interests in-kind budget	Stage 9: KSEK 100 Stage 10: KSEK 100 *(voestalpine)*

For a photo of Magnus Ekh and Fredrik Larsson, see below

This project is being run in parallel with our projects TS17, MU34, MU37, MU38 and MU40 with the two-fold purpose to increase the communication and interaction between the projects and improve numerical tools that can be used in current and future CHARMEC projects.

The simulation methodology developed in project TS17 is now being documented and implemented in project MU40. The different softwares used in the methodology have been adapted to a new computer cluster at Chalmers University (called VERA). The methodology contains multi-body simulations in SIMPACK, contact simulations in ABAQUS, metamodelling, finite element simulations of plasticity, and wear predictions. Partly this has been done in project MU40 with preparatory work conducted in project MU39. Furthermore, during this preparatory work a change of algorithm has been implemented for the plasticity simulations resulting in an improved computational efficiency.

In 2020 the PhD student Nicola Zani from University of Brescia in Italy visited Chalmers during four months. Here he worked at CHARMEC with his doctoral thesis ”Numerical and semi-analytical models applied to wheel-rail contact problems” which was successfully defended in early 2021. In particular, he interacted with Professor Anders Ekberg and Professor Professor Magnus Ekh regarding finite element models, cyclic plasticity models, ratchetting and multiaxial fatigue. The co-operation has resulted in a joint publication (see below), including Professor Angelo Mazzù, former supervisor of Nicola Zani.

Nicola Zani, Magnus Ekh, Anders Ekberg and Angelo Mazzù: Application of a semi-analytical strain assessment and multiaxial fatigue analysis to compare rolling contact fatigue in twin-disk and full-scale wheel/rail contact conditions, *Fatigue & Fracture of Engineering Materials & Structures*, vol 45, issue 1, 2022, pp 222 –238

MU40. DIGITAL TWINS OF REPROFILED RAILS

Digital tvilling för omslipade räler

Project leader and supervisor	Professor Fredrik Larsson, Industrial and Materials Science / Division of Material and Computational Mechanics
Assistant supervisors	Professor Magnus Ekh and Professor Ragnar Larsson, Industrial and Materials Science, and Docent Björn Pålsson, Mechanics and Maritime Sciences
Doctoral candidate	Ms Caroline Ansin, MSc (from 2020-12-01)
Period	2020-02-04 – 2021-06-30 (– 2025-11-30)
Chalmers budget (excluding university basic resources)	Stage 9: KSEK 250 (+ 254 in S2R) Stage 10: KSEK 2485 (+ 965 in S2R)
Industrial interests in-kind budget	Stage 9: KSEK 100 Stage 10: KSEK 250 *(voestalpine)*

PhD student Caroline Ansin (front) surrounded by (from the left) Professor Ragnar Larsson, Professor Fredrik Larsson, Docent Björn Pålsson and Professor Magnus Ekh in project MU40

A digital twin modelling framework for prediction of rail deterioration under traffic loading will be developed and exploited. The aim is that the digital twin should combine accurate predictions with fast and memory-efficient compu-

MU40. (cont'd)

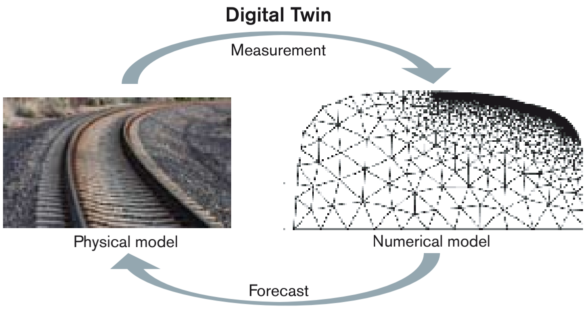


Illustration of the digital twin representing a curved rail section. The main purpose of the digital twin is to (i) describe the state of the physical entity (the rail) by conducting measurements and (ii) to allow for accurate predictions of future scenarios, known as forecasting. Thereby, the digital twin can be used to accurately predict, e g, the rate of deterioration of the rail under varying operational conditions

tations while also being continuously updated by the aid of field measurements. More precisely, the digital twin in this project will predict how the railhead surface after grinding changes its geometry due to plasticity and wear as well as damage in the form of rolling contact fatigue cracks and, finally, when the need for grinding occurs. Loading of the rail will be simulated from dynamic vehicle–track interaction accounting for representative traffic situations. The simulation results will be compared to experimental data from field, such as profile measurements (MiniProf, laser), and possibly additional measurements such as ultrasonic/eddy-current crack detection. Besides verification, the experimental data will be used in a digital twin framework to update and improve the simulation tool continuously. In addition to calibrating the model, the digital twin framework can also indicate if measurement devices show faulty results when simulation and measurement data are strongly deviating.

An important aim of the project is that it should make it possible to use the developed tools for cost-benefit evaluation of grinding geometries and intervals for a specific loading condition. To accomplish this, a parameterized rail cross section will be built up to efficiently facilitate a study of how grinding parameters will influence the rail degradation behaviour under different operational conditions. The focus in this project will be on a constant-radius part of a rail curve, where one or a few representative cross-sections will constitute the digital twin (see figure).

Work in the project started in 2020, with PhD-student Caroline Ansin being recruited in December 2020. Before that Professor Ralf Jänicke took part but then left Chalmers University for a position at Technische Universität Braunschweig in Germany.

For the joint reference group, see under project TS20.

MU41. CRACK INITIATION IN ANISOTROPIC WHEEL/RAIL MATERIAL

Sprickinitiering i anisotropt material hos hjul och räl

This doctoral project started early in Stage 10 and only a brief report is given here. Ms Nasrin Talebi was employed as PhD student in the project on 2021-11-17. Professor Magnus Ekh, Professor Johan Ahlström and Dr Knut Andreas Meyer are her supervisors. Project MU41 concerns Rolling Contact Fatigue (RCF) crack initiation which is often connected to the accumulation of plastic deformation in the surface layer of rails and wheels. The behaviour and strength of this highly deformed and anisotropic layer are thus key properties of rail and wheel materials. An experimental technique to analyse and measure these properties has been developed and exploited in the CHARMEC project MU34. Here an axial–torsion testing machine was used to subject the material to loading conditions similar to the RCF loading in field. Starting out from the experiments and the numerical models developed in project MU34, the current

PhD student Nasrin Talebi in project MU41

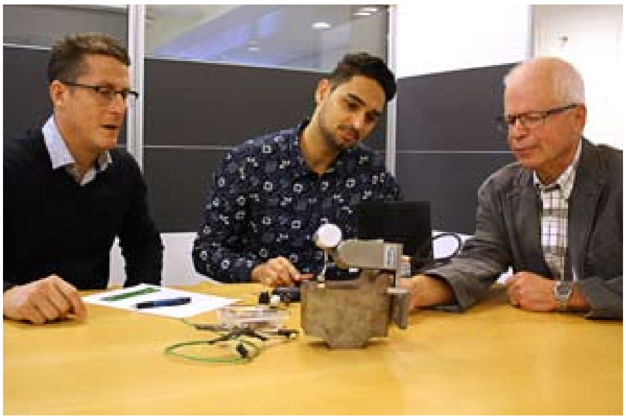
project aims to exploit and further develop fatigue crack initiation criteria for the anisotropic material. Additional experimental studies will be conducted in co-operation with project MU35. Another important aim is to improve the modelling of the anisotropic material under long-term cyclic and multiaxial loading. Throughout the project, the finite element method will be used to simulate rolling contact conditions and it will be investigated how field measurements can be used to improve and validate the modelling.

SD10. ENHANCED MECHANICAL BRAKING SYSTEMS FOR MODERN TRAINS

Förbättrade mekaniska bromssystem för moderna tåg

Project leader and supervisor	Docent Tore Vernersson, Mechanics and Maritime Sciences/ Division of Dynamics
Assistant supervisor	Professor Roger Lundén, Mechanics and Maritime Sciences
Doctoral candidate	Mr Mandeep Singh Walia (from 2014-09-01; Lic Eng March 2017, PhD November 2019)
Period	2013-03-01 – 2019-12-31
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 765 + 800 Stage 8: kSEK 3 000 + 900 Stage 9: kSEK 1 292 + 700
Industrial interests in-kind budget	Stage 7: kSEK 100 + 200 + 0 + 100 + 15 + 50 Stage 8: kSEK 100 + 200 + 0 + 100 + 15+ 50 Stage 9: kSEK 50 + 300 + 130 + 100 + 50 + 62 *(Bombardier Transportation/Alstom + Faiveley Transport + Green Cargo + Lucchini Sweden + SNC-Lavalin/ Atkins Sverige + SweMaint)*

This is a combined doctoral and senior research project



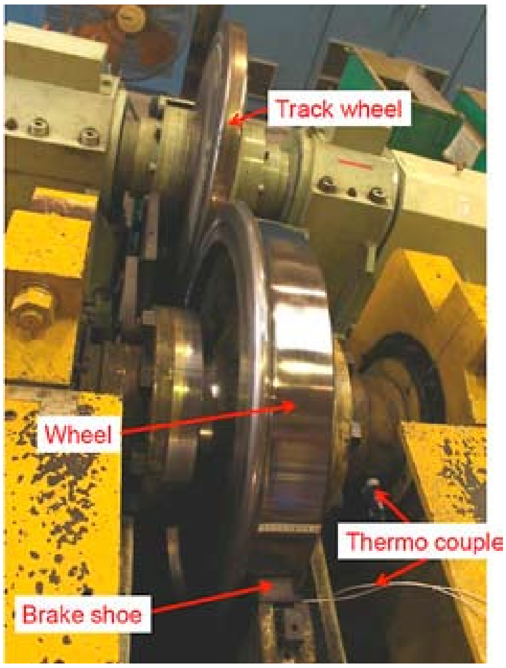
PhD student Mandeep Singh Walia (doctorate earned in November 2019) in project SD10 measuring a wheel profile using the MiniProf equipment device at Roslagsbanan Depot in Stockholm in June 2018. Together with Docent Tore Vernersson (left) and Professor Roger Lundén (right)

Modern trains are often equipped with a computer-controlled braking system that flexibly distributes the braking power between different components. For example, a system can have an electrodynamic (ED) braking device that acts in combination with mechanical (friction) brakes in the form of tread brakes and/or disc brakes. Primarily, the ED brakes are utilized and the regenerated energy can be fed back to the main power supply. However, as the efficiency of the ED brakes is speed-dependent, additional braking has to be performed using the mechanical brakes. The application of these can then range from the normal situation where they are only used in certain speed ranges to situations of ED brake malfunctioning or emergency where they must take all of the braking energy and are (more or less) constantly in use. The focus of project SD10 is on an overall effective partitioning of braking power between the components of the system. One key area is to create a basis for a judgement on what a broader employment of tread brakes compared to disc brakes would imply considering the smaller investment at installation and also the lower maintenance costs.

By using a combined experimental and numerical approach in the present project, the work of the previous project MU21 "Thermal impact on RCF of wheels" was continued in order to establish a modelling framework for tread braking with respect to tread damage. This work was performed in co-operation with Ali Esmaeili in project MU32 "Modelling of thermomechanically loaded rail and wheel steels" and with Kazuyuki Handa and Katsuyoshi Ikeuchi of the Railway Technical Research Institute (RTRI) in Tokyo (Japan), see the Triennial Report for Stage 8. Brake rig rolling contact experiments performed at RTRI studied the onset of thermal cracking of wheel treads for repeated stop braking cycles. These results have been used by us for verifying an FE based numerical simulation tool that can account for the simultaneous thermal loading from the tread braking and the impact from the mechanical rolling contact passages in the wheel–rail contact. The analyses have applied an elastoplastic material model calibrated for temperatures up to 625 °C as developed in project MU32. It was established that a plastic ratchetting type of fatigue criterion was suitable for life assessment concerning the thermal impact on RCF. The results indicate that tread temperatures higher than about 450 °C lead to a considerable increase in the ratchetting strain, which causes shorter fatigue lives of the wheel for the considered stop braking cases. On the other hand, in the temperature range 300–400 °C, a lower level of ratchetting damage is predicted due to the influence of dynamic strain ageing of the material, i e, hardening. It was also found that it is imperative to take into account local tread temperatures introduced, e g, by banded types of frictional contact between block and wheel as generated by thermoelastic interaction phenomena.

Tread plasticity in the form of tread surface depressions introduced by the wheel–rail contact was further investigated employing the modelling framework developed.

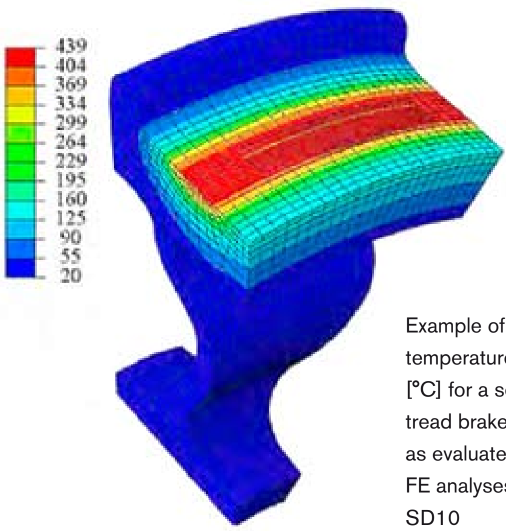
SD10. (cont'd)



Set-up of RTRI brake rig as used in project SD10

Simulation results reproducing specific constant temperature rolling tests performed at RTRI indicate that the high tread surface depressions occur during the initial revolutions during braking for a given temperature level. Further depressions are negligible for the following revolutions if the tread temperature is below 400 °C, whereas for surface temperatures above this level a ratchetting type of surface depression was observed for each repeated load cycle.

Brake wear and brake utilization was further investigated using a combination of field tests on Roslagsbanan in Stockholm (Sweden) and the present numerical simulations. In this context, brake wear means both wear of the brake blocks and wear of the wheel treads. An important result was that it is possible to distinguish between the tread wear from the wheel–rail contact and that from the wheel–block contact. The wear due to wheel–block contact amounted to about 55 % of the total measured wear for powered wheels, while for trailing wheels it was found to be about 96 %. The calibrated wear rate parameters for tread wear due to the wheel–block contact showed a 4 % variation between the two types of wheels. Additionally, it was found that the tread wear from pure rolling contact is relatively small as compared to the calculated wheel–block wear.



Example of calculated temperature distribution [°C] for a sector of a tread braked wheel as evaluated by 3D FE analyses in project SD10

Field experiments on a disc-braked postal wagon were performed in co-operation with Green Cargo and Faiveley Transport for assessing wear and braking performance. The wagon was equipped with two types of brake disc assemblies: one solid disc with organic composite pads and one segmented brake disc with sintered pads. FE models were established and calibrated using temperature data for both types of brake disc with their respective brake pads. It was found that the two disc types supplied similar cooling conditions, despite their different ventilation designs. Disc wear was six times and pad wear four times lower for the segmented disc than for the solid reference disc. In a simulated stop braking cycle, the segmented brake disc was found to have twice the calculated fatigue life (number of brake cycles until initiation of cracks on the brake disc friction surfaces) as compared to the reference brake disc.

The reference group for project SD10 had members from Bombardier Transportation (in Siegen/Germany, Sweden and UK), Faiveley Transport and SNC-Lavalin. Mandeep Singh Walia successfully defended his doctoral thesis on 20 November 2019 with Professor Paul Allen from the Institute of Railway Research at the University of Huddersfield (UK) as the faculty-appointed external examiner.

Mandeep Singh Walia, Tore Vernersson, Kazuyuki Handa, Katsuyoshi Ikeuchi and Roger Lundén: Wear and plastic deformation of the wheel tread at block braking – results from brake rig experiments and simulations, *Proceedings 19th International Wheelset Congress (IWC19)*, Venice (Italy) June 2019, 5 pp (authors received a "Best Paper Award". This is Paper D in Doctoral Dissertation below)

Mandeep Singh Walia, Tore Vernersson, Roger Lundén, Fredrik Blennow and Markus Meinel: Temperatures and wear at railway tread braking – field experiments and simulations, *Wear*, vols 440–441, 2019, article 203086, 9 pp (revised article from conference *CM2018*)

Mandeep Singh Walia: Mechanical braking systems for trains – a study of temperatures, fatigue and wear by experiments and simulations, Doctoral Dissertation, *Chalmers Mechanics and Maritime Sciences*, Gothenburg November 2019, 112 pp (Summary and five appended papers)

Mandeep Singh Walia, Gaël Le Gigan, Bjarke Raaby and Tore Vernersson: Performance of solid and segmented railway brake discs – temperatures, wear and fatigue investigated by field experiments and simulations, *Proceedings Europe's Braking Technology Conference & Exhibition (EuroBrake 2021,* online*)*, Paris May 2021, 12 pp (revised Paper E in Doctoral Dissertation above)

SD11. TREAD BRAKING – CAPACITY, WEAR AND LIFE

Blockbromsning – kapacitet, slitage och livslängd

Project leader and supervisor	Docent Tore Vernersson, Mechanics and Maritime Sciences/ Division of Dynamics
Assistant supervisor	Professor Roger Lundén, Mechanics and Maritime Sciences
Doctoral candidate	Mr Eric Voortman Landström, MSc (from 2020-02-01)
Period	2020-02-01 – 2021-06-30 (– 2025-01-31)
Chalmers budget (excluding university basic resources)	Stage 9: kSEK 1 490 + 600 Stage 10: kSEK 3 450 + 3 650
Industrial interests in-kind budget	Stage 9: kSEK 50 + 170 + 100 + 100 + 50 + 0 Stage 10: kSEK 100 + 200 + 100 + 100 + 50 + 50 *(Bombardier Transportation/Alstom + Faiveley Transport + Green Cargo + Lucchini Sweden + SNC-Lavalin/ Atkins Sverige + SweMaint)*

This is a combined doctoral and senior research project

Docent Tore Vernersson, PhD student Eric Voortman Landström and Professor Roger Lundén in project SD11

Tread braking is a low-cost solution for trains where the braking requirements do not exceed the limits of this system. The limits relate to different aspects such as safety (global wheel failure, winter-related loss of braking efficiency), costs (wear of wheels and pads, premature tread failure due to RCF), health (particle emission), or societal aspects (noise emission). The aim of project SD11 is to acquire in-depth knowledge and to establish limits for commercial applications of tread brakes relating to requirements of today and the near future. The project spans tread braking of freight wagons, metros and commuter trains and has its focus on the sliding contact between wheel and brake block and the rolling contact between wheel and rail. The main knowledge gaps that the project will bridge thus relate to tread braking and (i) simulation of global wheel behaviour at extreme temperatures, (ii) quantification of influence on RCF life of wheel, (iii) establishment of temperature-dependence of tread wear, (iv) research into improved brake blocks for winter conditions with optimized material combinations, (v) extension of tread braking wear models to also consider modelling of particle emission, and, finally, (vi) monitoring of brake blocks using internet-of-things concepts.

Starting out with focus on wheel behaviour at extreme temperatures, material models previously developed in project MU32 for mimicking wheel material ER7 steel have been evaluated with regard to performance in mechanical simulations of freight wheels for constant power braking with long duration. Further studies indicated that the simulations result in non-conservative predictions of tensile residual rim stresses, which implies that wheels designed using only simulations could be hazardous in revenue traffic. The previous calibration procedure of the material models employing only isothermal test data at several constant temperature levels is now being complemented by anisothermal materials testing of specimens. Here both temperature and strain variations in the material are simultaneously mimicked during extreme tread braking. This is performed in collaboration with Erika Steyn and Johan Ahlström in project MU36, using test specimens machined from both rim and web of wheels supplied by Lucchini RS in Italy. Chosen temperature and strain variations are based on simulated data from braking simulations. It has been found that the viscoplastic material models established in project MU32 could be suitable for prediction of anisothermal tests if the material parameters are recalibrated and minor modifications are made to the models. Additionally, it is foreseen that material damage caused by pearlite breakdown, in the form of spheroidization that occurs above some 400 °C, needs to be accounted for in the material model.

In parallel to the above, work with establishing a brake test rig at the Chalmers premises has been ongoing since spring 2020, see project SP34. The test rig and its functionality, which includes a so-called rail-wheel in rolling contact with the tread braked wheel, will be instrumental for the continued work in project SD11. In particular, experimental results will be important when it comes to developing new knowledge and numerical models regarding global wheel

SD11. (cont'd)

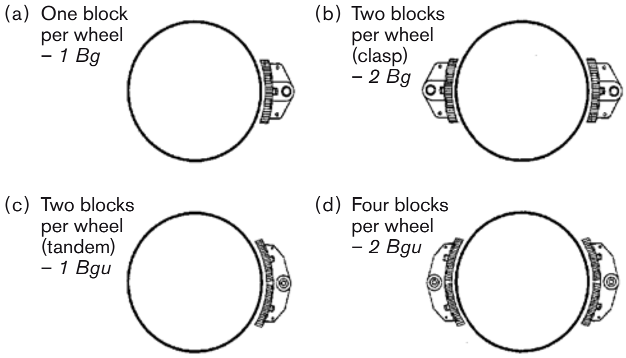
behaviour at extreme braking temperatures, investigations of temperature influence on RCF life and tread wear, and, finally, building knowledge of particle emissions from tread braked systems.

Tore Vernersson has been involved in planning and data analyses of winter field tests run by Transportstyrelsen (The Swedish Transport Agency) for assessment of LL brake block performance in winter conditions. Final reports from the 2018–2019 and 2019–2020 winter tests are now available on the Transportstyrelsen home page. This work had separate funding from Transportstyrelsen.

The joint reference group of projects SD11 and SP34 has members from Atkins Sverige, Bombardier Transportation / Alstom and Faiveley Transport.

Tore Vernersson, Anders Ekberg and Roger Lundén: Swedish tests of block brake performance in winter conditions – winter 2019–2020, *Chalmers Mechanics and Maritime Sciences / CHARMEC*, 2020-10-09, 79 pp

Tore Vernersson, Anders Ekberg and Roger Lundén: Swedish tests of LL brake blocks under winter conditions – winter 2020–2021, *Chalmers Mechanics and Maritime Sciences / CHARMEC*, 2021-10-27, 93 pp



Four common brake block arrangements. Two blocks can be used in either (b) clasp or (c) tandem arrangements. Bg and Bgu stand for "Bremsklotz geteilt" and "Bremsklotz geteilt unterteilt" (German terms)

Simulation of stop braking, drag braking and complete braking programs (sequences recorded in-field) is performed in an outdoor environment. Disc brakes and block brakes with a maximum wheel diameter of 1500 mm can be handled. An electric motor of maximum power 250 kW drives 2 to 12 flywheels, each at 630 kg and 267 kgm^2, with a maximum speed of 1500 rpm

The brake test rig (inertia dynamometer) at Surahammar (used in projects SD1, SD4, EU1 and EU8) at its inauguration in 1989. From the left: Roger Lundén, Josef Rauch (from Sura Traction, now Lucchini Sweden), Bengt Åkesson, Elisabet Lundqvist and Lennart Nordhall (both from Sura Traction), Mikael Fermér (from Chalmers Solid Mechanics), and Nils Månsson and Sven A Eriksson (both from SJ Machine Division)

Parameters controlled	**Results recorded**
Braking air pressure (max 5 bar)	Braking moment
Train speed (max 250 km/h)	Temperatures
Axle load (max 30 tonnes)	Strains and stresses
Environment (heat, cold, water, snow...)	Wear

Design for two extreme stop braking cases:

$2m$	v_0	s_{sign}	s_b	t_b	r	Q_0	E	D	n	M
tonnes	km/h	m	m	s	m/s^2	kW	kWh	m	rpm	Nm
30	140	1000	772	39.7	0.98	571	3.15	0.92	807	6760
16	250	3500	2837	81.7	0.85	472	5.36	0.88	1500	2990

EU15. WRIST

WRIST – Innovative Welding Processes for New Rail Infrastructures

Project leader	Professor Lennart Josefson, Industrial and Materials Science / Division of Material and Computational Mechanics
Co-workers	Dr Jim Brouzoulis, Mechanics and Maritime Sciences, Mr Tomas Andersson, MSc, ÅF, Mr Roeland Bisschop, MSc, and Mr Michele Maglio, MSc, the last two then at Industrial and Materials Science
Period	2015-05-01 – 2019-01-31
Budget EU	kEUR 417
Budget Chalmers	Stage 8: kSEK 400 Stage 9: kSEK 0

For a photo of Lennart Josefson, see page 46

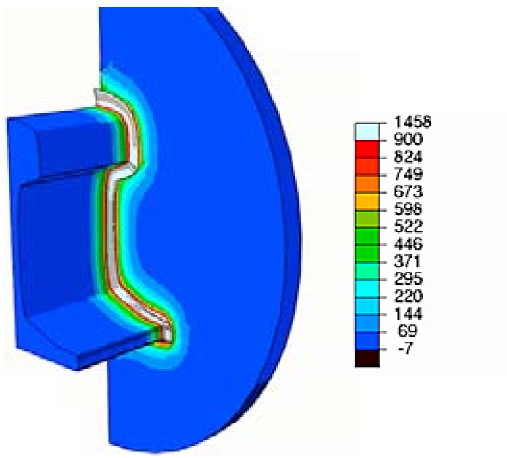
WRIST was a research project within the European Union's Horizon 2020 Programme, see www.wrist-project.eu, and was placed under the topic MG-8.1a-2014 – Smarter design, construction and maintenance. The aim of WRIST was to develop and demonstrate two new joining processes for rails in field (orbital friction welding and aluminothermite welding) that would address the key degradation mechanisms experienced by welds in current rail infrastructure and reduce the width of the heat affected zone (HAZ) in the joint. WRIST was co-ordinated by the Belgian Welding Institute (BWI). In addition to Chalmers/CHARMEC, the eight partners were University of Huddersfield (UK), TU Delft (The Netherlands), ProRail (The Netherlands), Goldschmidt Thermite Group (Germany), DENYS (Belgium), JACKWELD (UK), ID2 BV (The Netherlands) and ARCTIC (France).

WRIST was divided into nine work packages (WP). CHARMEC contributed (man-months in parentheses) in WP2 Further development of the new aluminothermite welding process (1 MM), WP3 Further development of the new orbital friction welding method (1 MM), WP4 Finite element modelling of the welding processes (CHARMEC was WP-leader with 20 MM), WP5 Design of the intermediate component for orbital friction welding (2 MM), and WP8 Dissemination, sustainable impact and exploitation (3 MM). The project was extended by nine months due to problems with the manufacturing of the orbital friction welding machine. The European Commission approved the final and concluding technical and financial reports in September 2019.

Our work has focused on developing numerical models for thermomechanical finite element analysis of the two welding methods. For the Orbital Friction Welding (OFW) method, a heat generation model, with the three variables friction coefficient, pressure and velocity, was validated against an experimental pilot case of friction welding (FW) of a thin-walled pipe (carried out at BWI), where process parameters, temperatures and microstructure were measured. Using this model, temperatures and deformations during OFW of bars has been simulated for the final design of the OFW providing information for the best choice of process parameters to avoid martensite formation in the weld. The final OFW machine, placed in Ghent (Belgium), was completed and operative too late, so only a few OFW welded bars were produced within the project. These bars exhibited cracks which indicated that a refinement of the machine would have been needed.

As to the aluminothermite welding, a thermomechanical model of the full process was developed by us. It included preheating, tapping, pouring of molten material, applying a compressive force (forging) during a short period at high temperatures, and shearing off of excess material. The model was verified using temperature measurements for the preheating and welding phases made by a subsidiary to the partner Goldschmidt Thermite Group (now Goldschmidt GmbH). Mechanical results, i e, the extent of the HAZ, were verified using microstructure and hardness measurements made by the partner TU Delft, and the residual stress field was verified against experimental results from the literature for the standard case with no compressive force (forging) applied. A separate cooling stage to reduce the total cooling time has also been evaluated. See also CHARMEC's Triennial Report for Stage 8.

Lennart Josefson, Roeland Bisschop, Maha Messaadi and Jan Hantusch: Residual stresses in thermite welded rails – significance of additional forging, *Welding in the World*, vol 64, issue 7, 2020, pp 1195–1212



Calculated temperatures (maximum close to 1500 °C) in the deformed rail at the end of the heating stage in orbital friction welding. Part of rotating disc is seen to the right

EU17. In2Track

In2Track – Research into Enhanced Tracks, Switches and Structures

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	The project engages most of the staff at CHARMEC
Period	2016-09-01 – 2019-04-30
Budget Trafikverket / EU	Stage 8: kSEK 8 007 Stage 9: kSEK 3 732
Budget Chalmers	Stage 8: kSEK 640 Stage 9: kSEK 139

Shift2Rail as of April 2018 (from CORDIS database)

In2Track (S2R-CFM-IP3-01-2016) was a project within the Horizon 2020 Framework Programme under the Shift2Rail Joint Technology Initiative with the project value MEUR 6.4 including the EU funding MEUR 2.8. The overall project co-ordinator was Trafikverket, see shift2rail.org/in2track/. CHARMEC's Anders Ekberg served as scientific–technical co-ordinator for the whole project In2Track.

The six work packages (WP) in In2Track were WP1 Project management, WP2 Enhanced switches and crossings, WP3 Enhanced track, WP4 Structures, WP5 Scientific and technical co-ordination and system integration, and WP6 Dissemination, communication and exploitation. CHARMEC was involved in WP2, WP3 and WP5 and assisted in WP1. Our contributions to In2Track included work performed in several parallel CHARMEC projects and the corresponding activities are here presented under these projects. Several presentations regarding CHARMEC's research in In2Track were given at the 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems in Delft (The Netherlands) on 24–27 September 2018. Co-ordination activities during Stage 9 included presentations of In2Track at the European Railway Maintenance group on 2018-09-04 in Solna (Sweden) by Anders Ekberg and Sam Berggren (Trafikverket), at a Steering Committee / Technical Management Team meeting on 2018-11-29 in Malmö (Sweden), and at a meeting and site visit to the Vertex vertical switch company in Kil (Sweden) on 2018-12-01.

In closing In2Track, Anders Ekberg presented WP3 and WP5 at a Skype meeting on a possible UIC implementation project on 2019-06-29, and at the final In2Track review in Brussels on 2019-10-03.

The In2Track final conference took place in Paris on 2019-01-22. Here Anders Ekberg presented part of the work in WP3 and participated in the panel at the round-table discussion. To facilitate implementation, Anders Ekberg and Björn Paulsson participated in a meeting on implementation at Trafikverket on 2019-02-25. Anders Ekberg further took part in an implementation meeting in Borlänge on 2019-03-25 and in a review meeting with the Shift2Rail JU (Joint Undertaking) in Brussels on 2019-04-03. He also made a presentation of In2Track at the IHHA2019 conference in Narvik. The work in In2Track has been continued in In2Track2 which started in November 2018.

Deliverables

Melanie Denley (editor): Identifying and understanding core S&C Issues, In2Track Deliverable 2.1, 2018, 153 pp and 2 annexes (2+38 pp)

Jamie Wilkes (editor): Enhanced S&C whole system analysis, design and virtual validation, In2Track Deliverable 2.2, 2019, 338 pp and 2 annexes (61+11 pp)

Andrew Turner (editor): Enhanced monitoring, operation, control and maintenance of S&C, In2Track Deliverable 2.3, 2019, 191 pp and 1 annex (7 pp)

Anders Ekberg (editor): Enhanced track structure – status, key influencing parameters and prioritised areas of improvement, In2Track Deliverable 3.1, 2018, 268 pp and 16 annexes (59+17+14+9+6+7+47+25+49+7+8+10+9+11+29+20 pp)

Samir Assaf (editor): Enhanced track design solutions through predictive analyses, In2Track Deliverable 3.2, 2019, 327 pp and 9 annexes (10+11+49+4+6+59+8+7+10 pp)

Anders Ekberg (editor): Enhanced inspection, maintenance and operation of track, In2Track Deliverable 3.3, 2019, 118 pp and 7 annexes (8+7+42+8+7+53+16 pp)

Anders Ekberg (editor): Report on coordination and quality, In2Track Deliverable 5.2, 2019, 35 pp

Anders Ekberg (editor): Main results and input to implementation from In2Track, *Chalmers Mechanics and Maritime Sciences*, 2019, 17 pp

Anders Ekberg and Sam Berggren: In2Track – some implementable results, *Chalmers Mechanics and Maritime Sciences*, 2019, 3 pp

For completeness, also the annexes delivered by Chalmers/CHARMEC to In2Track Deliverables 3.1, 3.2 and 3.3 are listed below. It should be noted that several of these articles were listed in the previous Triennial Report under CHARMEC projects which related to In2Track.

EU17. (cont'd)

Annexes from Chalmers to In2Track Deliverable 3.1

Robin Andersson: Squat formation and subsequent crack growth, *Chalmers Mechanics and Maritime Sciences*, 2018, 59 pp (revised version of Summary of Doctoral Dissertation by Robin Andersson, see project MU31 in the previous Triennial Report. Also listed under annexes to Deliverable 3.2)

Robin Andersson, Fredrik Larsson and Elena Kabo: Evaluation of stress intensity factors under multiaxial and compressive conditions using low order displacement or stress field fitting, *Engineering Fracture Mechanics*, vol 189, 2018, pp 204–220

Robin Andersson, Johan Ahlström, Elena Kabo, Fredrik Larsson and Anders Ekberg: Numerical investigation of crack initiation in rails and wheels affected by martensite spots, *International Journal of Fatigue*, vol 114, 2018, pp 238–251

Casey Jessop, Johan Ahlström, Lars Hammar, Søren Fæster and Hilmar Danielsen: 3D characterization of rolling contact fatigue crack networks, *Wear*, vols 366–367, 2016, pp 392–400 (revised article from conference *CM2015*)

Casey Jessop and Johan Ahlström: Crack formation on pearlitic rail steel under uniaxial loading – effect of initial thermal damage, *Proceedings 8th International Conference on Low Cycle Fatigue (LCF 8)*, Dresden (Germany) June 2017, DVM Berlin 2017, pp 275–280 (also listed under annexes to Deliverable 3.2)

Casey Jessop and Johan Ahlström: Friction between pearlitic steel surfaces, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 421–437

Casey Jessop: Damage and thermally induced defects in railway materials, 2017, 37 pp (Summary of Licentiate Thesis by Casey Jessop, see project MU29 in the previous Triennial Report)

Dimosthenis Floros, Fredrik Larsson and Kenneth Runesson: On configurational forces for gradient-enhanced inelasticity, *Computational Mechanics*, vol 61, issue 4, 2018, pp 409–432

Dimitrios Nikas: Formation of anisotropy in rails and its effect on crack formation and growth, 2018, 49 pp (revised version of Summary of Doctoral Dissertation by Dimitrios Nikas, see project MU28 in the previous Triennial Report)

Dimitrios Nikas, Xiodan Zhang and Johan Ahlström: Evaluation of local strength via microstructural quantification in a pearlitic rail steel deformed by simultaneous compression and torsion, *Materials Science & Engineering A*, vol 737, 2018, pp 341–347

Dimitrios Nikas, Knut Andreas Meyer and Johan Ahlström: Characterization of deformed pearlitic rail steel, *Proceedings 38th Risø International Symposium on Materials Science and Engineering*, Risø/Roskilde (Denmark) September 2017, *IOP Conference Series: Materials Science and Engineering*, vol 219, article 0121035, 7 pp

Knut Andreas Meyer, Dimitrios Nikas and Johan Ahlström: Microstructure and mechanical properties of the running band in a pearlitic rail steel – comparison between biaxially deformed steel and field samples, *Wear*, vols 396–397, issue 1, 2018, pp 12–21

Knut Andreas Meyer and Magnus Ekh: A comparison of two frameworks for kinematic hardening in hyperelasto-plasticity, *Proceedings 14th International Conference on Computational Plasticity – Fundamentals and Applications (COMPLAS 2017)*, Barcelona (Spain) September 2017, pp 342–350

Knut Andreas Meyer, Magnus Ekh and Johan Ahlström: Modeling of kinematic hardening at large biaxial deformations in pearlitic rail steel, *International Journal of Solids and Structures*, vol 130, 2018, pp 122–132

Annexes from Chalmers to In2Track Deliverable 3.2

Dimitrios Nikas: Rail and track deterioration under influence of thermal loading, *Chalmers Industrial and Materials Science,* 2018, 49 pp (revised version of Summary of Doctoral Dissertation by Dimitrios Nikas, see project MU28 in the previous Triennial Report)

Anders Ekberg, Elena Kabo and Dan Cedergårdh: Estimating resistance against track buckling, *Chalmers Mechanics and Maritime Sciences*, 2018, 4 pp

Casey Jessop and Johan Ahlström: Crack formation on pearlitic rail steel under uniaxial loading – effect of initial thermal damage, *Proceedings 8th International Conference on Low Cycle Fatigue (LCF 8)*, Dresden (Germany) June 2017, DVM Berlin 2017, pp 275–280 (also listed under annexes to Deliverable 3.1)

Robin Andersson: Squat formation and subsequent crack growth, *Chalmers Mechanics and Maritime Sciences*, 2018, 59 pp (revised version of Summary of Doctoral Dissertation by Robin Andersson, see project MU31 in the previous Triennial Report. Also listed under annexes to Deliverable 3.1)

Ali Esmaeili, Johan Ahlström and Magnus Ekh: Modelling of cyclic plasticity and phase transformations during repeated local heating events in rail and wheel steels, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 245–252

Anders Ekberg, Elena Kabo and Jens Nielsen: Predicting long crack growth in rails – the example of rail foot cracks, *Chalmers Mechanics and Maritime Sciences*, 2018, 7 pp

Anders Ekberg and Björn Pålsson: The role of contact mechanics in multiscale modelling of train–track interaction phenomena (Plenary Lecture), *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 228–237

Annexes from Chalmers to In2Track Deliverable 3.3

Knut Andreas Meyer, Johan Ahlström and Magnus Ekh: Characterization of yield surface evolution due to large plastic shear strains in pearlitic rail steel, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 745–752

Robin Andersson, Peter Torstensson, Elena Kabo, Fredrik Larsson and Anders Ekberg: Integrated analysis of dynamic vehicle–track interaction and plasticity induced damage in the presence of squat defects, *Wear*, vols 366–367, 2016, pp 139–145 (revised article from conference *CM2015*)

Dimosthenis Floros: Numerical methods for prediction of the multi-axial fatigue crack growth direction, *Chalmers Industrial and Materials Science*, 2018, 42 pp (revised version of Summary of Doctoral Dissertation by Dimosthenis Floros, see project MU33 in the previous Triennial Report)

Dimosthenis Floros, Anders Ekberg and Fredrik Larsson: Evaluation of mixed-mode crack growth criteria under rolling contact conditions, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 253–260

Elena Kabo, Anders Ekberg and Michele Maglio: Rolling contact fatigue assessment of repair rail welds, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 450–456

EU18. Fr8Rail

Fr8Rail – Development of Functional Requirements for Sustainable and Attractive European Rail Freight

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-worker	Docent Tore Vernersson, Mechanics and Maritime Sciences
Period	2016-09-01 – 2019-08-31
Budget Trafikverket	Stage 8: KSEK 330 Stage 9: KSEK 166

The Fr8Rail project is part of the Shift2Rail Research and Innovation Action. The overall objectives of the project were: (1) a 10 % reduction in the cost of freight transport, (2) a 20 % reduction in the time variations during dwelling, and (3) an increased attractiveness of logistic chains by making available 100 % of the rail freight transport information to logistic chain information systems. The CHARMEC contribution to the project was a study focusing on the performance of LL-type brake blocks, which have been introduced as a retrofit solution in order to resolve rolling noise issues related to the high tread roughness resulting from braking using cast iron brake blocks. However, the LL blocks introduce new problems related to wheel tread damage and braking performance under winter conditions.

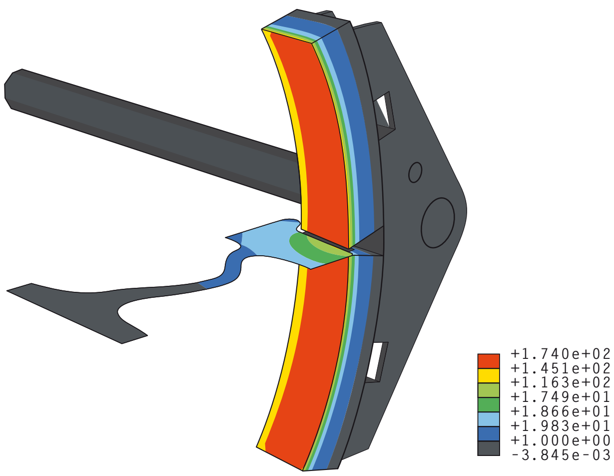
Reports from the UIC EuropeTrain project provided detailed information on braking operation and wear of blocks and wheel treads, with a total travelled distance for the dedicated test train of about 250 000 km. Utilization of numerical data from the reports in combination with response surface analyses meant that energy-related wear relations for treads and blocks could be established. The LL blocks were found to wear at a considerably slower rate than cast iron brake blocks. On the other hand, the LL blocks generated a higher degree of tread wear with a propensity for hollow wear, which may introduce unstable running of vehicles. Cast iron blocks seemed to yield the same tendency for this detrimental wear pattern for unloaded wagons, but not for loaded wagons. Simulation efforts revealed that local variations in tread temperature could be responsible for the generation of hollow wear. The LL block materials cause higher temperatures centrally at block and tread which gives high tread wear in this area. For cast iron blocks, the areas of contact between block and tread instead seem to continuously shift to new positions, effectively evening out the wear over the entire block width.

Simulation of thermal impact on RCF for freight-type axle loads was performed based on the modelling framework developed in projects SD10 and MU32. Stop braking conditions at 22.5 tonne axle loads confirmed previous findings that the local tread temperature is the main controlling parameter for RCF damage at tread braking.

The "natural" de-icing for different brake block materials at tread braking has also been investigated. A previously developed thermal model, with an axisymmetric representation for the wheel and a plane one for the brake blocks, was further enhanced by introducing a 3D representation of brake block and holder. For situations where ice-layers have previously built-up on the equipment, detailed studies revealed braking temperatures on different regions of block and of holder. Cast iron and sintered brake block materials showed substantially better de-icing characteristics as compared to organic composite brake block materials. Due to their substantially lower thermal conductivity, the latter produce a relatively low degree of de-icing in the assumed drag braking scenarios, see figure below. The improved de-icing of a built-up type of brake block, featuring an outer shell made from sinter material and an interior portion made from organic composite material, was demonstrated, see reports below. No efforts have been made to investigate the feasibility of manufacturing such a built-up brake block.

Fr8Rail Deliverable D4.4: Detailed running gear and wagon design concept, FR8-WP4-D-ViF-030-01, 2018-08-28, 443 pp (CHARMEC contributed to the chapter "Wheelset concepts and wheel material development")

Tore Vernersson, Anders Ekberg and Roger Lundén: Railway freight braking and LL brake blocks – three remaining challenges, *Proceedings 19th International Wheelset Congress (IWC19)*, Venice (Italy) June 2019, 7 pp (authors recieved a "Best Paper Award")



Example of simulation of natural de-icing of an organic composite brake block with holder after a short duration drag braking (30 kW for 5 min) with temperatures in °C. Original ice thickness was 5 mm. Dark grey areas are still ice covered

EU19. In2Track2

In2Track-2 – Research into Enhanced Track and Switch and Crossing System 2

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	The project engages most of the staff at CHARMEC
Period	2018-11-01 – 2021-05-31
Budget Trafikverket / EU	Stage 9: KSEK 28 998
Budget Chalmers	Stage 9: KSEK 2 298

In2Track2 (S2R-CFM-IP3-01-2018) is a project within the Horizon 2020 Framework Programme under the Shift2Rail Joint Technology Initiative with the project value MEUR 29.7 including the EU funding MEUR 13.2. The overall project co-ordinator is Network Rail, see projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2TRACK2.

The eight work packages (WP) in In2Track2 are WP1 Enhanced switch & crossing system, WP2 Next generation switch & crossing system, WP3 Optimised track system, WP4 Next generation track solutions, WP5 Proactive bridge and tunnel assessment, repair and upgrade, WP6 Project management, WP7 Technical co-ordination and technology demonstrator integration, and WP8 Dissemination, communication and exploitation. CHARMEC was engaged in WP1, WP2, WP3 and WP4.

Our contribution to In2Track2 included work from several parallel CHARMEC projects. The corresponding activities are presented under these projects. Only co-ordination activities and additional research activities are reported below. However, all deliverables and papers submitted to In2Track2 are listed in the following. Chalmers' work in the project was formally terminated on 2021-05-31. However, since there are pending reports from other partners we were later assigned additional work. The entire project formally ended on 2021-12-07.

Meetings

The official kick-off of the full project In2Track2 was held on 2018-11-06, the kick-offs of WP1 and WP3 on 2018-11-07, and those of WP2 and WP4 on 2018-11-14. All of them took place in London. Björn Pålsson participated in a WP1 meeting in Vienna on 2019-09-18 and Johan Ahlström in WP2 and WP4 meetings in London on 2019-10-16–17. A co-ordination meeting between Trafikverket and CHARMEC was held at Chalmers on 2019-11-27. In addition, CHARMEC researchers have also participated through Skype/WebEx in several co-ordination meetings with Trafikverket and within the work packages. Anders Ekberg and Jannik Theyssen participated in a WP3 meeting in Delft on 2020-02-27. Moreover, CHARMEC's staff has also taken part in regular web-based Task leader meetings in the different WPs. Björn Pålsson arranged a half-day workshop on Whole System Modeling (WSM) on 2020-03-30 for WP1 Task 1.1. Michele Maglio, Knut Andreas Meyer and Anders Ekberg presented research in In2Track2 at the Shift2Rail Innovation Day online 2020-10-23.

Interaction with In2Track and In2Track3

In closing the predecessor In2Track, Anders Ekberg presented WP3 and WP5 at the final review of In2Track in Brussels on 2019-10-03 and at a Skype meeting on a possible UIC implementation project on 2019-06-29. A planning meeting for the successor project In2Track3 was held in Stockholm on 2019-12-19. CHARMEC has contributed to the In2Track3 project proposal, which was submitted on 2020-05-27 (and subsequently approved with the score 14 of 15). This work includes major revisions due to withdrawal of Vossloh and descoping by Network Rail.

Research

Most research results are presented in relation to other CHARMEC projects. The presentation below only concerns some of the additional activities that have been carried out in In2Track2. The annexes to the chapters listed here have in many cases been updated since they were submitted to the project and the up-to-date versions are given below.

Discrete wheel/rail surface irregularities. Preparatory work for the study was carried out and reported in the paper "Wheel-rail impact loads, noise and vibration – a review of excitation mechanisms, prediction methods and mitigation measures" which was be presented at IWRN13 in Ghent (Belgium) in September 2019, see further under projects TS8 and VB12. A model for evaluating the probability of an instant rail break initiated at a single pre-existing rail foot crack due to a combination of temperature loading and measured distribution of wheel impacts has been developed. Statistical methods and a time-domain model for simulation of dynamic vehicle–track interaction were combined.

Noise from wheel impact loads. A review on the prediction of noise and vibration induced by wheel–rail impact loads has been written and presented at IWRN13 as reported in the previous paragraph.

S&C materials. An overview report on potentials and barriers for the development of switch and crossing materials has been finalized within WP2.

EU19. (cont'd)

Grinding & milling. In October 2019, Chalmers was commissioned by Trafikverket to produce a questionnaire on grinding and milling. The result was presented to the UIC-TEG in Brussels on 2020-01-22 by Björn Paulsson (TEG = Track Expert Group). In April 2020, CHARMEC was commissioned to conduct a feasibility study on grinding and milling as an extended work in In2Track2. The work has been carried out in three workstreams: extended study on world-wide practices, deeper investigations of scientific studies, and a top-down analysis of how rail deterioration is affected by surface treatment. Björn Paulsson presented parts of this feasibility study about grinding and milling to the UIC-TEG plenary meeting on 2020-10-13. This work continues in In2Track3.

Transition zones. A model for the prediction of differential track settlement in transition zones between ballasted track and slab track has been developed. This work will continue in project TS22.

Track health prediction. A large systematic overview of key parameters for track health prediction and requirements for the establishment of these has been compiled. The survey presents deterioration modes for different track components and identifies the influential parameters. These are linked to measurable parameters and to predictive models.

Reports

As of August 2021, CHARMEC's research in In2Track2 is finalized except for some chapter introductions/conclusions that await delayed input from other partners. CHARMEC's work included in the In2Track2 Deliverables is listed below. Note that several of the reports are also listed under other CHARMEC projects where the research was carried out. In addition to the writing of Deliverables, CHARMEC researchers have also been responsible for internal reviewing of large parts of the total research in In2Track2.

Deliverable 1.1

"Enhancements to Switch and Crossing system demonstrator":

Authoring of Chapters 4.1 "Modelling dynamics and degradation for whole system modelling", 5.6 "Outline of mechanical condition monitoring", and 7.6 "Application of the influence of S&C support on deterioration"
Introduction to Chapter 4 "Whole system model of switch & crossing"

Annexes to Chapter 4.1

Björn Pålsson, Ramakrishnan Ambur, Michel Sebès, Ping Wang, Jou-Yi Shih, Demeng Fan, Jingmang Xu and Jiayin Chen: A comparison of track model formulations for simulation of dynamic vehicle-track interaction in switches and crossings, *Vehicle System Dynamics*, 2021, 27 pp (also listed under project TS18) doi.org/10.1080/00423114.2021.19831832021

Yann Bezin and Björn Pålsson: Multibody simulation benchmark for dynamic vehicle-track interaction in switches and crossings – modelling description and simulation tasks, *Vehicle System Dynamics*, 2021, 16 pp (also listed under project TS18) doi.org/10.1080/00423114.2021.1942079

Rostyslav Skrypnyk, Uwe Ossberger, Björn Pålsson, Magnus Ekh and Jens Nielsen: Long-term rail profile damage in a railway crossing – field measurements and numerical simulations, *Wear*, vols 472–473, 2021, article 203331, 13 pp (also listed under project TS17)

Rostyslav Skrypnyk, Björn Pålsson, Jens Nielsen and Magnus Ekh: On the influence of crossing angle on long-term rail damage evolution in railway crossings, *International Journal of Rail Transportation*, 2021, 18 pp (also listed under project TS17) doi.org/10.1080/23248378.2020.1864794

Annexes to Chapter 5.6

Marko Milosevic, Björn Pålsson, Arne Nissen, Jens Nielsen and Håkan Johansson: Reconstruction of sleeper displacements from measured accelerations for model-based condition monitoring of railway crossing panels 2021, 21 pp (submitted for publication. Also listed under project TS21)

Marko Milosevic, Björn Pålsson, Arne Nissen, Jens Nielsen and Håkan Johansson: Condition monitoring of railway crossing geometry via measured and simulated track responses, 2021, 27 pp (to be submitted for publication. Also listed under project TS21)

Annexes to Chapter 7.6

Björn Pålsson: A parameterized turnout model for simulation of dynamic vehicle-turnout interaction with an application to crossing geometry assessment, *Proceedings 26th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2019)*, Gothenburg (Sweden) August 2019, pp 351–358 (also listed under project TS18)

Deliverable 2.1

"Next generation switches & crossings – technology developments and plans for progressing feasible S-CODE outputs":

Authoring of Chapter 8.3 "Potentials & barriers for S&C materials development"

Annexes to Chapter 8.3

Dimitrios Nikas and Anders Ekberg: Potentials & barriers for S&C materials development, Research Report 2020:02, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2020, 30 pp

Deliverable 3.1

"Description of demonstrators performed in this work and in future projects":

CHARMEC has provided general input on our research in relation to the demonstrators.

Deliverable 3.2

"Track and track component design and performance, demonstrators and simulations":

Authoring of Chapters 5.1.1 "Overall rail material characteristics", 5.1.2 "Influence of rail anisotropy", 5.1.3 "Overall sleeper and slab track characteristics", 5.1.4 "Assessment of slab track structures", 5.1.5 "Reduced noise emissions from slab track structures", 6.1.8 "Prediction of differential settlement", 6.1.9 "Means to mitigate transition zone problems", 7.3.1 "Prediction of crack growth in rails", and 7.3.2 "Mechanical response to thermal loading of rails"

EU19. (cont'd)

Introduction and Conclusions to Chapters 5 "Requirements for track design and maintenance", 5.1 "Describe and design the requirements for optimised track systems", 6.1 "Development of track systems", and 7.3 "Simulations of track system"

Annexes to the above Chapters:

5.1.1a David Carlsson and Daniel Gren: Experimental characterization of pearlitic rail steel after thermomechanical straining, MSc Thesis, *Chalmers Industrial and Materials Science*, Gothenburg 2019, 84 pp + appendix 33 pp hdl.handle.net/20.500.12380/256714

5.1.1b Dimitrios Nikas and Johan Ahlström: High temperature bi-axial low cycle fatigue behaviour of railway wheel steel, *Proceedings 12th International Conference of Multiaxial Fatigue and Fracture (ICMFF12)*, Bordeaux (France) June 2019, *MATEC Web of Conferences*, vol 300, 2019, article 07001, 8 pp (also listed under projects MU28 and MU30)

5.1.1c Somrita Dhar, Johan Ahlström, Xiaodan Zhang, Hilmar Danielsen and Dorte Juul Jensen: Multi-axial fatigue of head-hardened pearlitic and austenitic manganese railway steels – a comparative study, *Metallurgical and Materials Transactions A*, vol 51, 2020, pp 5639–5652 (also listed under project MU30) doi.org/10.1007/s11661-020-05941-8

5.1.2a Knut Andreas Meyer, Johan Ahlström and Magnus Ekh: Characterization of yield surface evolution due to large plastic shear strains in pearlitic rail steel, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 745–752 (also listed in the previous Triennial Report)

5.1.2b Knut Andreas Meyer, Magnus Ekh and Johan Ahlström: Anisotropic yield surfaces after large shear deformations in pearlitic steel, *European Journal of Mechanics – A/Solids*, vol 82, 2020, article 103977, 21 pp (also listed under project MU34) doi.org/10.1016/j.euromechsol.2020.103977

5.1.4a Emil Aggestam, Jens Nielsen and Niklas Sved: Simulation of dynamic vehicle–track interaction – comparison of two- and three-dimensional models, *Proceedings 26th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2019)*, Gothenburg (Sweden) August 2019, pp 415–422 (also listed under project TS19)

5.1.5a Jannik Theyssen, Emil Aggestam, Shengyang Zhu, Jens Nielsen, Astrid Pieringer, Wolfgang Kropp and Wanming Zhai: Calibration and validation of the dynamic response of two slab track models using data from a full-scale test rig, *Engineering Structures*, vol 234, 2021, article 111980, 17 pp (also listed under projects TS19 and VB13)

5.1.5b Jannik Theyssen, Astrid Pieringer and Wolfgang Kropp: The influence of track parameters on the sound radiation from slab tracks. *Proceedings 13th International Workshop on Railway Noise (IWRN13)*, Ghent (Belgium) September 2019, pp 3–40 (also listed under project VB13)

6.1.8a Jens Nielsen and Magnus Ekh: An iterative model for prediction of differential settlement in a transition zone between slab track and ballasted track, Research Report 2020:07, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2020, 15 pp

6.1.9a Emil Aggestam and Jens Nielsen: Multi-objective optimisation of transition zones between slab track and ballasted track using a genetic algorithm, *Journal of Sound and Vibration*, vol 446, 2019, pp 91–112 (also listed in the previous Triennial Report)

6.1.9b Xin Li, Jens Nielsen and Peter Torstensson: Simulation of wheel–rail impact load and sleeper–ballast contact pressure in railway crossings using a Green's function approach, *Journal of Sound and Vibration*, vol 463, article 114949, 2019, 16 pp (also listed under project TS15)

7.3.1a Casey Jessop and Johan Ahlström: Friction between pearlitic steel surfaces, *Wear*, vols 432–433, 2019, article 102910, 9 pp (revised article from conference *CM2018*. Also listed under projects MU29 and MU30)

7.3.1b Dimosthenis Floros, Anders Ekberg and Fredrik Larsson: Evaluation of crack growth direction criteria on mixed-mode fatigue crack growth experiments, *International Journal of Fatigue*, vol 129, 2019, article 105075, 14 pp (also listed under project MU33)

7.3.1c Dimosthenis Floros, Anders Ekberg and Fredrik Larsson: Evaluation of mixed-mode crack growth direction criteria under rolling contact conditions, *Wear*, vols 448–449, 2020, article 203184, 10 pp (revised article from conference *CM2018*. Also listed under project MU33)

7.3.2a Elena Kabo and Anders Ekberg: Mechanical response to thermal loading of rails, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2020, 17 pp

Deliverable 3.3

"Track and track component maintenance and asset management":

Authoring of Chapters 5.1.7 "Management and mitigation of rail deterioration", 5.2.4 "Improved repair and replacement strategies", 6.1.1 "Load characteristics of wheel damage", 6.1.2 "Limits for wheel geometries", 6.1.4 "Understanding and mitigation curve squeal", 7.3.1 "Identify key parameters for track health prediction", and 7.3.2 "Requirements on measured key parameters for track health prediction"

Introduction and Conclusions to Chapters 5 "Track maintenance", 6.1 "Impact of wheel performance on track", 7 "Prediction of track condition", and 7.3 "Extend the use of data from monitoring systems and health prediction"

Annexes to the above Chapters:

5.1.7a Anders Ekberg and Elena Kabo: Management and mitigation of rail deterioration, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2021, 11 pp

5.2.4a Ali Esmaeili, Johan Ahlström, Björn Andersson and Magnus Ekh: Modelling of cyclic plasticity and phase transformations during repeated local heating events in rail and wheel steels, *International Journal of Fatigue*, vol 151, 2021, article 106361, 15 pp (also listed under projects MU30, MU32 and MU37)

5.2.4b Can Yildirim, Casey Jessop, Johan Ahlström, Carsten Detlefs and Yubin Zhang: 3D mapping of orientation variation and local residual stress within individual grains of pearlitic steel using synchrotron dark field X-ray microscopy, *Scripta Materialia*, vol 197, 2021, article 113783, 5 pp (also listed under project MU30)

6.1.1a Davide Della Valle: Railway wheel tread damage – detection and consequences of wheel-rail impact loading, MSc Thesis 2019:34, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2019, 72 pp and 2 annexes 6+27 pp (also listed under project TS20)

6.1.1b Michele Maglio, Matthias Asplund, Jens Nielsen, Tore Vernersson, Elena Kabo and Anders Ekberg: Digitalisation of condition monitoring data as input for fatigue evaluation of wheel-sets, *Proceedings 19th International Wheelset Congress (IWC19)*, Venice (Italy) June 2019, 5 pp (also listed under project TS20)

EU19. (cont'd)

6.1.2a Jens Nielsen, Thomas Abrahamsson and Anders Ekberg: Probability of instant rail break induced by wheel–rail impact loading using field test data, *International Journal of Rail Transportation*, 2021, 23 pp (also listed under project SP30) doi.org/10.1080/23248378.2021.1874552

6.1.4a Wolfgang Kropp, Arthur Aglat, Jannik Theyssen and Astrid Pieringer: The application of dither for suppressing curve squeal, *Proceedings 23rd International Congress on Acoustics (ICA 2019)*, Aachen (Germany) September 2019, 8 pp (also listed under project VB12)

6.1.4b Wolfgang Kropp, Jannik Theyssen and Astrid Pieringer: The application of dither to mitigate curve squeal, *Journal of Sound and Vibration*, vol 514, article 116433, 17 pp, 2021 (also listed under project VB12)

7.3.1/7.3.2 Anders Ekberg and Elena Kabo: Key parameters and requirements for track health prediction, Research Report 2021:01, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2021, 71 pp (also listed under project SP31)

7.3.2b Astrid Pieringer and Wolfgang Kropp: Model-based estimation of rail roughness from axle box acceleration, 2021 (submitted for publication. Also listed under projects VB12 and SP31)

Deliverable 4.1

"Next generation track solutions":

Authoring of Chapter 5.3 "Requirements for ballastless track system solutions"

Deliverable 4.2

"Research into next generation track solutions":

Authoring of Chapters 7.1 "Requirements for next generation slab track solutions", 7.5 "Design of next generation track systems", 8.1 "Rail crack propagation", 9 "Vehicle born and embedded health monitoring and prediction. Introduction and Conclusions" and 9.7 "Identification of wheel loads for the next generation of operational control"

Annexes to the above Chapters

7.1a Emil Aggestam and Jens Nielsen: Simulation of vertical dynamic vehicle–track interaction using a three-dimensional slab track model, *Engineering Structures*, vol 222, 2020, article 110972, 16 pp (also listed under project TS19)

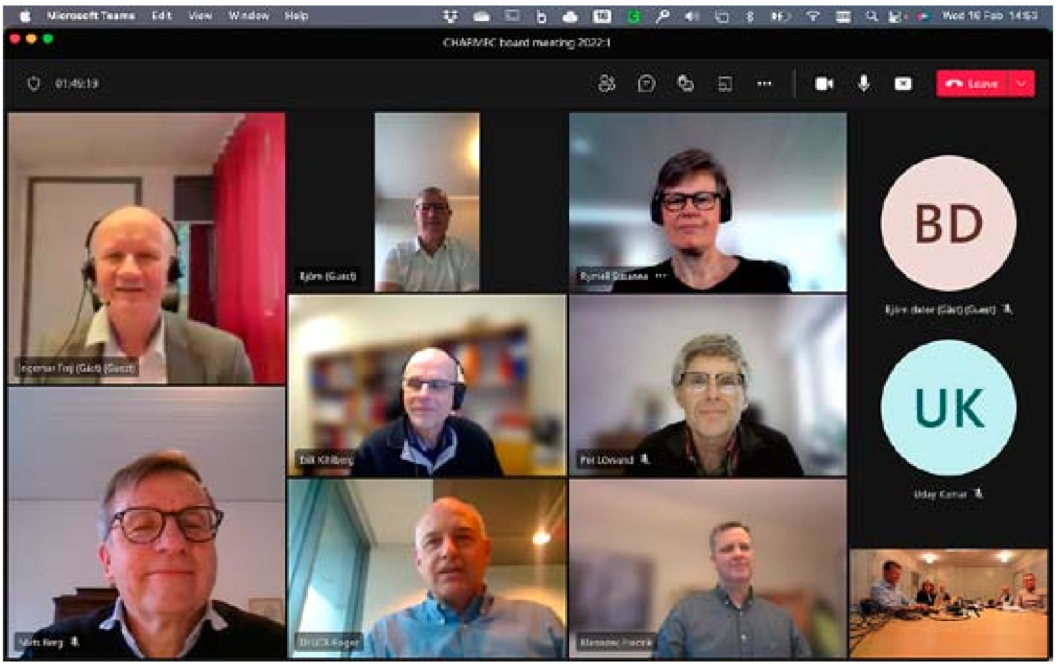
7.5.2a Robin Andersson, Elena Kabo and Anders Ekberg: Numerical assessment of the loading of rolling contact fatigue cracks close to rail surface irregularities, *Fatigue & Fracture of Engineering Materials & Structures*, vol 43, issue 5, 2020, pp 947–954 (also listed under project MU22)

7.5.2b Knut Andreas Meyer, Magnus Ekh and Johan Ahlström: Material model calibration against axial-torsion-pressure experiments accounting for the non-uniform stress distribution, *Finite Elements in Analysis and Design*, vol 163, 2019, pp 1–13 (also listed under project MU34)

7.5.2c Knut Andreas Meyer: Evaluation of material models describing the evolution of plastic anisotropy in pearlitic steel, *International Journal of Solids and Structures*, vols 200–201, 2020, pp 266–285 (also listed under project MU34)

9.7a Michele Maglio, Astrid Pieringer, Jens Nielsen and Tore Vernersson: Wheel–rail impact loads and axle bending stress simulated for generic distributions and shapes of discrete wheel tread damage, *Journal of Sound and Vibration*, vol 502, 2021, article 116085, 19 pp (also listed under projects TS20 and VB12)

9.7b Michele Maglio: Influence of wheel tread damage on wheelset and track loading – field tests and numerical simulations, Licentiate Thesis, *Chalmers Mechanics and Maritime Sciences*, Gothenburg October 2020, 102 pp (Summary and three appended papers; only the summary part (28 pp) of the thesis was submitted to In2Track2. Also listed under project TS20)



Screenshot from the online CHARMEC Board meeting on 16 February 2022

EU20. Fr8Rail2

Fr8Rail2 – Digitalization and Automation of Freight Rail

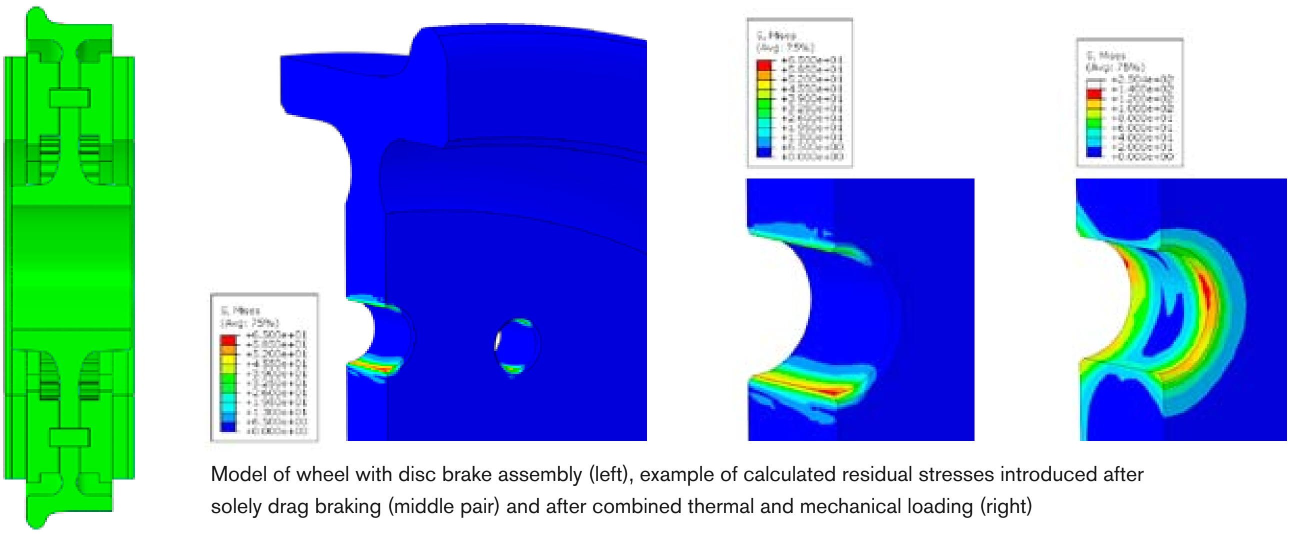
Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-worker	Docent Tore Vernersson, Mechanics and Maritime Sciences
Period	2018-09-01 – 2020-11-30
Budget Trafikverket / EU	Stage 9: kSEK 280

The Fr8Rail2 project (S2R-CFM-IP5-01-2018) is a project within the Horizon 2020 Framework Programme under the Shift2Rail Joint Technology Initiative. The ten work packages (WP) in Fr8Rail2 were WP1 Wagon Design & Automatic Coupling, WP2 Wagon Intelligence, WP3 Real-time network management and improved methods for timetable planning, WP4 Connected Driver Advisory Systems (C-DAS), WP5 Freight Automation, WP6 Freight Propulsion, WP7 Long Trains, WP8 Conditioned Based Maintenance, WP9 Project Management and, finally, WP10 Dissemination. CHARMEC was only involved in WP1.

In Fr8Rail2, freight wagons with single-axle running gear having wheel-mounted brake discs should be employed on the so-called Extended Market Wagon. Wheels on such wagons are traditionally dimensioned with respect to mechanical loads only. The present work aimed to clarify whether the design process should include also the thermal loading on the wheel web from the brake discs. The study is essential for avoiding the risk of later requirements for short inspection intervals etc. The study built on previous work at CHARMEC, in which material damage and fatigue life have been calculated for wheel webs of tread braked metro wheels (project SD7). To this end, stresses and strains were studied as resulting from mechanical loads, emanating from the wheel–rail contact, and from thermal loads, stemming from the frictional contact between brake blocks and wheel tread. The impact from the additional thermal loading on the damage and life of the wheel was studied using numerical models.

When analysing only braking, ignoring the simultaneously acting mechanical loads, it was found to generate a plastic material response in areas near the holes in the wheel web used for mounting of the brake discs. The study of the resulting stress-strain cycles, analysed using the Coffin-Manson fatigue criterion, indicated that the calculated lives for the drag braking load cases are longer than one million brake cycles, even for the highest studied brake power level of 45 kW (duration 20 min) per wheel. The residual stresses introduced by braking modify the stress field in the wheel and introduce an offset of the stress variations in the web resulting from the wheel–rail contact forces. The multiaxial fatigue criterion shows that the residual stresses introduced by braking modify the calculated equivalent fatigue stresses, but not at critical positions for the wheel design studied here. However, tentative analyses of wheel–rail contact forces acting during drag braking indicate that the equivalent fatigue stresses will be affected for this more realistic loading case. The residual stresses resulting after this combined load case have an impact on the equivalent fatigue stresses in the entire web, making them increase not only near the holes in the web but also near the wheel hub by some 16 % and 7 %, respectively, for braking at 40 kW for 20 min. This finding indicates that further research will be required to fully understand the influence from wheel-mounted brake discs.

Tore Vernersson and Anders Ekberg: Wheels for core and extended market wagon – thermomechanical assessment of wheel with wheel mounted brake discs, chapter in Fr8Rail2 Deliverable 1.5, 2021, 18 pp



Model of wheel with disc brake assembly (left), example of calculated residual stresses introduced after solely drag braking (middle pair) and after combined thermal and mechanical loading (right)

EU21. In2Track3

In2Track3 – Research into Optimised
and Future Railway Infrastructure

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	The project engages most of the staff at CHARMEC
Period	2021-01-01 – 2021-06-30 (– 2023-12-31)
Budget Trafikverket / EU	Stage 9: ksek 1 680 Stage 10: ksek 23 692
Budget Chalmers	Stage 9: ksek 160 Stage 10: ksek 1 798

Pernilla Edlund when visited by Anders Ekberg at Trafikverket's office in Gothenburg in March 2022

In2Track3 (S2R-CFM-IP3-01-2020) is a project within the Horizon 2020 Framework Programme under the Shift-2Rail Joint Technology Initiative with the project value MEUR 26.7 including the EU funding MEUR 11.8. The overall project co-ordinator is Trafikverket, see projects.shift2rail.org/s2r_ip3_n.aspx?p=IN2TRACK3, with CHARMEC's Anders Ekberg serving as scientific & technical co-ordinator.

The eight work packages (WP) in In2Track3 are WP1 Enhanced switches & crossings system demonstrator, WP2 Next generation switches & crossings demonstrator, WP3 Enhanced track, WP4 Next generation track, WP5 Assessment and improvement of tunnels and bridges, WP6 Project management, WP7 Technical co-ordination and scientific quality assurance, and WP8 Dissemination, exploitation and communication. CHARMEC is engaged in WP1, WP2, WP3, WP7 and WP8.

Our contributions to In2Track3 involved work from several parallel CHARMEC projects. The corresponding activities in In2Track3 are presented under these projects. Only co-ordination and additional research activities are reported below.

The official starting date for the new project was postponed to 2021-01-01 due to a required rescheduling caused by major revisions of one partner's contributions. Before that, a first kick-off was held on 2020-12-09. The official kick-off took place on 2021-03-15. The kick-offs were internet-based as were all of the following meetings. In the period leading up to the first kick-off, CHARMEC provided report skeletons for all Deliverables. These were then re-written (because of a revised project description) for the official kick-off.

During the first half-year of the project, CHARMEC's researchers have chaired and/or participated in around ten WP and Task meetings and have chaired three meetings in the Technical Management Team. First drafts of the Deliverables with responsible persons, background, objectives and aims have been reviewed. Pernilla Edlund of Trafikverket is co-ordinator of Intrack3. She authored the below reports with assistance of Anders Ekberg and others.

Pernilla Edlund: Project handbook In2Track3, Deliverable 6.1, 2021, 18 pp

Pernilla Edlund: In2Track3 – the project in short & general presentation (PowerPoint presentations), 2021, 8+12 pp

Derailment of the last two coaches in a Swedish passenger train on 6 July 1997 between Lästringe and Tystberga on a regional line south of Stockholm and north of Nyköping. The day was calm with few clouds and a maximum temperature of about 25°C. According to eyewitnesses, the lateral buckling and displacement of the track gradually grew as the train braked

SP26. HOLISTIC OPTIMIZATION OF TRACKS

Holistiskt optimerade spår

Project leader	Professor Jens Nielsen, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	Dr Eric Berggren, EBER Dynamics, Dr Rikard Bolmsvik, Abetong, and Mr Anders Hammar and Mr Fredrik Jansson, MSc, both of Trafikverket
Period	2013-11-01 – 2018-09-30
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 164 Stage 8: KSEK 566 Stage 9: KSEK 0

The project is financed by VINNOVA (through CHARMEC's budget)

Project SP26 aimed to reduce both the life cycle cost and the environmental footprint of railway tracks and railway transportation by developing (i) an enhanced method for characterization of railway tracks and detection of track sections with poor support conditions that require maintenance and (ii) a design process for durable, cost-efficient and environmentally friendly concrete sleepers based on the knowledge of the (current and future) status of the sleeper support conditions.

Long-term track geometry degradation and track stiffness variation have been assessed for selected track sections in Sweden on the heavy haul line Malmbanan (Iron Ore Line) and on Södra and Västra Stambanorna (Southern and Western Main Lines). The test sites include different combinations of traffic volume, traffic types and climatic and ground conditions. For example, using 20 years of track geometry car recordings on a section of the Iron Ore Line, the vertical track geometry has been analysed for wavelengths in the interval 1–25 m. Based on standard deviation or peak value of longitudinal level, a compact format for the illustration of long-term track geometry degradation and identification of track sections with severe track geometry degradation has been suggested (see the Triennial Report for Stage 8 on page 59). A method developed by the partner company EBER Dynamics for continuous measurement of track vertical stiffness along the line has been used, allowing for detection of track sections with poor support conditions. It was concluded that this method for stiffness measurement provides good information on the variation and distribution of track stiffness along the line and that it can be used as an efficient tool for the maintenance planning of a more robust railway track.

From the left: Fredrik Jansson and Anders Hammar of Trafikverket and Eric Berggren of EBER Dynamics in project SP26. Photo taken in 2018

Under sleeper pads (USP) have been installed on a 300 m test section of the Western Main Line near Lerum. The test section and adjacent reference sections will be used for a long-term assessment of sleeper and track geometry degradation with and without USP. Guidelines for concrete sleeper design and support conditions have been provided, and an iterative procedure for numerical prediction of accumulated long-term degradation of vertical track geometry due to differential settlement of ballast/subgrade has been developed. To minimize life cycle cost and environmental footprint, recommendations for superstructure design and maintenance planning of a more robust railway track are:

1. Preventive maintenance based on regular monitoring of track geometry degradation, prediction of degradation rates and identification of problem sites
2. Preventive maintenance based on continuous track stiffness measurement to identify sections of track with poor support conditions
3. Application of a sleeper design where the bottom surface area under the two rail seats is increased (to ensure that the load distribution from the rail down to the ballast results in low contact pressures reducing the risk of ballast degradation and settlement) and where the bottom surface area at the centre is reduced (to bring down sensitivity in the event of ballast settlement which could result in a high centre bending moment and subsequent cracking)
4. Increased use and continued assessment of performance of USP to improve load distribution and reduce contact stresses between sleeper and ballast

Jens Nielsen, Eric Berggren, Anders Hammar, Fredrik Jansson and Rikard Bolmsvik: Degradation of railway track geometry – correlation between track stiffness gradient and differential settlement, *IMechE Journal of Rail and Rapid Transit*, vol 234, issue 1, 2020, pp 108–119 doi.org/10.1177/0954409718819581

SP28. PREVENTION AND MITIGATION OF DERAILMENTS

Hindrad uppkomst och mildrad konsekvens av urspårningar

Project leader	Dr h c Björn Paulsson, Mechanics and Maritime Sciences (and formerly Trafikverket)
Co-workers	Professor Anders Ekberg, Professor Elena Kabo and Docent Björn Pålsson, Mechanics and Maritime Sciences
Period	2016-08-01 – 2019-06-30
Chalmers budget (excluding university basic resources)	Stage 8: kSEK 296 Stage 9: kSEK 0

The project is financed by Trafikverket and UIC (through CHARMEC's budget)

Björn Paulsson, Elena Kabo and Anders Ekberg in project SP28. Photo taken at the inaugeration cermony for Professor Anders Ekberg on 18 March 2022. For a photo of Björn Pålsson, see page 25

This project, abbreviated PMD, was initiated by the UIC Train Track Interaction Group (TTIG) and supported by Trafikverket. It focused on implementation of results from previous research and development projects by formulating the main results into an "International Railway Solution" (IRS) that has been published by the UIC, see below.

The background to the project was an evaluation from the European Railway Agency (ERA) in 2005 that showed that costs for derailments increased. This led to the EU research project D-RAIL (CHARMEC project EU13) which highlighted that costs for derailments can be reduced by the introduction of modern monitoring equipment. The project has built on results from D-RAIL and other projects, such as the UIC projects HRMS (CHARMEC project SP25) and Axle Load Checkpoints (ALC), and clarified operational recommendations in the IRS 70729, see again below.

The PMD project had an Advisory Board which held several meetings. The project has been reported to the UIC TTIG on six occasions and to the UIC Freight Forum on two occasions. The IRS 70729 was scientifically reviewed by the University of Huddersfield in the UK and the Polytechnic University of Milan in Italy. It was approved by the Rail System Forum at UIC in May 2019. Presentations have been given to ERA and SNCF.

Björn Paulsson has also supported Trafikutskottet in the Swedish Parliament concerning input to a public investigation on how to meet future climate changes. Here he stressed the importance of using risk analyses to work more proactively and adaptively. He also emphasized the importance of using university resources. The input was presented at a public and televised hearing.

Prevention and Mitigation of Derailment (PMD), UIC, IRS 70729, 2019, 48 pp. ISBN 978-2-7461-2851-4

Derailment of a freight train at Hökmora close to Avesta/Krylbo in Sweden on 1 February 2018 after collision with a truck at a level crossing. Photo by Stefan Bratt (courtesy Trafikverket)

SP29. INCLUDING WEAR CAUSED BY BRAKING IN TRAIN DRIVING SIMULATORS

Inkludering av nötning orsakad av bromsning i lokförarsimulatorer

Project leader	Dr (now Docent) Peter Torstensson, Swedish National Road and Transport Research Institute (VTI)
Co-workers	Dr Anders Andersson, Swedish National Road and Transport Research Institute (VTI), Dr Sara Janhäll, Research Institutes of Sweden (RISE), Docent Tore Vernersson, Chalmers Mechanics and Maritime Sciences, and Mr Fredrik Blennow, MSc, and Mr Kristoffer Mossheden, MSc, both of Faiveley Transport Nordic
Period	2018-06-18 – 2018-12-18
Budget Chalmers	Stage 9: KSEK 191

The project was partly financed by the strategic innovation programme InfraSweden2030

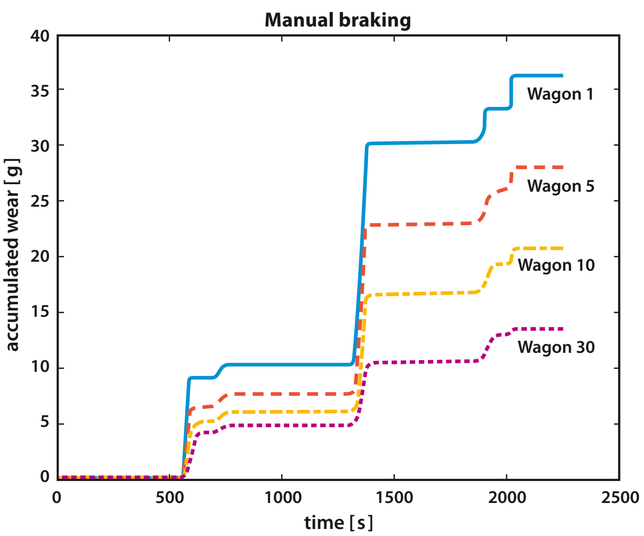
For a photo of Peter Torstensson, see page 15

CHARMEC, VTI, RISE and Faiveley Transport have collaborated in a research effort to numerically predict wear and particle emissions generated by braking and wheel–rail contact of a freight train. Previously developed simulation approaches and wear models in project SD8 were used as a starting point for prediction of wear generated by a train having 30 wagons. Trafikverket have forecast a significant increase in Sweden of both passenger and freight transport by rail, a development partly driven by urbanization and the associated need for surface-effective and sustainable commuter traffic. It is then important to mitigate adverse health effects of rail transportation caused by non-exhaust particle and noise emissions. The ability to predict particle emissions would enable preventive actions in the vehicle design (at the sources close to the wheel–rail contacts and brakes) and in the design of infrastructure (both track superstructure and surrounding buildings). Moreover, changes in driving modes for the traffic could improve the conditions of existing infrastructure.

The present feasibility study demonstrated the possibility to expand the area of use of VTI's existing train driving simulators to also assess the wear generated during train operation. To this end, a freight train driving simulator is here combined with two separate mathematical models for calculation of the wear caused in the brake block–wheel and wheel–rail contacts. This new functionality has been illustrated by letting an experienced train driver guide a freight train of total length 619 m and mass 2 782 tonnes on "Jönköpingsbanan", see figure below. The results indicate a significant variation in generated wear between the 30 wagons in the simulated trainset with the largest and smallest amount of wear found near the locomotive and towards the back of the train, respectively. This difference is due to the delay in braking action that increases with the length of the pneumatic braking system. As part of the current project also a literature study with focus on numerical prediction of non-exhaust railway particle emissions is presented.

Anders Andersson, Fredrik Blennow, Sara Janhäll, Peter Torstensson and Tore Vernersson: Med sikte på simulering av järnvägens partikelemissioner (Towards simulation of non-exhaust railway particle emissions; in Swedish), *Transportforum*, Linköping (Sweden) January 2019

Peter Torstensson, Tore Vernersson, Sara Janhäll, Anders Andersson, Fredrik Blennow and Kristoffer Mossheden: Use of numerical simulation to map and mitigate railway particle emissions, *InfraSweden2030*, Linköping (Sweden) 2019, 34 pp www.infrasweden2030.se/wp-content/uploads/sites/36/2020/03/Use-of-numerical-simulation-to-map-and-mitigate-railway-particle-emissions.pdf



Calculated accumulated worn mass during the simulator driving of a freight train consisting of a Bombardier Traxx locomotive and 30 wagons between the stations Forserum and Jönköping on the Jönköping railway line ("Jönköpingsbanan") in Sweden during about 40 minutes

SP30. RAILWAY VEHICLE RISK ANALYSES

Riskanalyser för järnvägsfordon

Project leader	Professor Elena Kabo, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	Dr Astrid Pieringer, Architecture and Civil Engineering, Professor Magnus Ekh, Industrial and Materials Science, Professor Aila Särkkä, Mathematical Sciences, and Professor Thomas Abrahamsson, Professor Anders Ekberg, Professor Jens Nielsen and Dr (now Docent) Björn Pålsson, all four of Mechanics and Maritime Sciences
Period	2019-01-01 – 2019-12-31
Budget	Cash from Chalmers Area of Advance Transport KSEK 600 (counted as in-kind contribution to CHARMEC)

Railway traffic in the EU is expected to increase significantly, but the rail network does not expand at a similar rate and operational disturbances are carrying increasing costs. At the same time, safety and environmental concerns are more important than ever. This situation calls for innovative solutions, but also clear and well-founded safety, reliability and environmental criteria that the solutions must meet. Holistic risk analyses are required in contrast to current risk analyses that often focus on one issue at a time and are mainly based on expert rankings. Such holistic analyses must employ a large amount of available data on asset management. The generally low-quality data then call for a structured analysis that relates the data to risks and effects, e g, through numerical simulations enhanced by machine learning. This was the motivation for the current study in project SP30 where a set of selected topics has been investigated. They include structured risk assessments of fatigue of high-speed train chassis subjected to pressure waves and rail breaks considering stochastic distributions of input data. The study has also established uncertainties related to, e g, material characteristics in high-temperature processes, roughness spectra in noise emission analyses, and system parameters in characteristics evaluations.

Anders Ekberg and Elena Kabo: Risk of fatigue of train car chassis due to pressure waves between meeting trains, Research Report 2020:01, *Chalmers Mechanics and Maritime Sciences*, 15 pp (also listed under project MU22)

Ali Esmaeili, Magnus Ekh, Johan Ahlström and Björn Andersson: Modelling of cyclic plasticity and phase transformations during repeated local heating events in pearlitic steels, *Proceedings 6th International Conference on Material Modelling (ICMM6)*, Lund (Sweden) June 2019 (Summary and PowerPoint presentation. Also listed under project MU37)

Jens Nielsen, Thomas Abrahamsson and Anders Ekberg: Probability of instant rail break induced by wheel–rail impact loading using field test data, *International Journal of Rail Transportation*, 2021, 23 pp (also listed under project EU19) doi.org/10.1080/23248378.2021.1874552

Participants in 20th Nordic Seminar on Railway Technology at Chalmers on 12–13 June 2018. Front persons are (from the left) Uday Kumar, Ingemar Frej, Björn Paulsson, Anders Ekberg, Thomas Nordmark, Stefan von Mach, Roger Lundén, Rostyslav Skrypnyk and Richard Stock

SP31. INTELLIGENT RAILWAY DIGITALIZATION

Intelligent digitalisering av järnvägen

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	Dr Astrid Pieringer, Researcher (Swedish: forskare), Architecture and Civil Engineering, Professor Thomas Abrahamsson, Mechanics and Maritime Sciences, Professor Magnus Ekh, Industrial and Materials Science, Docent Krister Wolff, Mechanics and Maritime Sciences, and Professor Elena Kabo, Mechanics and Maritime Sciences
Period	2020-01-01-2020-12-31
Budget	Cash from Chalmers Area of Advance Transport KSEK 570 (counted as in-kind contribution to CHARMEC)

Today massive amounts of data are already collected on railways and railways are also currently investing heavily in new sensors and new data processing systems. However, the collected data are often poorly correlated to the information that is of interest when it comes to optimizing and controlling operations, planning maintenance and improving vehicle designs. The current project supports investigations on which data that are of importance in different areas. It then explores how these data can be used to enhance numerical simulations and which feasibility that exists for automated data collection and links to digital twins.

This limited study has been carried out in three work packages: (i) Identification of key influencing parameters, (ii) Relation to measurable parameters, and (iii) Potential of (autonomous) data gathering and updating of digital twins.

Key deterioration phenomena for the railway track have been identified and possibilities to quantify current status and to predict future deterioration have been detailed. From these investigations, key parameters regarding various forms of deterioration have been identified and related to inspection methods and pertinent measurable parameters. An enhanced method for measuring rail roughness from (revenue) vehicles that allows for a separation of wheel and rail roughness has been developed and has been tested using simulated data. Parameter identifiability and methods for Finite Element Model cross-validation have been implemented in a model calibration/validation code, see below.

A suitable basis for an autonomous robot was identified. A track vehicle robot was purchased by Trafikverket together with a high performance lidar sensor, see photo. This was financed through the Shift2Rail project In2Smart2. A first version of a model-scale railway testbed has been verified using a basic case. The proposed software architecture has been tested and verified in the scaled testbed.

Anders Ekberg and Elena Kabo: Key parameters for track health prediction, Research Report 2021:01, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2021, 71 pp (also listed under project EU19)

Astrid Pieringer and Wolfgang Kropp: Model-based estimation of rail roughness from axle box acceleration, 2021 (submitted for publication. Also listed under projects VB12 and EU19)

Thomas Abrahamsson: StructDyn 2020, *MATLAB Central File Exchange*, 2021 www.mathworks.com/ matlabcentralfileexchange/ 10731-structdyn-2020

Thomas Abrahamsson: FEMcali, *MATLAB Central File Exchange*, 2021 www.mathworks.com/matlabcentral/ fileexchange/44317-femcali

The first test-drive of the autonomous railway inspection and repair system (RIRS) robot, as acquired by Trafikverket, on the closed railway test track Tortuna-Tillberga in Sweden. Note that a 3D lidar sensor was (temporarily) mounted on the cart for data collection from the actual test track

SP32. SUSTAINABLE RAILWAY ASSET MANAGEMENT

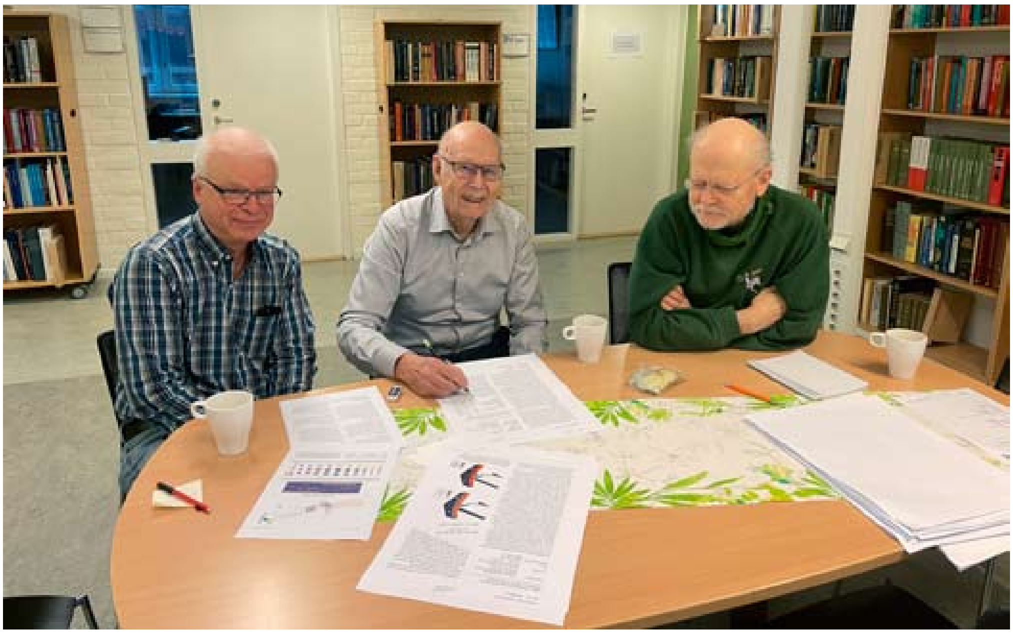
Hållbar förvaltning av järnvägar

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	Dr Astrid Pieringer, Researcher (Swedish: forskare), Architecture and Civil Engineering, Professor Magnus Ekh, Industrial and Materials Science, Professor Johan Ahlström, Industrial and Materials Science, Professor Elena Kabo, Mechanics and Maritime Sciences, and Professor Jens Nielsen, Mechanics and Maritime Sciences
Period	2021-01-01 – 2021-06-30 (– 2021-12-31)
Budget	Cash from Chalmers Area of Advance Transport KSEK 290 for Stage 9 and KSEK 290 for Stage 10 (counted as in-kind contribution to CHARMEC)

Tracks and vehicles of railway systems are highly utilized and have a long operational life. This means that maintenance and (re-)investments are core issues. From a sustainability perspective this is a highly desirable situation since, if handled properly, they can reduce the environmental footprint of both infrastructure and vehicle fleet. Thus asset management is here a key challenge. From a technical perspective (which is the focus of the present project) this relates to a proper knowledge of the current and future status of a system's tracks and vehicle fleet. The outcome of the present project will take this a step further by investigating how condition monitoring data can be employed and combined with numerical simulations to improve asset management decisions on maintenance and investments. Project SP32 also investigates the possibility to estimate uncertainties related to the technical basis used for asset management decisions.

The present study connects to the international series of standards ISO 55000 and links to existing methods for risk analyses. The work is carried out in five work packages: WP1 Key parameters, measurable parameters, and link between these, WP2 Possibilities to predict maintenance needs and investment benefits, WP3 Uncertainties in predictions of maintenance and investment, WP4 Influence of input parameters and assumptions on uncertainties, and WP5 Link to risk analyses.

So far the work has served as a basis for a new compendium that introduces asset management with focus on mechanical deterioration of railway assets, and the ISO 55000 series. The compendium will be part of the curriculum in an upcoming course on railway technology at Chalmers University, see page 86.



From the left: Roger Lundén, Bengt Åkesson and Tomas Wahlberg doing editing and layout work in March 2022

SP33. MORE ROBUST SWITCHES THROUGH IMPROVED CONTROL OF THE SWITCH RAIL

Robustare spårväxlar genom förbättrad tungkontroll

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	Professor Elena Kabo, Dr Björn Paulsson and Docent Björn Pålsson, Mechanics and Maritime Sciences
Period	2021-01-01 – 2021-06-30 (– 2021-12-31)
Budget Chalmers	Stage 9: KSEK 420 Stage 10: KSEK 260

The project is financed by Trafikverket (through CHARMEC's budget)

Swedish tongue control sensors (indicated by yellow ovals) in a switch. Photo: Björn Paulsson

Project SP33 is a limited feasibility study with focus on establishing if (and to some extent, how) it would be possible to decrease the number of contact sensors in a switch while maintaining an acceptable level of risk for the railway traffic. A long-term objective is to considerably reduce traffic disruptions caused by signals from today's contact sensors. So far, the study has dealt with (i) safety levels in current regulations, (ii) international experience, (iii) properties of ballast, (iv) forces from vehicles, (v) calculations, and (vi) signalling aspects.

A first result obtained from the present study is that today's safety levels are largely unknown. Re-analyses of a previous evaluation of failure reports showed that none of the investigated incidents in Sweden during roughly 7.5 years could have been prevented by use of signals from the existing switch rail sensors. Extensive studies of technical reports and failure investigations also revealed that the current use of sensors for switch rail control relates back to a one-page technical report from 1987. It has not been possible to verify or invalidate the results presented in this old and brief report. Investigations into international practices have established that the current switch rail control seems to be exclusively used in Sweden.

Regarding ballast properties, a MSc thesis project (see below) has been performed to investigate deformation and fracture characteristics of the ballast in Swedish tracks. Here preliminary analyses of forces and deformations during switch rail control when a ballast stone is trapped between the switch rail (the tongue) and the stock rail have been carried out. A feasibility study has evaluated whether the relevant traffic scenarios can be simulated in a commercially available multibody simulation software. Also, a first assessment of potential consequences for the signalling system of removed switch rail sensors has been carried out.

Based on results from the present study, a proposal to Trafikverket for an extended project has been drafted, submitted and approved. The aim of this new doctoral project (TS24) will be to significantly enhance knowledge and quantify risk levels, initially for the case of switch rail controls but later in a broader context with an aim to employ numerical simulations to enhance risk analyses.

Robin Hafström: Loading and crushing of trapped ballast stones – loading and deformation of a ballast stone trapped in a railway switch, MSc Thesis 2020:61, *Chalmers Mechanics and Maritime Sciences,* 43 pp

Main component of brake rig in project SP34 being inspected by (from the left) Jan Möller, Roger Lundén and Tore Vernersson from CHARMEC and Jens Johansson and Christian Johansson from the supplier Steens Mekaniska in Tidaholm (Sweden)

SP34. FULL-SCALE BRAKE TEST RIG

Fullskalig provrigg för bromsar

Project leader	Docent Tore Vernersson, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	Professor Roger Lundén, Research Engineer Jan Möller and Mr Eric Voortman Landström, MSc, Mechanics and Maritime Sciences
Period	2020-02-01 – 2021-06-30 (– 2024-06-30)
Chalmers budget (excluding university basic resources)	Stage 9: ksek 600 Stage 10: ksek 1 500
Industrial interests in-kind budget	Stage 9: ksek 0 Stage 10: ksek 200 + 200 *(Faiveley Transport + Lucchini Sweden)*

A versatile full-scale brake test rig is being designed and constructed at Chalmers to support CHARMEC's work to acquire in-depth knowledge of tread brakes and to establish limits for their commercial applications considering requirements of today and the near future. The focus is on the sliding contact between wheel and brake block and on the rolling contact between wheel and rail. This test facility will be useful in the study of tread braking of freight wagons, metros and commuter trains and it should also be functional in future research on disc brakes.

Design concepts, detailed dimensions and choice of components have continuously been evaluated and a design was finalized in June 2021. In the process we have strived towards compact dimensions and a wide-ranging usability when it comes to frictional brake testing. The rig will ultimately have two electric motors that can be used either for jointly powering the block braked wheel during simulated drag braking and stop braking, or for separately powering the block braked wheel and a so-called rail-wheel in order to supply a frictional force at their rolling contact. In a first stage, only the part of the rig for the tread braked wheel will be built. Remaining parts will follow as required by demands in parallel research projects. The brake rig is localized in a laboratory hall at Chalmers University of Technology.

Results from tests in the brake rig will be instrumental for the continued work in project SD11. Particularly, experimental results will be essential for the calibration of numerical models of global wheel behaviour at extreme temperatures and for the investigation of the temperature influence on RCF life and tread wear and, finally, for the provision of knowledge on particle emissions from tread braked systems.

For the joint reference group, see under project SD11.

Roger Lundén, Tore Vernersson, Jan Möller and Eric Voortman Landström at the brake rig under construction

ACADEMIC AWARDS

(up to June 2021)

Research in railway mechanics at Chalmers University of Technology has resulted in the conferring of the higher academic degrees listed below

Licentiate of Engineering (Lic Eng)

Jens Nielsen	1991-02-19
Mikael Fermér	1991-04-09
Åsa Fenander	1994-09-09
Annika Igeland	1994-10-06
Johan Jergéus	1994-11-22
Anders Ekberg	1997-02-18
Tore Vernersson	1997-09-29
Johan Jonsson	1998-05-13
Johan Ahlström	1998-12-11
Lars Jacobsson	1999-01-28
Johan Oscarsson	1999-03-12
Martin Petersson	1999-10-12
Rikard Gustavson	2000-05-11
Clas Andersson	2000-11-17
Torbjörn Ekevid	2000-12-19
Daniel Thuresson	2001-05-16
Carl Fredrik Hartung	2002-11-22
Lars Nordström	2003-01-24
Simon Niederhauser	2003-02-28
Anders Johansson	2003-09-05
Per Heintz	2003-12-03
Göran Johansson	2004-06-03
Per Sjövall	2004-10-01
Anders Karlström	2004-10-21
Elias Kassa	2004-12-16
Eka Lansler	2005-01-12
Anders Bergkvist	2005-06-09
Håkan Lane	2005-06-10
Niklas Köppen	2006-11-10
Johanna Lilja	2006-11-23
Johan Tillberg	2008-06-04
Johan Sandström	2008-10-14
Astrid Pieringer	2008-12-02
Jessica Fagerlund	2009-06-08
Peter Torstensson	2009-11-27
Krste Cvetkovski	2010-04-23
Jim Brouzoulis	2010-05-07
Hamed Ronasi	2010-09-24
Albin Johnsson	2011-02-24
Björn Pålsson	2011-04-14
Martin Schilke	2011-06-08
Sara Caprioli	2011-12-20
Andreas Draganis	2011-12-21
Shahab Teimourimanesh	2012-02-23
Nasim Larijani	2012-05-24
Kalle Karttunen	2013-01-17
Emil Gustavsson	2013-03-22
Sadegh Rahrovani	2014-02-27
Milad Mousavi	2014-06-05
Xin Li	2014-11-25
Ivan Zenzerovic	2014-12-02
Robin Andersson	2015-06-04
Dimitrios Nikas	2016-06-10
Dimosthenis Floros	2016-11-25
Ali Esmaeili	2016-12-16
Casey Jessop	2017-03-03
Mandeep Singh Walia	2017-03-20
Knut Andreas Meyer	2017-10-06
Emil Aggestam	2018-05-25
Rostyslav Skrypnyk	2018-06-07
Jannik Theyssen	2020-06-09
Michele Maglio	2020-10-09
Marko Milosevic	2021-06-04

Doctor of Engineering (PhD)

Jens Nielsen	1993-12-16
Mikael Fermér	1993-12-17
Annika Igeland	1997-01-24
Åsa Fenander	1997-05-23
Johan Jergéus	1998-01-30
Anders Ekberg	2000-04-07
Johan Jonsson	2000-06-09
Jonas Ringsberg	2000-09-15
Johan Ahlström	2001-03-02
Johan Oscarsson	2001-04-20
Rikard Gustavson	2002-11-07
Torbjörn Ekevid	2002-12-18
Clas Andersson	2003-06-04
Anders Skyttebol	2004-09-10
Roger Johansson	2005-06-08
Anders Johansson	2005-09-23
Lars Nordström	2005-11-10
Simon Niederhauser	2005-12-09
Tore Vernersson	2006-06-08
Per Heintz	2006-09-28
Göran Johansson	2006-09-29
Daniel Thuresson	2006-10-06
Anders Karlström	2006-10-13
Håkan Lane	2007-05-25
Elias Kassa	2007-10-19
Per Sjövall	2007-11-09
Johan Tillberg	2010-12-10
Astrid Pieringer	2011-05-20
Johan Sandström	2011-11-14
Hamed Ronasi	2012-03-29
Jim Brouzoulis	2012-10-05
Krste Cvetkovski	2012-10-16
Peter Torstensson	2012-11-02
Martin Schilke	2013-03-15
Björn Pålsson	2014-02-28
Shahab Teimourimanesh	2014-03-07
Nasim Larijani	2014-06-10
Andreas Draganis	2014-09-03
Sara Caprioli	2015-01-15
Emil Gustavsson	2015-05-29
Kalle Karttunen	2015-06-11
Sadegh Rahrovani	2016-03-18
Milad Mousavi	2016-09-30
Ivan Zenzerovic	2018-01-19
Robin Andersson	2018-06-08
Dimitrios Nikas	2018-10-18
Ali Esmaeili	2019-01-10
Dimosthenis Floros	2019-01-18
Casey Jessop	2019-06-13
Xin Li	2019-09-26
Knut Andreas Meyer	2019-10-04
Mandeep Singh Walia	2019-11-20
Rostyslav Skrypnyk	2020-06-05
Emil Aggestam	2021-06-11

Licentiate theses submitted by CHARMEC researchers during Stage 9

Docent (highest academic qualification in Sweden)

Roger Lundén	1993-03-23
Jens Nielsen	2000-11-09
Jonas Ringsberg	2004-04-02
Anders Ekberg	2005-08-26
Elena Kabo	2008-12-15
Johan Ahlström	2010-03-08
Tore Vernersson	2016-09-20
Peter Torstensson	2021-05-18
Björn Pålsson	2021-06-18

Research Professors

Elena Kabo	2017-09-01
Jens Nielsen	2018-01-01

INTERNATIONAL CONFERENCES

During Stage 9 (and the months immediately following Stage 9) researchers from CHARMEC have participated in, and contributed to, the following major seminars, workshops, symposia, conferences and congresses (some of them held online because of the coronavirus pandemic):

The 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018) in Delft (The Netherlands) 24–27 September 2018

The 6th International Conference on Material Modelling (ICMM6) in Lund (Sweden) 26–28 June 2019

Fachtagung Bahnakustik – Infrastruktur, Fahrzeuge, Betrieb in Planegg / Munich (Germany) 15–16 November 2018

International Heavy Haul Association STS Conference (IHHA2019) in Narvik (Norway) 10–14 June 2019

The 19th International Wheelset Congress (IWC19) in Venice (Italy) 16–20 June 2019

The 12th International Conference of Multiaxial Fatigue and Fracture (ICMFF12) in Bordeaux (France) 24–26 June 2019

The 26th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2019) in Gothenburg (Sweden) 12–16 August 2019

The 40th Risø International Symposium on Materials Science and Engineering in Risø / Roskilde (Denmark) 2–6 September 2019

The 29th International Conference on Noise and Vibration Engineering (ISMA2020) in Leuven (Belgium) 7–9 September 2020

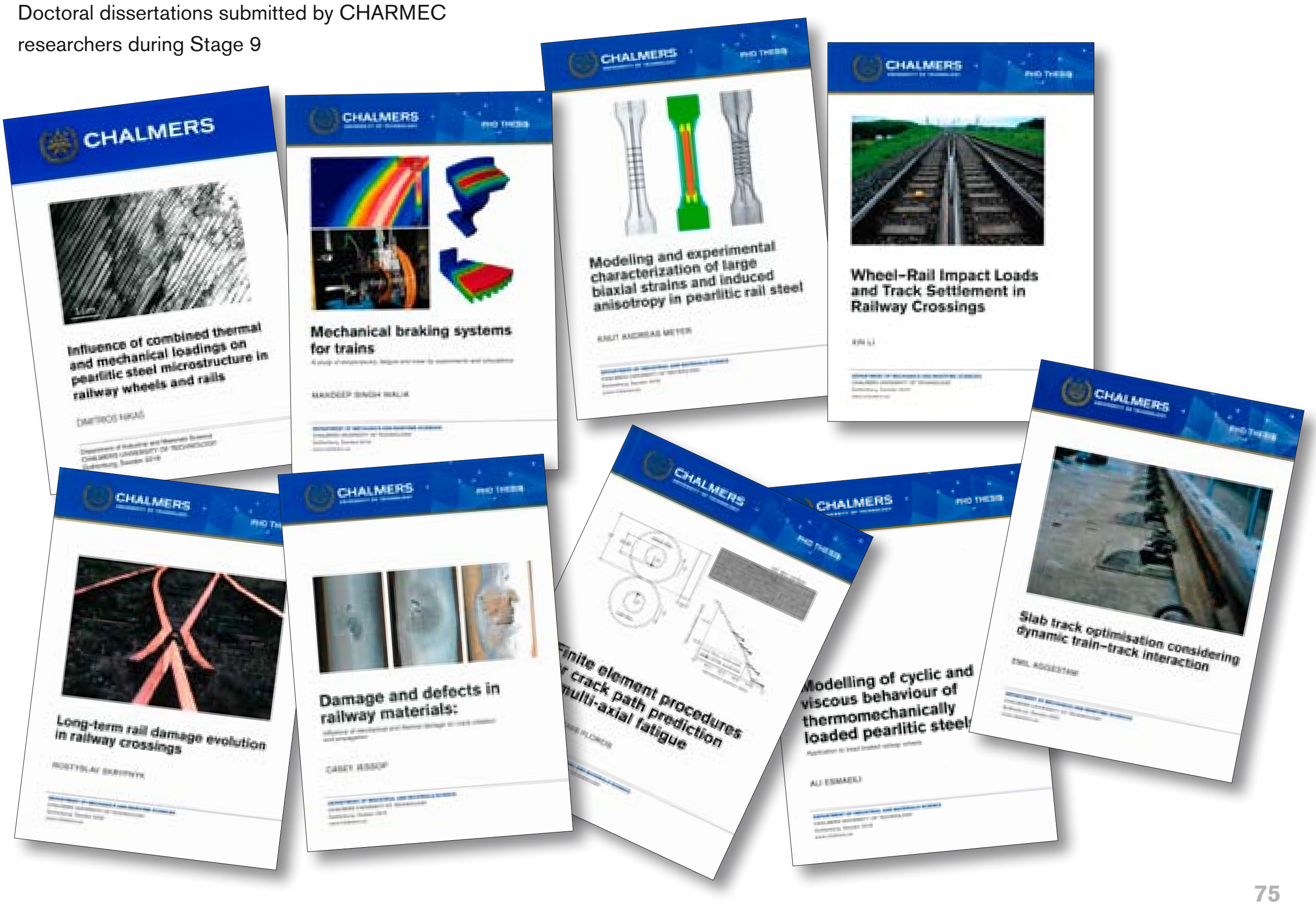
The 23th International Congress on Acoustics (ICA 2019) in Aachen (Germany) 9–13 September 2019

The 13th International Workshop on Railway Noise (IWRN13) in Ghent (Belgium) 16–20 September 2019

Europe's Braking Technology Conference & Exhibition (EuroBrake 2021, online) in Paris (France) 17–21 May 2021

The 27th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2021, online) in St Petersburg (Russia) 17–19 August 2021

Doctoral dissertations submitted by CHARMEC researchers during Stage 9



PARTNERS IN INDUSTRY

The status report that follows applies as of October 2021. The first year of each partner's involvement with CHARMEC is indicated (and before that, by bilateral agreement with the railway mechanics group at Chalmers Solid Mechanics).

Abetong AB (1995 and 1988)
Abetong, whose head office is in Växjö, belongs to the HeidelbergCement Group, and manufactures prefabricated and pretensioned concrete structural components. About 550 people are employed in Sweden where the annual turnover is slightly over MSEK 1 350. Areas of interest for Abetong are the design and manufacture of railway sleepers fitted with fastenings and pads for rails.

Of particular interest in the co-operation with CHARMEC are tools for the identification of loads on sleepers installed in tracks, for the structural analysis and design of sleepers for main lines and turnouts, and for prediction of the amount of noise emitted by the sleepers. Due to the planned building of high-speed tracks in Sweden, Abetong has decided to expand its existing railway activities to include knowledge within slab track systems. As a consequence the company has initiated two new slab track oriented PhD projects at CHARMEC running during the period 2016–2021. Both Trafikverket and Abetong have benefitted from the results obtained.

Alstom (2000 through the former Adtranz and Bombardier Transportation companies)
Leading societies to a low carbon future, Alstom develops and markets mobility solutions that provide a sustainable foundation for the future of transportation. Alstom's product portfolio ranges from high-speed trains, metros, monorail and trams to integrated systems, customized services, infrastructure, signalling and digital mobility solutions. With Bombardier Transportation joining Alstom on 29 January 2021, the enlarged group's combined proforma revenue amounts to GEUR 14 for the 12-month period ending on 31 March 2021. The group has its headquarters in France, is listed on Paris Stock Exchange and is a part of the CAC40 index. Alstom has 70 000 employees with a presence in 70 countries. To develop and support its products and solutions, Alstom employs around 17 500 engineers.

A key focus is CHARMEC's activities about the effects of wheel–rail interaction on contact mechanics, ride dynamics, wheel wear, wheel damage mechanisms, rail wear, rail damage and noise generation. Other notable areas of interest in the co-operation with CHARMEC include wheelset component material technology as well as braking system friction pairs and their performance.

Atkins Sverige AB (1995 and 1992 through former SNC-Lavalin Rail & Transit)
Atkins, part of SNC-Lavalin Group, is a global fully integrated professional services and project management company and a major player in the ownership of infrastructure. From offices around the world, the company are engineering a better future for our planet and its people. Its teams create sustainable solutions that connect people, data and technology in order to deliver and operate the most complex projects – including financing, consulting, design, engineering, operations. maintenance and matters in-between – to clients across Transportation, Cities & Development, Energy, Water, Environment & Geosciences, Minerals & Metallurgy, Industrial & Manufacturing and Security, Aerospace & Defence. In Sweden, Atkins is primarily focused on Transportation and Cities & Development. The company has offices in Stockholm, Göteborg, Malmö, Helsingborg and Västerås, and employs approximately 400 people.

Faiveley Transport Nordic AB (1997)
The Wabtec Corporation is a leading global provider of equipment, systems, digital solutions, and value-added services for the freight and transit rail sectors with headquarters in Wilmerding in Pennsylvania (USA) and listing on NYSE. The former Faiveley Transport group is since 2016 part of the Wabtec group. The total number of employees in Wabtec is around 27 000, of whom 200 are located in the Nordic region with Landskrona (Sweden) as base.

The main area of interest in the co-operation with CHARMEC is brake systems. The components for tread braking are being investigated, with particular focus on the interaction between brake block and wheel tread. New and better materials for the blocks are sought, with emphasis on the simulation and reduction of wheel and block wear.

Green Cargo (2000)
This state-owned Swedish rail logistics company has its head office in Stockholm/Solna and employs about 2 000 people at 40 locations throughout Sweden and Norway. Green Cargo operates around 360 locomotives and 5 000 freight wagons, which together annually cover approximately 20 000 million gross tonne-kilometre. The Green Cargo network consists of approximately 200 domestic nodes and a number of links to international destinations throughout Europe. Goods are transported by rail freight wherever possible, and rail operations are complemented by road freight to the final destination through co-operation with approximately 200 haulage companies. Areas of interest in the co-operation with CHARMEC include braking performance, noise emission, fatigue strength, and improved designs and materials for wheels and axles.

PARTNERS … (cont'd)

Lucchini Sweden AB (1995 and 1987)
Lucchini Sweden is a railway wheelset manufacturer in Surahammar with more than 150 years in the business. The company is the only wheelset manufacturer in Scandinavia, and is a wholly-owned subsidiary of Lucchini RS in Italy, one of the major suppliers of wheels and wheelsets for trains in the world.

Areas of interest for Lucchini Sweden in the co-operation with CHARMEC are the design, manufacturing, mounting, running, braking and maintenance of wheelsets. Of particular interest are new materials for wheels and axles, and noise emission from wheels. The main end users of the wheelsets are passenger and freight train operators in Sweden, Denmark, Finland and Norway. Other major customers include manufacturers of new rolling stock and also maintenance providers.

SJ AB (2006)
SJ is a Swedish partner that offers train travel, both as an independent operator and in collaboration with others. SJ is one of Sweden's most sustainable brands and is helping Sweden achieve its climate goals. The 5 400 employees of the group in Sweden and Norway enable lots of people to choose train travel, as being the most sustainable mode of transport for longer journeys. As the market-leading train operating company, SJ connects Sweden and Norway and is the gateway to Scandinavia's capitals. Every day our passengers and co-workers meet on one of SJ's 1 500 departures from over 400 stations. SJ is a private limited company owned by the Swedish government and tasked with operating profitable public railway transport.

SweMaint AB (2006)
SweMaint, whose head office is in Gothenburg, is the leading private North European provider of maintenance services specifically for railway freight wagons. SweMaint operates from 12 locations in Sweden with a total of about 250 employees. The annual turnover is around MSEK 420 and the market share in Sweden is approximately 65%.

One of SweMaint's main business areas is the management and operation of a wheelset pool for freight wagons. More than 8 000 wagons with 18 800 wheelsets are connected to the pool with an additional 3 100 in a turn-over stock, ready to use. Each year 5 000 wheel-sets are exchanged and most of them are being refurbished by our workshop. Areas of interest in the co-operation with CHARMEC are the general improvement of wheelset quality, and the development of cost-effective preventive maintenance programmes.

Trafikverket (1995 and 1990)
Trafikverket (the Swedish Transport Administration) is responsible for the construction, operation and maintenance of all state-owned roads and railways in Sweden. Trafikverket is also responsible for producing long-term plans for the transportation systems on roads and railways, at sea and in the air. Trafikverket, whose head office is in Borlänge, has around 9 300 employees.

Trafikverket's areas of interest in the co-operation with CHARMEC are the design, construction and maintenance of all types of track structures with focus on high availability and reliability. Of particular interest are wear and corrugation of the railhead (requiring maintenance grinding) and the overall degradation of the track structure. Here it is particularly important to understand and predict the effects on the track of proposed higher train speeds and increased axle loads. Other important research areas are vibration, noise and safety.

voestalpine Metal Engineering Division GmbH & CoKG (2003 and 2002)
This Austrian company is one of four divisions of the voestalpine Group and has about 13 000 employees worldwide. For the financial year 1 April 2020 – 31 March 2021, the sales of the voestalpine Group (including all four divisions) amounted to MEUR 11 267. The Metal Engineering Division integrates all steel activities of the Group in the five business units Railway Systems, Welding Consumables, Wire Technology, Tubulars, and Steel.

voestalpine Rail Technology GmbH, part of business unit Railway Systems, runs Europe's largest rail rolling mill in Leoben/Donawitz (Austria). All rails can be produced in supply lengths of up to 120 m with head-special-hardened (HSH®) premium rail quality. voestalpine Railway Systems is the global leader for system solutions in the field of railway infrastructure, offering outstanding products, logistics and services for rails, turnouts, signalling and monitoring applications. A fully integrated material chain, together with value-adding industry setups beyond steel, enable voestalpine to understand the interdependencies of all the track components in order to optimize the performance and reduce the life cycle cost of the system. The headquarter is located in Leoben/Donawitz (Austria). Switches and crossings are manufactured in Zeltweg (Austria) and elsewhere.

RESULTS AND EFFECTS IN INDUSTRY

In October 2021, Trafikverket and our partners in the Industrial Interests Group for Stage 9 and Stage 10 expressed the following views.

Abetong

CHARMEC has provided Abetong with an outstanding research environment. Of particular significance for the company is the employment since 2003 of a PhD who trained for five years at CHARMEC, with its invaluable network and expertise in fields that are of major interest to Abetong. In the past, Abetong's role as supplier of precast concrete sleeper technology had only moderate influence on the suppliers of other track components. Armed with greater understanding of the interaction between sleepers and the rest of the track structure, communication with other suppliers has now improved.

Abetong's participation in CHARMEC constantly provides us with better knowledge of the complex interaction between the full track structure and the running train. In the long run, this should lead to an overall optimization of the track structure, using components in harmony rather than a cluster of suboptimized components. Our improved understanding is also valuable when assessing the new ideas presented within the business field of Abetong.

Alstom

During Stage 9 as well as within the previous CHARMEC Stages, the wheelset research projects with a focus on rolling contact fatigue, contact mechanics and damage mechanism development have been essential for the continued development of our understanding of the behaviour of railway wheels and their materials in service. Through our active involvement we have been able to initiate or influence the development of new projects to build upon the knowledge gained from the previous projects and to address arising business needs. Alstom seeks to constantly improve the suitability, reliability and performance of their mobility solutions and therefore CHARMEC's work in specialist areas such as wheel–rail contact mechanics, railway noise mechanisms, material technology and friction pair behaviour is of importance for this ongoing development cycle.

Atkins Sverige

With the involvement in CHARMEC Atkins have, among other things, been able to increase networking, build and share knowledge, increase brand awareness among students and get inspiration for new ventures and further development of existing services, all this benefitting our clients. Atkins especially value the network and the access to the highly skilled research environment for complex topics. We also appreciate the possibility to develop and enhance our employees' knowledge and experience within complex subject matters, which gives Atkins a possibility to contribute and help the business moving forward.

Faiveley Transport Nordic

The ongoing renewal of block braking systems is driven by the need for higher train speeds, increased axle loads and lower noise levels. Faiveley Transport is continuously developing new block braking solutions for the world market. A broad approach, which combines theoretical models and results from rig and field tests, has been developed together with CHARMEC. The block braking of freight and passenger wagons should be optimized with regard to high braking power in combination with low wear on blocks and wheels, and low noise levels from the wheels. The CHARMEC projects address the extremely high level of safety and reliability that is required for these systems.

Green Cargo

The co-operation with CHARMEC has been very important in several cases relating to fatigue analysis and prediction. CHARMEC personnel supplied Green Cargo with the necessary crack propagation calculations to develop, from a safety perspective, an appropriate maintenance schedule for wheel axles of a certain type. CHARMEC has also investigated critical loads on locomotive wheels to understand why cracks are developing on a certain wheel type. Such analysis is critical if Green Cargo is to be able to develop appropriate remedies to overcome this problem. The vast research library on wheel and rail mechanics helped, through the creation of a calculation model, Green Cargo and Trafikverket quickly to understand the mechanical consequences of introducing heavy locomotives with three-axle bogies on the Swedish infrastructure. This is one out of many initiatives towards introducing longer and heavier trains. Furthermore, CHARMEC has continued to support the development of composite brake blocks, a very important initiative for decreasing freight transport noise.

Lucchini Sweden

A significant achievement in the co-operation with CHARMEC in recent years has been the development of new freight wagon wheelsets for 25, 30, 32.5 and 35 tonne axle loads suitable for a Nordic climate. These wheelsets must fulfil stringent requirements to comply with various national and international standards. The brake test rig on the company's premises in Surahammar, originally developed in collaboration with Chalmers but decommissioned a few years ago, has been very important in this work.

Optimized geometries of wheels and axles for new applications have recently been developed, some of which will be submitted for approval according to Technical Specifications for Interoperability (TSI). CHARMEC personnel have assisted Lucchini with technical developments and design calculations, improved workshop practices, documentation and marketing of products, as well as taking part in technical meetings with customers. Previously, CHARMEC represented Lucchini Sweden on the CEN and ERWA committees.

SJ

CHARMEC has provided support and expertise to SJ in several projects. A recent example is the joint project TS20 where installed measuring equipment on an SJ vehicle gave input to CHARMEC's model for evaluation of the influence of wheel damage on wheel–rail contact forces. In addition, expert consultancy at investigations of root causes for wheel cracks has been provided. Within the research areas of interest for SJ, CHARMEC's work is highly appreciated as it deals with a full railway system perspective. The centre plays an important role in the bringing together of people from industry, operators, infrastructure and universities. SJ has also consulted with CHARMEC when assessing technical reports.

SweMaint

CHARMEC has provided SweMaint with an information hub and research environment – and a speaking partner for technical issues of importance to the company. CHARMEC has assisted with studies on how to improve the reliability of wheels and axles, and by discussing technical improvements. For the future we look forward to increasing our understanding of strategic maintenance programmes, both in relation to the wheelset and to the wagon itself, with a view to optimize the economic performance of the complete vehicle.

Trafikverket

CHARMEC research has helped Trafikverket meet new market demands for higher axle loads and lower noise and vibration levels. The results of this research have had a substantial impact on cost-effectiveness for both Trafikverket and its customers.

The development of new projects dealing with switches and crossings (turnouts) has been an important step forward. The co-operation related to the EU projects has been particularly important. Other projects of interest to us have dealt with alarm limits for out-of-round wheels, improved design of insulating rail joints, safeguarding against rail breaks and track buckling (sun-kinks), and reduced noise emission and ground vibrations. Several projects have resulted in new specifications and new designs. CHARMEC research has also driven international standardization, which has led to substantial cost savings.

The Principal Agreement for Stage 10 means that CHARMEC will support Trafikverket with competence in research, technical competitive edge resources, implementation of research results, and identification of future research areas and projects. This role is unique and will give Trafikverket new possibilities, in particular in the EU Horizon Europe Programme named Europe's Rail.

voestalpine

Understanding the mechanisms of crack initiation and crack growth in rails caused by repeated wheel–rail contact loading is vital for voestalpine Rail Technology. During Stages 5–9 the co-operation with CHARMEC has focused on simulation models for the early growth of small cracks, the prediction of crack propagation directions and wear, and the propagation of squats. These studies will continue in more detail during Stage 10. For voestalpine Railway Systems, the co-operation with CHARMEC has led to a better theoretical understanding of forces, stresses and material behaviour inside a turnout. The research of the past was focused on the development of an integrated simulation tool to allow prediction of plastic deformation, wear and RCF over the lifetime of a crossing for different materials. Also, this activity will continue in Stage 10.

A forerunner to this SJ 3000 train has the Swedish high-speed record of 303 km/h. It was reached during a testing activity within a research project in collaboration between Trafikverket, Bombardier, SJ, KTH and Chalmers. Courtesy: SJ

SPECIAL EVENTS AND ACHIEVEMENTS (Stage 9)

Board meetings relocated and digitalized

Three of the twelve meetings of the CHARMEC Board during Stage 9 were combined with visits to organizations outside Chalmers: to SNC-Lavalin (now Atkins Sverige) in Gothenburg on 23 November 2018; to Trafikverket in Stockholm on 23 May 2019, and to Green Cargo in Eskilstuna on 28 November 2019. Due to the coronavirus pandemic and its effects, the five meetings on 28 May 2020, 17 September 2020, 27 November 2020, 16 February 2021 and 27 May 2021 were digitally held (Teams). From May 2020, the seminars given in connection with the Board meetings could also be followed via internet.

Leaving members

Sven-Ivar Karlsson left his position at SNC-Lavalin (now Atkins Sverige) during Stage 9 and was from January 2021 replaced in CHARMEC's Board by their Maria Edén. At the start of Stage 9, Bengt Fors from Green Cargo was succeeded by Markus Gardbring and Fredrik Holmberg from Bombardier Transportation (now Alstom) by Roger Deuce.

Project catalogue

In May 2018, during the preparation of CHARMEC's Stage 9, a 30-page catalogue with possible new research projects was compiled and discussed with the centre's partners.

Trafikverket

Trafikverket (the Swedish Transport Administration) is responsible for all of Sweden's modes of transport – on roads and railways, at sea and in the air – and it builds, maintains and operates the entire national railway infrastructure. Trafikverket appropriates a basic contribution for CHARMEC's research, and for the centre's training and examination of PhDs in railway mechanics. The chair of the CHARMEC Board has been held by Banverket/Trafikverket since the centre's start in 1995.

Research and Innovation Day of Trafikverket

Annually, in May, Trafikverket organizes The Research and Innovation Day in which CHARMEC's researchers participate. During Stage 9 presentations were given by staff from Trafikverket, including the then Director General Lena Erixon, and from other organizations, followed by discussions.

Transportstyrelsen

Transportstyrelsen (The Swedish Transport Agency) is working to achieve good accessibility, high quality, secure and environmentally aware rail, air, sea and road transport. It has the overall responsibility for drawing up regulations and ensuring that authorities, companies, organizations and citizens abide by them. During Stage 9, CHARMEC's Tore Vernersson has been involved in planning and data analyses of winter field tests run by Transportstyrelsen, see project SD11 on page 55.

High-speed tracks in Sweden

Trafikverket is planning sections of high-speed rail lines in Sweden. To establish demands on such lines with so-called fixed track, also known as slab track, CHARMEC runs the projects TS19 and VB13, see pages 20 and 30, which are financially supported by Trafikverket. Also the term ballastless track is in use here.

Areas of Advance

Chalmers University has profiled its research activities around six Areas of Advance (Swedish: Styrkeområden). Two of these areas related to CHARMEC are Materials Science, in which CHARMEC provides applications that in many respects are extreme, and Transport, in which railway mechanics issues are crucial for a competitive railway transport system. We participate in seminars arranged by the two areas and some of our researchers have received financial support from them. Our projects "Railway vehicle risk analyses", "Intelligent railway digitalization" and "Sustainable railway asset management", see projects SP30, SP31 and SP32 on pages 69, 70 and 71, are financed by the Area of Advance Transport.

KTH Railway Group

At KTH (the Royal Institute of Technology in Stockholm), our Professor Roger Lundén serves on the Board of the KTH Railway Group, and Professor Sebastian Stichel, Director of the Group, serves on the Board of CHARMEC. Several of CHARMEC's doctoral students have taken general courses in railway technology at KTH. CHARMEC's senior researchers participate in grading committees of PhD theses and act as discussion leaders at licentiate seminars at KTH, and, in the same way, KTH's senior researchers serve at Chalmers. Collaboration also takes place between research groups at KTH and Chalmers, for example in the European projects. KTH is represented in the joint reference group of projects TS20, MU22, MU30, MU34–38 and MU40.

JVTC at LTU

Collaboration with Luleå JVTC (the Railway Research Centre at Luleå University of Technology in northern Sweden) takes place in the European projects. Professor Uday Kumar, who is Director of JVTC, is invited to the CHARMEC Board meetings, and, in the same way, CHARMEC's Director Anders Ekberg is invited to the JVTC Board meetings.

DTU

During Stage 9 and earlier, Johan Ahlström in projects MU28, MU29 and MU30 has co-operated with researchers at DTU (Technical University of Denmark) to enable advanced microscopy, X-ray tomograpy and synchrotron X-ray diffraction experiments. He and his research group regularly attend the annual Risø International Symposium on Materials Science and Engineering in Denmark.

RTRI

During Stage 9, CHARMEC has continued its co-operation in our SD projects with the Railway Technical Research Institute (RTRI) in Tokyo (Japan).

China

At the State Key Laboratory of Traction Power of Southwest Jiaotong University (SWJTU) in Chengdu (P R China), their full-scale test rig for railway track was used by our doctoral students Emil Aggestam and Jannik Theyssen during two weeks in April 2019, see the slab-track projects TS19 and VB13 on pages 20 and 30.

Semi-annual reports

Every six months, as of 31 December and 30 June, all CHARMEC leaders of current projects prepare a two-page report on the progress of their projects during the preceding six months. The ten headings specified by the Board in each report are Background and aims, Previous reports, Reference group, Work performed, Results achieved, Published material, Future plans, Check against initial schedule, Follow-up of budget, and Miscellaneous. All these two-page reports are edited, compiled in a document (about 50 pages) and submitted to the CHARMEC Board before their next meeting when the reports are studied and discussed.

All semi-annual reports have been written in English since 30 June 2003. Bengt Åkesson continues to be responsible for the editing together with Roger Lundén.

Impact from CHARMEC projects

Starting in 2019, a list of foreseen impacts from the results of ongoing doctoral research projects has been added at the end of the semi-annual reports under the four headings Long-term, Short-term, Academic implementation, and Industrial implementation. In CHARMEC's reporting of each doctoral dissertation, a list entitled "Implementable results" is now being added. At a ceremony on 25 October 2019, the annual Chalmers award for societal impact was bestowed on CHARMEC for our work on co-ordinated alarm limits for wheel loads in Europe, see project MU22 on page 32 and projects EU13, SP13 and SP28 in the previous Triennial Reports.

Anders Ekberg and Fredrik Hörstedt during the ceremony when CHARMEC received the Chalmers award for societal impact

Project reference groups

Most of CHARMEC's projects have had a Project Reference Group (PRG) since Stage 3. A PRG should be a forum for the informal presentation and discussion of research results and for the planning of future activities (within the framework decided by the Board for the overall project plan). The mutual transfer of knowledge between researchers and industry (including Trafikverket) should be furthered, and the implementation in industry be promoted. Doctoral students should be encouraged by the PRG to make study visits and to learn about the activities of the centre's partners. Employees of these partners should be encouraged to spend time working at Chalmers. A PRG meets once or twice a year, and the project leader is the convener. Several projects have a joint PRG.

At a meeting (2008:2), the Board decided that all doctoral projects should have a PRG, that notes should be taken at all PRG meetings, that these notes should be sent to CHARMEC's Director and be archived, and that the locations and dates of the PRG meetings should be listed in the semi-annual reports. The directives for the PRG have continuously been updated since 2001.

Photo by Anders Ekberg taken on 14 January 2019 outside the entrance of Red Bull Ring in Spielberg, Austria. From the left: Hayder Al-Maliki, Roger Lundén, Björn Pålsson, Hannes Gsodam, Christof Bernsteiner, Uwe Ossberger, Stephan Scheriau, Tomislav Mihalj, Sven Eck, Johan Ahlström, Werner Daves, Rostyslav Skrypnyk, Hans Peter Brantner, Claudia Gruber, Christof Marte, Christoph Kammerhofer, Knut Andreas Meyer, Magnus Ekh, Jens Nielsen, Thomas Titze, Werner Ecker, Julian Wiedorn and Dino Velic

Doctoral examinations

Our 54 doctoral examinations in railway mechanics are listed on page 74. As seen, nine of these took place during Stage 9 and four during Stage 8.

Appointment of docents

The highest academic qualification in Sweden (above the doctor's level) is that of "docent". On 18 May 2021, Peter Torstensson (doctor in project TS11 and leader of project TS16) held his docent lecture "Societal impact of railway dynamics" online and was appointed. The reviewing experts were Professor Paul Meehan, University of Queensland, Brisbane (Australia), and Professor Antoinette Maniatty, Rensselaer Polytechnic Institute, Troy, NY (USA). Similarly, on 18 June 2021, Björn Pålsson (doctor in project TS13 and leader of projects TS18 and TS21) held his docent lecture "Switches & Crossings – Discontinuities in the railway continuum" online and was appointed. Here the reviewing experts were Docent Jenny Jerrelid, KTH Vehicle Technology and Solid Mechanics, and Professor Francesco Braghin, Politecnico di Milano, Milano (Italy).

Post-doc position

Knut Andreas Meyer, doctor in project MU34 in October 2019, started a two-year post-doc from September 2020. However, he left Chalmers in July 2021 for a position at TU Braunschweig (Germany) but serves as assitant supervisor in project MU41, see page 51.

Guest researchers

Professor Paul Meehan from Queensland University in Australia made a renewed visit to CHARMEC on 23-29 May 2019 to give a lecture and to meet our researchers for discussions of his projects with Australia's Rail Cooperative Research Centre. He stayed with us for longer periods in May 2005 and June 2015. From voestalpine in Zeltweg, Uwe Ossberger visited CHARMEC on 18 – 19 March 2019. Doctoral student Nicola Zani from University of Brescia in Italy spent March – May 2020 at CHARMEC studying multiaxial fatigue and material mechanics, see projects MU22 and MU39 on pages 32 and 50. The time of the visit coincided with the coronavirus pandemic, meaning that he had to spend two weeks in quarantine and thereafter also do most of his work from a student flat.

Björn Paulsson

Former employee of Trafikverket in Borlänge and co-worker at UIC in Paris, Dr h c Björn Paulsson, has continued to be engaged by CHARMEC during Stage 9. Primarily, he was involved in projects EU17, EU19, SP28 and SP33, see pages 57, 61, 67 and 72. Björn Paulsson served as the first chairman 1995 – 2008 of the Board of CHARMEC.

SPECIAL EVENTS ... (cont'd)

Exchange with voestalpine

As previously, meetings between CHARMEC researchers and their Austrian colleagues at voestalpine in Leoben and Zeltweg were held twice a year during Stage 9. Experts were invited to these two-day workshops from the Austrian Academy of Science (Erich Schmid Institute of Materials Science) and the Materials Center Leoben, which are both linked to the University of Leoben, and from the Competence Center Virtuelles Fahrzeug (ViF) in Graz. Also experts from Linsinger, LINMAG Rail Service and Railway Infrastructure Design (RID) at TU Graz were invited, each on one occasion. The six meetings during Stage 9 were held on 14–15 January 2019 in Leoben and Zeltweg, 28–29 May 2019 in Gothenburg, 13–14 January 2020 in Leoben and Zeltweg, and, online, on 3 June 2020, 11 January 2021 and 7 June 2021.

Lucchini

Bilateral agreements have been running since 1987 between Lucchini Sweden (formerly Sura Traction, ABB Sura Traction 1990–96, Adtranz Wheelset 1996–2000) and Chalmers Mechanics and Maritime Sciences (formerly Chalmers Applied Mechanics and, earlier, Chalmers Solid Mechanics). CHARMEC's personnel have assisted the Lucchini company and its forerunners on a continuous basis in the design, analysis, testing, documentation and marketing of wheelsets. Roger Lundén has previously represented Lucchini Sweden on the CEN and ERWA committees, see Triennial Report Stage 8 on page 72. The collaboration involves the mother company Lucchini RS in Lombardy, Italy. Today, wheelsets are manufactured and wheelsets and bogies are maintained in Surahammar.

InnoTrans

InnoTrans is an international trade fair for rail transport technology which is held every two years in Berlin. The latest InnoTrans exhibition was held on 18–21 September 2018 and had 3062 exhibitors (with 38 being from Sweden) from 61 countries. Michele Maglio in project TS20 and his supervisor Elena Kabo visited InnoTrans on 20 September 2018. At Lucchini's exhibit their new product Smartset® was demonstrated. It is being used on SJ's double-decker X40 and data from measurements are being used in our project TS20, see page 23.

IRR Huddersfield

During Stage 9, CHARMEC continued our contacts with the Institute of Railway Research (IRR) at the University of Huddersfield (UK). For instance, a delegation from IRR, including their Head, Professor Yann Bezin, visited us on 21–22 May 2019 for a workshop on switches. We also cooperate with IRR in EU projects.

Brake test rig

The Swedish brake test rig on the Lucchini premises in Surahammar, see page 55, was decommissioned during Stage 8, and results from experiments performed at RTRI in Japan have since then been used by us. Following a decision by the CHARMEC Board, the design and construction of a new rig in a laboratory hall at Chalmers Mechanics and Maritime Sciences is ongoing, see projects SD11 and SP34 on pages 54 and 73.

CM2018 and CM2021

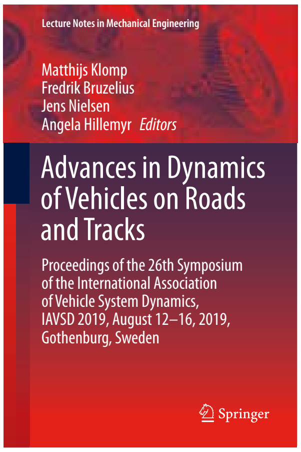
The International Conference on Contact Mechanics and Wear of Rail/Wheel Systems, abbreviated CM and held every third year, is central to CHARMEC's activities. Since September 2018, our Anders Ekberg is chairman of the international committee for these conferences. CM2018 was held in Delft (The Netherlands) on 23–27 September 2018. Visitors were 213 people from 18 countries, and of them 13 researchers from CHARMEC. They contributed with nine oral presentations, including one held in a plenary session by Anders Ekberg and Björn Pålsson, see project EU17 on page 57, and they held the chair in four sessions. Because of the coronavirus pandemic, the CM2021 conference was postponed until 4–7 September 2022.

IAVSD2019

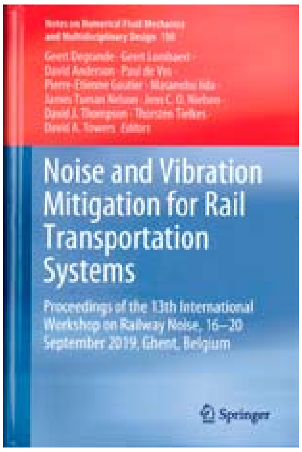
The 26th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2019) was arranged by the International Association for Vehicle System Dynamics (IAVSD) in Gothenburg (Sweden) on 12–16 August 2019. In total 380 people from 28 countries took part. The symposium was organized by our Department of Mechanics and Maritime Sciences at Chalmers together with the two centres CHARMEC and SAFER. Responsible for the scientific content of the railway part were Jens Nielsen from CHARMEC and Fredrik Bruzelius from VTI. For a photo of proceedings, see the next page.

IWRN13

The 13th International Workshop on Railway Noise (IWRN13) was arranged in Leuven (Belgium) on 16–20 September 2019. In total 159 people from 23 countries took part. Jens Nielsen presented an invited keynote lecture which was co-authored with our Astrid Pieringer together with David Thompson (University of Southampton) and Peter Torstensson (VTI), see project TS8 on page 14. Two of the oral contributions were given by CHARMEC researchers in acoustics, see projects VB12 and VB13 on pages 29 and 31. Our Jens Nielsen is a member of the international committee for the IWRN workshops.



Front cover of proceedings featuring 218 peer-reviewed articles from IAVSD2019



Front cover of proceedings featuring 78 peer-reviewed articles from IWRN13

XIX INTERNATIONAL WHEELSET CONGRESS JUNE 16-20, 2019 VENICE

IWC19

The 19th International Wheelset Congress (IWC19) was held in Venice (Italy) on 16–20 June 2019 hosted by Lucchini RS together with the ERWA and UNIFE organizations. Four researchers from CHARMEC attended the congress. Of them Mandeep Singh Walia (project SD10) and Tore Vernersson (project EU18) received a Best Paper Award for their contributions. A technical visit was made to a depot in Vicenza where Trenitalia's high-speed fleet is maintained. Our Professor Elena Kabo was a member of the technical committee for the IWC conference and she also chaired one of the plenary sessions.

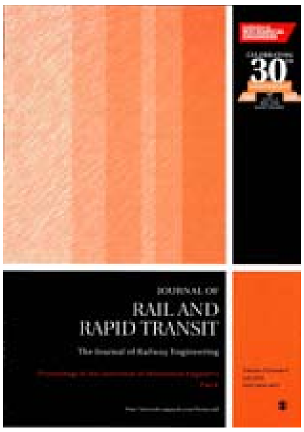
Summaries of interesting conference papers

A tradition at CHARMEC is that those of our researchers who are visiting a conference, such as CM etc, should write a short summary of the contents of those two or three contributions at the conference which he/she found most interesting, and that these summaries are made available to all CHARMEC researchers and Board members.

LKAB and Heavy Haul

Researchers from CHARMEC have continued to assist the mining company LKAB in Kiruna (Sweden) in managing wheel damage. The affected trains have an axle load of 30 tonnes and are operating on Malmbanan (Iron Ore Line in northern Sweden and Norway). An increase of the axle load to 32.5 tonnes is now being implemented.

CHARMEC is a member of the local organization Nordic Heavy Haul (NHH), which in turn is a member of the International Heavy Haul Association (IHHA). IHHA organizes the International Heavy Haul Association conferences. In Narvik (Norway), the conference was held on 10-14 June 2019 with about 540 people from 25 countries participating. From CHARMEC, Anders Ekberg and Roger Lundén took part. Anders Ekberg and Stuart Grassie made a joint oral presentation. A study visit was made to the Norwegian part Ofotbanen of the Iron Ore Line going westwards from Kiruna. Every day 10 trains with 68 wagons drawn by two 5.4 MW six-axle locomotives arrive in Narvik to the unloading station in the harbour. Anders Ekberg took part in the Nordic Heavy Haul meeting on 13 May 2020. On 11 February 2021 he made a presentation "Assessing, monitoring and predicting health of track and vehicles" at a Nordic Heavy Haul seminar on development of the Iron Ore Line. See photo of an iron ore wagon on page 49.



In a Special Issue of IMechE Journal of Rail and Rapid Transit from July 2019, papers from the previous IHHA conference in Cape Town (South Africa) 2–6 September 2017 have been published with Roger Lundén being one of five Guest Editors.

Front cover of Special Issue from IHHA conference in Cape Town September 2017

Peer reviewing and keeping in touch

CHARMEC's project leaders and researchers are heavily involved in the peer reviewing of manuscripts for scientific journals, among them: Acta Materialia, ASME Applied Mechanics Reviews, Computational Mechanics, Computer Methods in Applied Mechanics and Engineering, Engineering Failure Analysis, Engineering Fracture Mechanics, Engineering Structures, European Journal of Mechanics – A/Solids, Fatigue & Fracture of Engineering Materials & Structures, IMechE Journal of Rail and Rapid Transit, Ingegneria Ferroviaria, International Journal for Numerical Methods in Engineering, International Journal of Damage Mechanics, International Journal of Fatigue, International Journal of Plasticity, International Journal of Railway Technology, International Journal of Rail Transportation, International Journal of Thermal Sciences, Journal of Materials Engineering and Performance, Journal of Materials Processing, Journal of Sound and Vibration, Journal of the Mechanics and Physics of Solids, Philosophical Magazine, Railway Engineering Science, Soil Dynamics and Earthquake Engineering, Transportation Geotechnics, Tribology International, Vehicle System Dynamics, Wear, and ZAMM.

In addition, we review papers submitted to international congresses, conferences, symposia and workshops and we act as experts in academic promotion issues. All of these activities are appreciated by us as an important way to keep in touch with international developments in science and technology and their railway applications.

Nordic Track Technology Engineering Training

This is a one-week course with Swedish title Nordisk Banteknisk Ingenjörs-Utbildning (NBIU) that is held annually for participants from Denmark, Finland, Norway and Sweden. CHARMEC's Professor Jens Nielsen contributes with the lecture "An introduction to train-track dynamics". During Stage 9, the 34th and 35th NBIU took place, but was cancelled 2020 due to the coronavirus pandemic. Jens Nielsen's taking part in the 35th NBIU which was the 22th time he contributed.

Nordic Rail Fair

On two different days, two groups of researchers from CHARMEC visited the 13th Nordic Rail Fair held in Jönköping (Sweden) on 8–10 October 2019. We no longer have a stand at the fair.

Nordic seminars on railway technology

During Stage 9, the 21th seminar was planned to be held in Tampere (Finland) but had to be postponed because of the coronavirus pandemic. It is now planned for 21–22 June 2022.

Swedtrain

Swedtrain is the Swedish Association of Railway Industries but also has CHARMEC as a member. We take part in the annual Järnvägsdagen (Railway Day) arranged by Swedtrain and partners. At the meeting on 11 November 2019, Sweden's Minister of Infrastructure, Tomas Eneroth, attended and spoke about the planning of the country's new main lines for high-speed trains.

VTI

Staff from CHARMEC take part in the annual meetings arranged by VTI, the Swedish National Road and Transport Research Institute, headquartered in Linköping. Docent Peter Torstensson from project TS16 is now employed at the VTI office in Gothenburg but is still involved in the research at CHARMEC. We also co-operate with VTI in project SP29, see page 68.

DB Systemtechnik

DB Systemtechnik GmbH is the engineering office of Deutsche Bahn AG. A co-operation with them was established through our Dr Astrid Pieringer who worked in their Department of Acoustics, Vibrations, Aerodynamics and HVAC (Heating, Ventilation and Air Conditioning) in Munich during the period May 2018–June 2019. This stay was part of the Marie Skłodowska-Curie Individual Fellowship granted to her. For further information, see project VB12 on page 28.

CRRC

A delegation from the Chinese train manufacturer CRRC (in Changchun) visited CHARMEC on 10 September 2019 to discuss a possible future co-operation. Special interests were wheel polygonalization, rolling contact fatigue and vibrations/noise.

UTMIS

This acronym stands for "Utmattningsnätverket i Sverige" (the Fatigue Network in Sweden) and involves people from several branches of engineering, including railway mechanics. Researchers from CHARMEC attend seminars arranged by UTMIS.

Track to the Future

As a member of the international scientific committee for this British research project, Anders Ekberg took part in a meeting in Ilminster (UK) on 19–20 July 2018.

EU projects

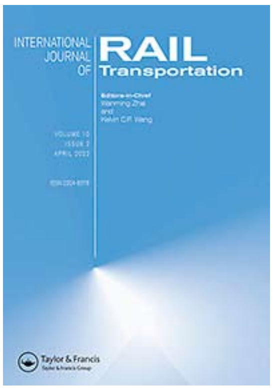
Since its start in 1995, CHARMEC has run European Union (EU) projects beginning with EU1 and EU2 in 1996–1999 and continuing up to EU15, EU17, EU18, EU19, EU20 and EU21 during Stage 9, see pages 56–65. Lately, these EU projects have belonged to the Horizon 2020 Framework Programme and have fallen under the Shift2Rail Joint Technology Initiative, see below.

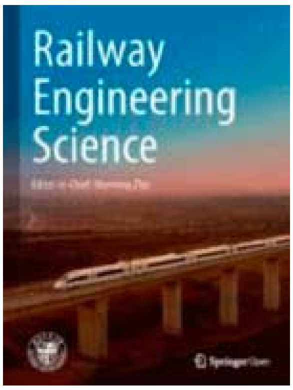
Editorial Boards of JRRT, IJRT and Railway Engineering Science

Journal of RAIL AND RAPID TRANSIT

Since 2005, Roger Lundén is a member of the Editorial Board of the IMechE Journal of Rail and Rapid Transit (JRRT). Editor of the journal is Professor Simon Iwnicki of Huddersfield University in the UK. Many research results in railway mechanics from Chalmers/CHARMEC have been published in this periodical (more than 60 articles up to autumn 2021). IMechE stands for the Institution of Mechanical Engineers which has its premises on Birdcage Walk in Westminster, London (UK). A Special Issue of JRRT was published in 2019 containing selected peer-reviewed contributions from the conference IHHA11, see above, with Roger Lundén being one of five Guest Editors.

Since 2013, Jens Nielsen is a member of the Editorial Board of the International Journal of Rail Transportation (IJRT). This is an online journal with Professor Wanming Zhai of Southwest Jiaotong University (P R China) and Dr Kelvin Wang of Oklahoma State University (USA) being Editors. Since 2019 Jens Nielsen is also a member of the Editorial Board of the journal Railway Engineering Science. Also here Professor Wanming Zhai is Editor (in 1998 he visited CHARMEC, see page 55 in the Triennial Report Stage 2).





Master programme in Mobility Engineering

This new programme was launched at Chalmers University in the autumn 2021 with the four subprogrammes Automotive, Naval, Aerospace, and Rail. CHARMEC has contributed to the formulation the programme and especially its "Rail" and the content has been discussed by the CHARMEC Board. Anders Ekberg, Elena Kabo, Jens Nielsen and Björn Pålsson have developed the new course "Railway Technology" and the applied part "Railway Technology Project". In addition, CHARMEC researchers have contributed to the course "Introduction to Propulsion and Energy Systems for Transport". Both national and international students participate.

Anders Ekberg in KVVS

In December 2020, Professor Anders Ekberg was appointed a member of Kungliga Vetenskaps- och Vitterhets-Samhället, KVVS, i Göteborg (The Royal Society of Arts and Sciences in Gothenburg). KVVS was founded in 1778 by the Swedish king Gustav III.

Advanced fatigue design

During Stage 9, a graduate course under this heading was given by Anders Ekberg focusing on multiaxial fatigue, non-linear fracture mechanics and contact phenomena. Doctoral students from CHARMEC took part.

Railway mechanics course

In June 2020, Anders Ekberg and Björn Pålsson digitally held the three-day open course "Selected topics in railway mechanics with focus on deterioration" with 73 participants including doctoral students from CHARMEC.

IVA Research2Business Sessions

IVA Royal Swedish Academy of Engineering Sciences

In September 2020, CHARMEC's research was presented by Anders Ekberg at two of these sessions held by IVA (IngenjörsVetenskapsAkademien / Royal Swedish Academy of Engineering Sciences).

Impact cases and radio broadcasting

Two impact cases and one radio interview with Anders Ekberg have been published (in Swedish).

Shift2Rail

Shift2Rail is an initiative within the EU Horizon 2020 programme with "focused research and innovation in the rail area by accelerating the integration of new and advanced technologies into innovative rail product solutions". It is a so-called Joint Technology Initiative (JTI) which means an aim to establish public-private partnerships. Shift2Rail was approved by EU in June 2014 with a total budget of MEUR 920. Trafikverket is one of nine founding members and there are presently (December 2021) 19 member organizations in Shift2Rail. Chalmers/CHARMEC is a so-called linked third party to Trafikverket and our research concerns IP3 (Innovation Programme 3) "Cost-Efficient and Reliable High-Capacity Infrastructure" and IP5 "Technologies for Sustainable & Attractive European Rail Freight". See further pages 57–65.

Europe's Rail

Within Horizon Europe, Shift2Rail (part of Horizon 2020) is now being followed by the new programme Europe's Rail being run during the years 2021–2027. CHARMEC has co-operated with Trafikverket, who is one of the 25 Founding Members of the JU (Joint Undertaking), in the formulation of research areas for the programme. The vision of Europe's Rail JU is "To deliver, via an integrated systems approach, a high-capacity, flexible, multimodal, sustainable and reliable integrated European railway network by eliminating barriers to interoperability and providing solutions for full integration, for European citizens and cargo". The Mission Statement of Europe's Rail is "Rail Research and Innovation to make Rail the everyday mobility". Each of the research projects will belong to one of the seven Flagship Areas

1. Network management planning and control & Mobility management in a multimodal environment
2. Digital & automated up to autonomous train operations
3. Intelligent & integrated asset management
4. A sustainable and green rail system
5. Sustainable competitive digital green rail freight services
6. Regional rail services / Innovative rail services to revitalise capillary lines
7. Innovation on new approaches for guided transport modes

There are also the two System Pillars "Transversal Topics" and "Exploratory Research" with the aim to work towards a European train control system and unified train operation and to make the European railways as interoperable as possible and avoiding national rules and approaches. The first calls for project proposals will be launched in March 2022 with projects expected to be started during the autumn 2022.

Trafikverket´s Areas of Excellence

During 2021, and in response to the challenges the railway sector is facing, Trafikverket identified and established ten so-called Areas of Excellence in which key research should be carried out. Thereby the existing co-operation with the four railway research centres CHARMEC, KTH Railway Group, Luleå Railway Research Center / JVTC and KAJT would be renewed, consolidated and expanded. Agreements, with a horizon of ten years, between Trafikverket and the centres were signed during the spring 2021. The establishment of the Areas of Excellence is also expected to attract more partners and make them enter with new funding and thereby increase the total supply of qualified research. The ten Areas of Excellence are

1. Vehicle technology / Vehicle dynamics
2. Wheelsets and brake systems
3. Track technology
4. Civil engineering structures and foundations
5. Electric power / Power supply and traction systems
6. Safety signalling systems
7. Traffic planning and traffic control
8. Operation and maintenance
9. Capacity and punctuality
10. The railway system

Chalmers/CHARMEC will carry out work in areas 2, 3 and 4 and to some extent also in areas 1, 8 and 10. Furthermore, Chalmers/CHARMEC will be co-ordinating areas 2, 3 and 4 (in consultation with KTH regarding bridges). See further pages 12, 32, 90 and 91.

Professor Mario Plos at Chalmers Department of Architecture and Civil Engineering co-ordinates Excellence Area 4, Civil engineering structures and foundations

This is a presentation of the cash and in-kind investments for Stage 9, both per party and per programme area. Information about the money received and used is from Chalmers' accounts for the CHARMEC Competence Centre, and the accounts for each department's CHARMEC projects. The in-kind investments from the Industrial Interests Group and Chalmers have been calculated according to the principles stated in the Principal Agreement for Stage 9 dated 27 August 2018.

Report per party

Budgeted cash and in-kind investments per party according to the Principal Agreement for Stage 9 are presented in Table 1. Included are also cash contributions from Chalmers, Trafikverket and VINNOVA (InfraSweden2030) that were not included in the Principal Agreement for Stage 9. Cash contributions from the EU are also included. In the Shift2Rail projects, Chalmers/CHARMEC is a so-called Linked Third Party which means that Chalmers/CHARMEC only has a contract with Trafikverket, although the funding partly originates from EU and the finances are reported in a similar way as for an ordinary EU project.

Cash investments

At the meeting of the CHARMEC Board on 23 November 2018, information was given to Trafikverket and the Industrial Interests Group that the payments from the partners to CHARMEC would be settled in a similar manner as for the previous stages. This meant that CHARMEC would invoice on six different occasions: 2018-11-01, 2019-03-01, 2019-09-01, 2020-03-01, 2020-09-01 and 2021-03-01. This proposal was accepted by all partners.

In December 2016, Trafikverket approved a project proposal from Chalmers/CHARMEC providing two years of funding for the project TS19 "Design criteria for slab track structures" with the total budget kSEK 2 000, of which kSEK 1 760 were assigned to Stage 8 and kSEK 240 to Stage 9. In February 2017, Trafikverket approved a project proposal from Chalmers/CHARMEC providing two years of funding for the project VB13 "Prediction and mitigation of noise from vehicles on slab tracks" with the total budget kSEK 2 000, of which kSEK 833 were assigned to Stage 8 and kSEK 1 167 to Stage 9. In November 2020, Trafikverket approved a project proposal from Chalmers/CHARMEC providing one year of funding for the project SP33 "More robust switches through improved control of the switch rail" with the total budget kSEK 680, of which kSEK 420 were assigned to Stage 9 and kSEK 260 to Stage 10. At the end of Stage 9, all the amounts for projects TS19, VB13 and SP33 had been invoiced according to their budgets for Stages 8 and 9.

In 2015, the EU approved a project proposal from Chalmers/CHARMEC and our European partners providing kEUR 417 to the EU15 project "WRIST". Chalmers/CHARMEC participates in the EU Shift2Rail programme as a Linked Third Party to Trafikverket. In 2016, Trafikverket and

Table 1. Cash and in-kind contributions (kSEK) per party during Stage 9

Party	Cash		In-kind		Total	
	Budget	Paid	Budget	Performed	Budget	Paid/Performed
Chalmers	13 383	13 383	2 660	2 660	16 043	16 043
Abetong	1 554	1 554	714	0	2 268	1 554
Alstom	1 800	1 800	750	588	2 550	2 388
Atkins	195	195	150	39	345	234
Faiveley	900	900	600	584	1 500	1 484
Green Cargo	660	660	330	420	990	1 080
Lucchini	1 485	1 485	600	658	2 085	2 143
SJ	660	660	–	–	660	660
SweMaint	162	162	162	40	324	202
Trafikverket	28 421	28 421	–	–	28 421	28 421
voestalpine	2 316	2 316	2 460	2 998	4 776	5 314
EU	15 739	15 739	–	–	15 739	15 739
VINNOVA	100	100	–	–	100	100
From Stage 8	5 776	5 776	–	–	5 776	5 776
Total	73 151	73 151	8 426	7 987	81 577	81 138

Note Alstom: formerly Bombardier Transportation

Chalmers signed a contract providing kSEK 11 739 to the EU17 project "In2Track" and a contract providing kSEK 500 to the EU18 project "Fr8Rail". In 2018, Trafikverket and Chalmers signed a contract providing kSEK 33 000 to the EU19 project "In2Track2". In 2019, Trafikverket and Chalmers signed a contract providing kSEK 280 to the EU20 "Fr8Rail2". In 2020, Trafikverket and Chalmers signed a contract providing kSEK 550 additional funding to the EU19 project "In2Track2" for "Grinding and milling – Feasibility study". In 2021, Trafikverket and Chalmers signed a contract providing kSEK 33 000 to the EU21 project "In2Track3".

In 2018, a proposal from the Swedish National Road and Transport Research Institute (VTI) to VINNOVA's Strategic Innovation Programme InfraSweden2030 was approved and included a funding of kSEK 100 to the SP29 project "Including wear caused by braking in train driving simulators".

Chalmers University supports CHARMEC financially. For Stage 9, the agreed amount was kSEK 2 160 centrally from the Department of Mechanics and Maritime Sciences and kSEK 2 673 from its Division of Dynamics. At the Department of Industrial and Materials Science, its Division of Computational Mechanics contributed kSEK 3 016 and its Division of Engineering Materials kSEK 1 983. The Division of Technical Acoustics at the Department of Architecture and Civil Engineering contributed kSEK 535.

Chalmers supports EU projects, which during Stage 9 has meant a contribution of kSEK 489 + 2 527 = kSEK 3 016 to the projects EU17 and EU19.

The following amounts in cash, totalling kSEK 32 153, due for CHARMEC's Stage 9, have been received as per agreements:

6 × kSEK 259 Abetong
6 × kSEK 300 Bombardier Transportation/Alstom
6 × kSEK 150 Faiveley Transport Nordic
6 × kSEK 110 Green Cargo
6 × kSEK 247.5 Lucchini Sweden
6 × kSEK 110 SJ
6 × kSEK 32.5 SNC-Lavalin/Atkins Sverige
6 × kSEK 27 SweMaint
6 × kSEK 2 750 + 11 921 = kSEK 28 421 Trafikverket
6 × kSEK 212 voestalpine Rail Technology
6 × kSEK 174 voestalpine Railway Systems

From EU, kSEK 705 in cash have been received for the project EU15 in Stage 9. From EU, through Trafikverket, kSEK 1 657 + 12 631 + 746 = kSEK 15 034 in cash have been received for the Shift2Rail projects EU17, EU19 and EU21 in Stage 9. Additionally, kSEK 3 975 + 166 + 20 919 + 280 + 1 254 = kSEK 26 594 have been received from Trafikverket for projects EU17, EU18, EU19, EU20 and EU21. However, the full amount kSEK 16 500 of the basic funding has been refunded to Trafikverket.

Table 2. Budgeted and used cash and in-kind contributions (kSEK) during Stage 9, with the Industrial Interests Group and Chalmers shown separately, for each programme area and for management and administration

	Cash		In-kind industry		In-kind Chalmers		Total	
Programme area	Budget	Used	Budget	Used	Budget	Used	Budget	Used
TS	5 538	5 722	1 764	1 122	0	0	7 302	6 844
VB	1 668	2 085	320	113	100	100	2 088	2 298
MU	6 059	6 300	2 520	2 751	200	200	8 779	9 251
SD	4 082	4 225	1 162	911	400	400	5 644	2 858
EU	41 174	41 186	0	0	0	0	41 174	41 186
SP	1 211	968	0	430	1 460	1 460	2 671	2 858
Management	3 543	3 566	0	0	500	500	4 043	4 066
Total	63 275	64 052	5 766	5 327	2 660	2 660	71 701	72 039

Note 1 Budget under "Cash" is as of 9 December 2021. These amounts have been transferred to the projects

Note 2 In-kind contributions from Chalmers include the support kSEK 1460 from Chalmers Area of Advance Transport in projects SP30, SP31 and SP32

Note 3 The balance in cash to be transferred to CHARMEC's Stage 10 by 30 June 2021 is kSEK 73 151 – 63 275 = kSEK 9 876, but has been reduced to the preliminary amount of kSEK 9 000

FINANCIAL … (cont'd)

From VINNOVA, kSEK 100 in cash have been received for project SP29 for Stage 9.

In total, kSEK 2 160 + 2 673 + 3 016 + 1 983 + 535 + 3 016 = kSEK 13 383 have been received from Chalmers for Stage 9. The amounts are shown in Table 1.

In-kind contributions

The in-kind contributions made by Trafikverket and the Industrial Interests Group correspond reasonably well to the agreement for Stage 9, see Table 1. The work performed is presented briefly in the section "Projects and results". The in-kind contributions have been returned on a form from CHARMEC, which the partner concerned has completed and signed. NUTEK's guidelines as of 1995-11-07 were enclosed with the form. Salary costs (number of hours and hourly rates) and other costs (use of machines, materials and computers, travel expenses, services purchased etc) are shown on the form. All costs relate to the CHARMEC projects specified in the current report. Parts of the in-kind contributions from Chalmers (totally kSEK 2660) originate from the Area of Advance "Transport" (kSEK 1460) at Chalmers with support of kSEK 600 to the SP30 project "Railway vehicle risk analyses", kSEK 570 to the SP31 project "Intelligent railway digitalization" and kSEK 290 to the SP32 project "Sustainable railway asset management".

Report per programme area

The accounts for each individual project have been allocated funds according to budgets decided by the CHARMEC Board. A compilation by programme area is given in Table 2, where in-kind contributions are also shown.

Previous Triennial Reports

White	1 July 2015 – 30 June 2018	84 pp
Orange	1 July 2012 – 30 June 2015	132 pp
Black	1 July 2009 – 30 June 2012	128 pp
Yellow	1 July 2006 – 30 June 2009	104 pp
Green	1 July 2003 – 30 June 2006	94 pp
Red	1 July 2000 – 30 June 2003	81 pp
Blue	1 July 1997 – 30 June 2000	56 pp
Black	1 July 1995 – 30 June 1997	26 pp

All reports are available on
www.chalmers.se/charmec → Achievements

MANAGEMENT AND ADMINISTRATION

Director	Professor Anders Ekberg (from 2012-10-01)
Period	1995-07-01 – 2021-06-30 (2024-06-30)
Chalmers budget (excluding university basic resources)	Stage 1: kSEK 1 084 Stage 2: kSEK 4 000 Stage 3: kSEK 4 400 Stage 4: kSEK 3 900 Stage 5: kSEK 3 900 Stage 6: kSEK 3 700 Stage 7: kSEK 3 900 Stage 8: kSEK 2 900 Stage 9: kSEK 3 543 Stage 10: kSEK 3 100

For industrial interests, in-kind budget and results, see pages 14–73

Anders Ekberg has devoted approximately half of his full-time position to the management and administration of the CHARMEC Competence Centre and the launching of Trafikverket's Areas of Excellence as well as the preparation of Europe's Rail Programme during Stage 9 – and the rest of his time to duties as teacher, researcher and research supervisor in Applied Mechanics. Roger Lundén, Professor of Railway Mechanics and Director of CHARMEC April 1997 to September 2012, has assisted in the administration of the centre's activities and financing and at Board meetings. Pernilla Appelgren and Jonas Lindqvist from Chalmers Mechanics and Maritime Sciences have assisted in financial issues. Bengt Åkesson, Professor Emeritus of Solid Mechanics and first Director of CHARMEC, has assisted in the quality assessment of research reports and administrative documents.

Jonas Lindqvist och Pernilla Appelgren

CHARMEC STAGE 10

The Principal Agreement for CHARMEC's Stage 10 (1 July 2021 – 30 June 2024) largely follows VINNOVA's Principal Agreement for the Centre's Stage 4. As with Stages 5, 6, 7, 8 and 9, Trafikverket (earlier Banverket) has been included in the agreement for Stage 10 and partly holds the administrative role that was previously filled by VINNOVA. However, the financial agreements with Trafikverket are since Stage 8 detailed in a separate contract. The rights and obligations of the three parties (Chalmers University of Technology, Trafikverket and the Industrial Interests Group) in essence comply with those in the Principal Agreements for Stages 4, 5, 6, 7, 8 and 9.

The programme areas in Stage 10 are the same as those during Stage 9, see TS, VB, MU, SD, EU and SP on page 11.

Since Stage 8, CHARMEC has been involved, through Trafikverket, in the EU Horizon 2020 Joint Technology Initiative Shift2Rail (www.shift2rail.org). Trafikverket was one of the Joint Undertaking (JU) members of Shift2Rail, which had a total budget of MEUR 920. Trafikverket carried out most of its research activities in co-operation with research environments, among them CHARMEC. This means that Trafikverket's financing was combined with that of Shift2Rail, implying that CHARMEC's total budget increased. This larger involvement in EU projects has created new possibilities and challenges for CHARMEC and our partners. As an example, we were in Stage 9 involved as Scientific and Technical co-ordinator of one of the Shift2Rail projects (see EU21 In2Track3 on page 65). Since the end of 2021, the Europe's Rail Joint Undertaking is established as a successor to Shift2Rail (even though the Shift2Rail project In2Track3 continues). Trafikverket's research co-operation in Europe's Rail is expected to continue in a similar manner as in Shift2Rail. To further support this activity, Trafikverket has in 2021 established ten Areas of Excellence to ensure the long-term competence in these areas through research and development, see page 87.

The President of Chalmers University of Technology, Professor Stefan Bengtsson, signed the contracts for Stage 10 on 16 August 2021. Funding (kSEK) for Stage 10 (as of 14 September 2021) is shown in the adjoining table. He also appointed the following Board members for CHARMEC's Stage 10 (decision dated 16 August 2021):

Ingemar Frej	Trafikverket (chair)
Rikard Bolmsvik	Abetong
Roger Deuce	Alstom
Maria Edén	Atkins Sverige
Fredrik Blennow	Faiveley Transport
Markus Gardbring	Green Cargo
Erik Kihlberg	Lucchini Sweden
Susanne Rymell	SJ
Tilo Reuter	SweMaint
Björn Drakenberg	voestalpine Railway Systems
Sebastian Stichel	KTH Railway Group
Per Lövsund	Chalmers Mechanics and Maritime Sciences

For photos of the new Board, see page 9.

On 22 April 2021 Dr Angela Hillemyr, Head of the Department of Mechanics and Maritime Sciences, appointed Anders Ekberg Director of CHARMEC for Stage 10.

	Cash	In-kind	Total
Industrial Interests Group	8 646	5 409	14 055
Trafikverket (Areas of Exc)	17 500	–	17 500
Chalmers	11 867	1 200	13 067
Chalmers (AoA Transport)	–	2 000	2 000
Trafikverket (projects)	3 858	–	3 858
EU / Trafikverket (Shift2Rail)	26 402	–	26 402
From Stage 9	9 000	–	9 000
Total	77 273	8 609	85 882

CONCLUDING REMARKS

Stage 9 of our Competence Centre in Railway Mechanics has been successful. Co-operation between the university, industry and Trafikverket has continued to develop, and national and international networks have continued to be broadened, in particular through large involvements in European projects. I believe that CHARMEC provides first rate research, is a knowledgeable dialogue partner, an important information hub, and an expert network builder. Stage 9 has also shown that Railway Mechanics more than ever is key to the development of sustainable land transport both in Sweden and internationally. Here, reliability and environmental and economic aspects are gradually becoming more incorporated into CHARMEC's research to provide more holistic analyses. CHARMEC looks forward to Stage 10 with confidence. Our motto "academic excellence combined with industrial relevance" will continue to be honoured.

Gothenburg in March 2022

ANDERS EKBERG

CHARMEC RESEARCH 1995 – 2021 (Status as of January 2022)

TS Interaction of train and track
Programme area 1

TS1 Calculation models of track structures [3]
Prof Thomas Abrahamsson / Doc Jens Nielsen
Mr Johan Oscarsson [2]

TS2 Railhead corrugation formation [3]
Prof Tore Dahlberg [4]
Ms Annika Igeland [2] *(now Annika Lundberg)*

TS3 Sleeper and railpad dynamics [3]
Prof Tore Dahlberg [4]
Ms Åsa Fenander [2] *(now Åsa Sällström)*

TS4 Lateral track dynamics [3]
Prof Thomas Abrahamsson / Doc Jens Nielsen
Mr Clas Andersson [2]

TS5 Out-of-round wheels – causes and consequences [3]
Doc Jens Nielsen / Prof Roger Lundén
Mr Anders Johansson [2]

TS6 Identification of dynamic forces in trains [3]
Prof Thomas Abrahamsson / Dr Peter Möller
Mr Lars Nordström [2]

TS7 Dynamics of track switches [3]
Prof Jens Nielsen / Prof Tore Dahlberg [4]
Mr Elias Kassa [2]

TS8 Integrated track dynamics
Prof Jens Nielsen

TS9 Track dynamics and sleepers [3]
Prof Thomas Abrahamsson / Prof Jens Nielsen
Ms Johanna Lilja [1]

TS10 Track response when using Under Sleeper Pads (USP) [3]
Dr Rikard Bolmsvik / Prof Jens Nielsen

TS11 Rail corrugation growth on curves [3]
Prof Jens Nielsen / Dr Anders Frid
Mr Peter Torstensson [2]

TS12 Identification of wheel–rail contact forces [3]
Doc Fredrik Larsson / Dr Håkan Johansson / Prof Kenneth Runesson / Dr Peter Möller / Prof Jens Nielsen
Mr Hamed Ronasi [2]

TS13 Optimization of track switches [3]
Prof Jens Nielsen / Prof Thomas Abrahamsson
Mr Björn Pålsson [2]

TS14 Multicriterion optimization of track properties [3]
Prof Thomas Abrahamsson / Prof Jens Nielsen
Mr Sadegh Rahrovani [2]

TS15 Improved availability and reduced life cycle cost of track switches [3]
Prof Jens Nielsen / Prof Elena Kabo / Dr Peter Torstensson
Ms Xin Li [2]

TS16 Time-domain model of railway braking noise [3]
Dr Peter Torstensson

TS17 Optimization of materials in track switches [3]
Prof Jens Nielsen / Prof Magnus Ekh / Doc Björn Pålsson
Mr Rostyslav Skrypnyk [2]

TS18 Numerical simulations of train-track deterioration
Doc Björn Pålsson

TS19 Design criteria for slab track structures [3]
Prof Jens Nielsen / Dr Rikard Bolmsvik / Prof Anders Ekberg
Mr Emil Aggestam [2]

TS20 Wheel tread damage – identification and effects
Prof Elena Kabo / Prof Anders Ekberg / Prof Jens Nielsen / Doc Tore Vernersson
Mr Michele Maglio [1]

TS21 Model-based condition monitoring of S&C
Doc Björn Pålsson / Prof Jens Nielsen / Prof Håkan Johansson
Mr Marko Milosevic [1]

TS22 Transition zone design for reduced track settlements
Prof Jens Nielsen / Prof Magnus Ekh / Prof Jelke Dijkstra
Mr Kourosh Nasrollahi

VB Vibrations and noise
Programme area 2

VB1 Structural vibrations from railway traffic [3]
Prof Sven Ohlsson / Prof Thomas Abrahamsson
Mr Johan Jonsson [2]

VB2 Noise from tread braked railway vehicles [3]
Prof Roger Lundén / Dr Peter Möller
Mr Tore Vernersson [2] */ Mr Martin Petersson* [1]

VB3 Test rig for railway noise [3]
Prof Roger Lundén
Mr Tore Vernersson [2]

VB4 Vibrations and external noise from train and track [3]
Prof Roger Lundén / Dr Anders Frid / Doc Jens Nielsen
Mr Carl Fredrik Hartung [1]

VB5 Wave propagation under high-speed trains [3]
Prof Nils-Erik Wiberg
Mr Torbjörn Ekevid [2]

VB6 Interaction of train, soil and buildings [3]
Dr Johan Jonsson

VB7 Vibration transmission in railway vehicles [3]
Prof Thomas Abrahamsson / Prof Tomas McKelvey
Mr Per Sjövall [2]

VB8 Ground vibrations from railways [3]
Prof Anders Boström / Prof Thomas Abrahamsson
Mr Anders Karlström [2]

VB9 Dynamics of railway systems [3]
Prof Nils-Erik Wiberg / Dr Torbjörn Ekevid
Mr Håkan Lane [2]

VB10 External noise generation from trains [3]
Prof Wolfgang Kropp
Ms Astrid Pieringer [2]

VB11 Abatement of curve squeal noise from trains [3]
Prof Wolfgang Kropp / Dr Astrid Pieringer
Mr Ivan Zenzerovic [2]

VB12 High-frequency wheel–rail interaction
Dr Astrid Pieringer / Prof Wolfgang Kropp

VB13 Prediction and mitigation of noise from vehicles on slab tracks
Prof Wolfgang Kropp / Dr Astrid Pieringer
Mr Jannik Theyssen [1]

Departments involved at Chalmers:
Architecture and Civil Engineering, ACE
Industrial and Materials Science, IMS
Mechanics and Maritime Sciences, M2

Upper name(s):
Project leader(s) and supervisor(s)

Lower name(s):
Doctoral candidate

MU Materials and maintenance
Programme area 3

MU1 **Mechanical properties of ballast** [3]
Prof Kenneth Runesson
Mr Lars Jacobsson [1]

MU2 **New materials in wheels and rails** [3]
Prof Birger Karlsson
Mr Johan Ahlström [2]

MU3 **Martensite formation and damage around railway wheel flats** [3]
Prof Roger Lundén
Mr Johan Jergéus [2]

MU4 **Prediction of lifetime of railway wheels** [3]
Prof Roger Lundén
Mr Anders Ekberg [2]

MU5 **Mechanical properties of concrete sleepers** [3]
Prof Kent Gylltoft
Mr Rikard Gustavson [2] *(now Rikard Bolmsvik)*

MU6 **Rolling contact fatigue of rails** [3]
Prof Lennart Josefson
Mr Jonas Ringsberg [2]

MU7 **Laser treatment of wheels and rails** [3]
Prof Birger Karlsson
Mr Simon Niederhauser [2]

MU8 **Butt-welding of rails** [3]
Prof Lennart Josefson / Doc Jonas Ringsberg
Mr Anders Skyttebol [2]

MU9 **Rolling contact fatigue of railway wheels** [3]
Doc Anders Ekberg / Dr Elena Kabo
Prof Roger Lundén

MU10 **Crack propagation in railway wheels** [3]
Prof Hans Andersson / Dr Elena Kabo / Doc Anders Ekberg
Ms Eka Lansler [1]

MU11 **Early crack growth in rails** [3]
Prof Lennart Josefson / Doc Jonas Ringsberg / Prof Kenneth Runesson
Mr Anders Bergkvist [1]

MU12 **Contact and crack mechanics for rails** [3]
Prof Peter Hansbo
Mr Per Heintz [2]

MU13 **Wheel and rail materials at low temperatures** [3]
Dr Johan Ahlström / Prof Birger Karlsson

MU14 **Damage in track switches** [3]
Doc Magnus Ekh / Prof Kenneth Runesson
Mr Göran Johansson [2]

MU15 **Microstructural development during laser coating** [3]
Prof Birger Karlsson / Dr Johan Ahlström

MU16 **Alternative materials for wheels and rails** [3]
Dr Johan Ahlström / Prof Birger Karlsson
Mr Niklas Köppen [1]

MU17 **Elastoplastic crack propagation in rails** [3]
Doc Fredrik Larsson / Prof Kenneth Runesson / Prof Lennart Josefson
Mr Johan Tillberg [2]

MU18 **Wheels and rails at high speeds and axle loads** [3]
Doc Anders Ekberg / Prof Lennart Josefson / Prof Kenneth Runesson / Prof Jacques de Maré
Mr Johan Sandström [2]

MU19 **Material anisotropy and RCF** [5] **of rails and switches** [3]
Prof Magnus Ekh / Prof Kenneth Runesson / Doc Anders Ekberg
Ms Nasim Larijani [2]

MU20 **Wear impact on RCF** [5] **of rails** [3]
Prof Magnus Ekh / Doc Fredrik Larsson / Doc Anders Ekberg
Mr Jim Brouzoulis [2]

MU21 **Thermal impact on RCF** [5] **of wheels** [3]
Doc Anders Ekberg / Doc Elena Kabo / Prof Magnus Ekh / Dr Tore Vernersson
Ms Sara Caprioli [2]

MU22 **Improved criterion for surface initiated RCF** [5]
Prof Anders Ekberg / Prof Elena Kabo / Prof Roger Lundén

MU23 **Material behaviour at rapid thermal processes** [3]
Doc Johan Ahlström / Prof Christer Persson
Mr Krste Cvetkovski [2]

MU24 **High-strength steels for railway rails** [3]
Prof Christer Persson / Prof Magnus Ekh
Mr Martin Schilke [2]

MU25 **Thermodynamically coupled contact between wheel and rail** [3]
Doc Anders Ekberg / Doc Fredrik Larsson / Prof Kenneth Runesson
Mr Andreas Draganis [2]

MU26 **Optimum inspection and maintenance of rails and wheels** [3]
Doc Ann-Brith Strömberg / Doc Anders Ekberg / Prof Michael Patriksson
Mr Emil Gustavsson [2]

MU27 **Progressive degradation of rails and wheels** [3]
Doc Elena Kabo / Doc Anders Ekberg / Prof Michael Patriksson
Mr Kalle Karttunen [2]

MU28 **Mechanical performance of wheel and rail materials** [3]
Prof Johan Ahlström / Prof Christer Persson / Prof Magnus Ekh
Mr Dimitrios Nikas [2]

MU29 **Damage in wheel and rail materials** [3]
Prof Johan Ahlström / Prof Christer Persson
Ms Casey Jessop [2]

MU30 **Modelling of properties and damage in wheel and rail materials**
Prof Johan Ahlström

MU31 **Squats in rails and RCF** [5] **clusters on wheels** [3]
Prof Elena Kabo / Prof Fredrik Larsson / Prof Anders Ekberg / Dr Peter Torstensson
Mr Robin Andersson [2]

MU32 **Modelling of thermomechanically loaded rail and wheel steels** [3]
Prof Magnus Ekh / Prof Johan Ahlström / Doc Tore Vernersson
Mr Ali Esmaeili [2]

MU33 **Numerical simulation of rolling contact fatigue crack growth in rails** [3]
Prof Fredrik Larsson / Prof Anders Ekberg
Mr Dimosthenis Floros [2]

MU34 **Influence of anisotropy on deterioration of rail materials** [3]
Prof Magnus Ekh / Prof Johan Ahlström
Mr Knut Andreas Meyer [2]

Notes:
1. Licentiate (*teknologie licentiat*)
2. PhD (*teknologie doktor*)
3. This project has been concluded
4. Later at Linköping Institute of Technology
5. Rolling Contact Fatigue

The abbreviation ***Doc*** is used for ***Docent*** which is the highest academic qualification in Sweden (above the doctor's level)

MU (cont'd)

MU35 **Characterization of crack initiation and propagation in anisotropic material**
Prof Johan Ahlström / Prof Magnus Ekh
Mr Daniel Gren

MU36 **Material characteristics in welding and other local heating events**
Prof Johan Ahlström / Prof Magnus Ekh
Ms Erika Steyn

MU37 **Numerical simulations of welding and other high-temperature processes**
Prof Magnus Ekh / Prof Johan Ahlström / Prof Lennart Josefson
Mr Björn Andersson [1]

MU38 **Growth of rolling contact fatigue cracks**
Prof Fredrik Larsson / Prof Anders Ekberg / Prof Elena Kabo
Mr Mohammad Salahi Nezhad

MU39 **Numerical modelling of material deterioration in railway applications**
Prof Magnus Ekh / Prof Fredrik Larsson

MU40 **Digital twins of reprofiled rails**
Prof Fredrik Larsson / Prof Magnus Ekh / Prof Ragnar Larsson / Doc Björn Pålsson
Ms Caroline Ansin

MU41 **Crack initiation in anisotropic wheel / rail material**
Prof Magnus Ekh / Prof Johan Ahlström / Dr Knut Andreas Meyer
Ms Nasrin Talebi

SD Systems for monitoring & operation
Programme area 4

SD1 **Braking of freight trains – a systems approach [3]**
Prof Göran Gerbert
Mr Daniel Thuresson [2]

SD2 **Sonar pulses for braking control [3]**
Prof Bengt Schmidtbauer / Mr Hans Sandholt

SD3 **Computer control of braking systems for freight trains [3]**
Mr Håkan Edler / Prof Jan Torin
Mr Roger Johansson [2]

SD4 **Control of block braking [3]**
Prof Roger Lundén
Mr Tore Vernersson [2]

SD5 **Active and semi-active systems in railway vehicles [3]**
Prof Jonas Sjöberg / Prof Thomas Abrahamsson
Ms Jessica Fagerlund [1]

SD6 **Adaptronics for bogies and other railway components [3]**
Prof Viktor Berbyuk / Doc Mikael Enelund
Mr Albin Johnsson [1]

SD7 **Thermal capacity of tread braked railway wheels [3]**
Prof Roger Lundén / Dr Tore Vernersson
Mr Shahab Teimourimanesh [2]

SD8 **Wear of disc brakes and block brakes [3]**
Dr Tore Vernersson / Prof Roger Lundén

SD9 **Multiobjective optimization of bogie system and vibration control [3]**
Prof Viktor Berbyuk / Prof Mikael Enelund
Mr Milad Mousavi [2]

SD10 **Enhanced mechanical braking systems for modern trains [3]**
Doc Tore Vernersson / Prof Roger Lundén
Mr Mandeep Singh Walia [2]

SD11 **Tread braking – capacity, wear and life**
Doc Tore Vernersson / Prof Roger Lundén
Mr Eric Voortman Landström

EU Parallel EU projects
Programme area 5

EU1 **EuroSABOT [3]**
Prof Roger Lundén
Mr Tore Vernersson / Mr Martin Petersson

EU2 **Silent Freight [3]**
Dr Jens Nielsen
Mr Martin Petersson / Mr Markus Wallentin

EU3 **Silent Track [3]**
Dr Jens Nielsen
Mr Clas Andersson

EU4 **ICON [3]**
Prof Lennart Josefson
Mr Jonas Ringsberg

EU5 **EuroBALT II [3]**
Prof Tore Dahlberg [4]
Mr Johan Oscarsson

EU6 **HIPERWHEEL [3]**
Prof Roger Lundén
Doc Jens Nielsen / Dr Anders Ekberg

EU7 **INFRASTAR [3]**
Prof Lennart Josefson / Prof Roger Lundén / Doc Jens Nielsen / Dr Jonas Ringsberg / Prof Birger Karlsson

EU8 **ERS [3]**
Prof Roger Lundén
Mr Martin Helgen/Doc Jan Henrik Sällström/ Mr Tore Vernersson

EU9 **EURNEX [3]**
Prof Roger Lundén
Doc Anders Ekberg

EU10 **INNOTRACK [3]**
Prof Roger Lundén / Doc Anders Ekberg and co-workers

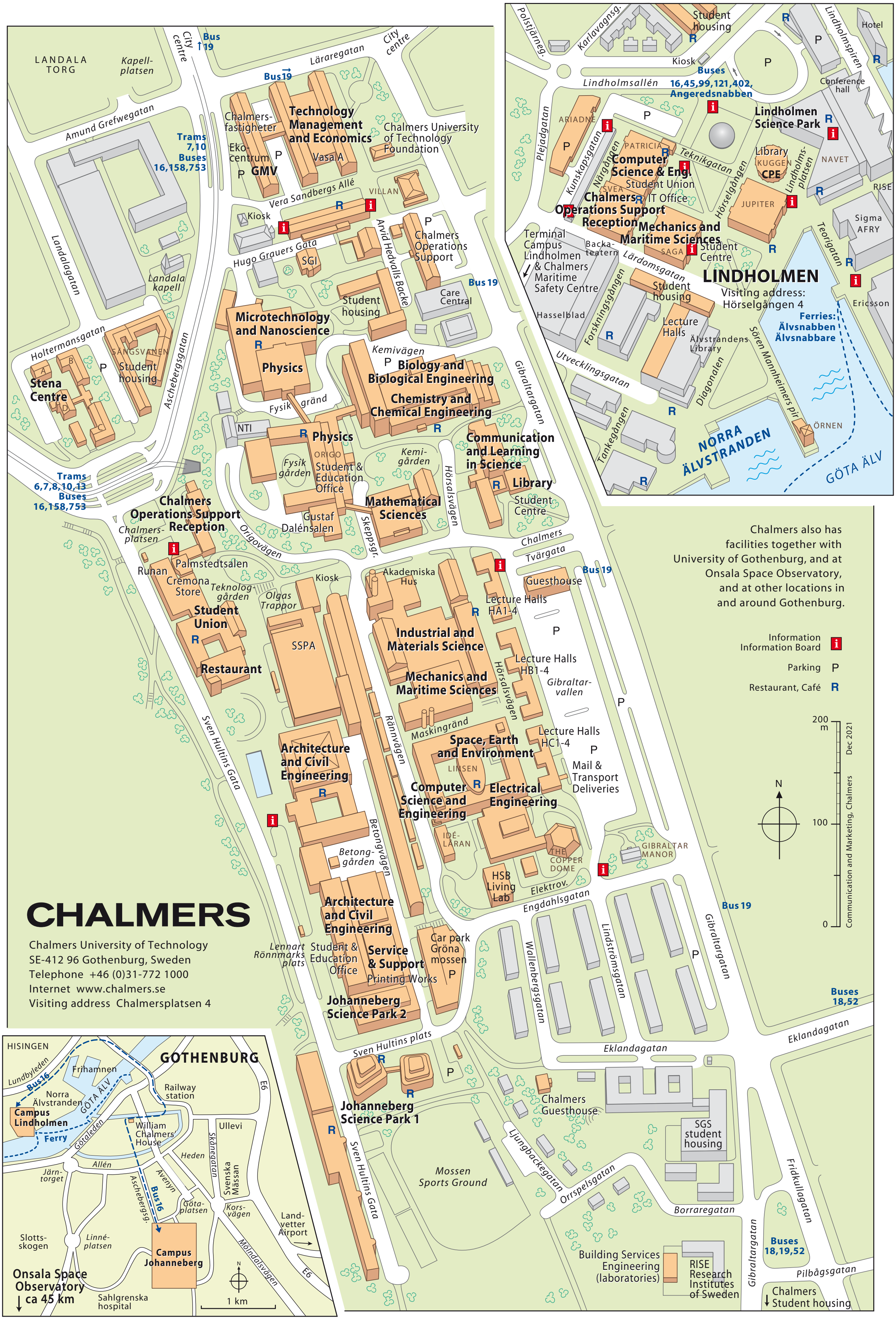
EU11 **QCITY [3]**
Prof Jens Nielsen

EU (cont'd)

EU 12	**RIVAS** 3 *Prof Jens Nielsen and co-workers*
EU 13	**D-RAIL** 3 *Doc Anders Ekberg and co-workers*
EU 14	**Capacity4Rail** 3 *Prof Anders Ekberg and co-workers*
EU 15	**WRIST** 3 *Prof Lennart Josefson / Dr Jim Brouzoulis*
EU 16	**In2Rail** 3 *Prof Anders Ekberg and co-workers*
EU 17	**In2Track** 3 *Prof Anders Ekberg and co-workers*
EU 18	**Fr8Rail** 3 *Prof Anders Ekberg / Doc Tore Vernersson*
EU 19	**In2Track2** 3 *Prof Anders Ekberg and co-workers*
EU 20	**Fr8Rail2** 3 *Prof Anders Ekberg / Doc Tore Vernersson*
EU 21	**In2Track3** *Prof Anders Ekberg and co-workers*

SP Parallel special projects
Programme area 6

SP 1	**Lucchini Sweden AB (bilateral agreement)**
SP 2	**Noise from Swedish railways**
SP 3	**Track force measurements on X2**
SP 4	**VAE AG (bilateral agreement)**
SP 5	**voestalpine Schienen GmbH (bilateral agreement)**
SP 6	**Development of a quiet rail**
SP 7	**Lateral track stability**
SP 8	**Design of insulated joints**
SP 9	**Sleeper design for 30 tonne axle load**
SP 10	**Noise reduction measures and EU project QCITY**
SP 11	**Vertical contact forces of high-speed trains**
SP 12	**New sleeper specifications**
SP 13	**Alarm limits for wheel damage**
SP 14	**Particle emissions and noise from railways**
SP 15	**Computer program for design of block brakes**
SP 16	**Dynamic properties of timber sleepers and concrete replacement sleepers**
SP 17	**Switch sleeper specifications**
SP 18	**Ground vibrations – influence of vehicle parameters**
SP 19	**Optimum track stiffness**
SP 20	**Classification of wheel damage forms**
SP 21	**Optimum material selection for track switches**
SP 22	**Implementing INNOTRACK results at Trafikverket**
SP 23	**Optimized prestressed concrete sleeper**
SP 24	**Derailment risks in switches**
SP 25	**Harmonized measurement sites for track forces**
SP 26	**Holistic optimization of tracks**
SP 27	**Optimized prestressed concrete sleeper – phase II**
SP 28	**Prevention and mitigation of derailments**
SP 29	**Including wear caused by braking in train driving simulators**
SP 30	**Railway vehicle risk analyses**
SP 31	**Intelligent railway digitalization**
SP 32	**Sustainable railway asset management**
SP 33	**More robust switches through improved control of the switch rail**
SP 34	**Full-scale brake test rig**



Chalmers also has facilities together with University of Gothenburg, and at Onsala Space Observatory, and at other locations in and around Gothenburg.

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Departments and research groups / divisions / areas

ARCHITECTURE AND CIVIL ENGINEERING
Applied Acoustics
Architectural Theory and Methods
Building Design
Building Services Engineering
Building Technology
Construction Management
Geology and Geotechnics
Structural Engineering
Urban Design and Planning
Water Environment Technology

BIOLOGY AND BIOLOGICAL ENGINEERING
Chemical Biology
Food and Nutrition Science
Industrial Biotechnology
Systems and Synthetic Biology

CHEMISTRY AND CHEMICAL ENGINEERING
Applied Chemistry
Chemical Engineering
Chemistry and Biochemistry
Energy and Materials

COMMUNICATION AND LEARNING IN SCIENCE
Engineering Education Science
Information Resources and Scientific Publishing
Language and Communication
Learning and Learning Environments

COMPUTER SCIENCE AND ENGINEERING
Computer and Network Systems
Computing Science
Data Science and AI
Interaction Design and Software Engineering

ELECTRICAL ENGINEERING
Communications, Antennas, and Optical Networks
Electric Power Engineering
Signal Processing and Biomedical Engineering
Systems and Control

INDUSTRIAL AND MATERIALS SCIENCE
Design & Human Factors
Engineering Materials
Material and Computational Mechanics
Materials and Manufacture
Product Development
Production Systems

MATHEMATICAL SCIENCES
Algebra and Geometry
Analysis and Probability Theory
Applied Mathematics and Statistics

MECHANICS AND MARITIME SCIENCES
Combustion and Propulsion Systems
Dynamics
Fluid Dynamics
Marine Technology
Maritime Studies
Vehicle Safety
Vehicle Engineering and Autonomous Systems (VEAS)

MICROTECHNOLOGY AND NANOSCIENCE
Applied Quantum Physics
Electronic Materials and Systems
Microwave Electronics
Nanofabrication
Photonics
Quantum Device Physics
Quantum Technology
Terahertz and Millimetre Waves

PHYSICS
Chemical Physics
Condensed Matter and Materials Theory
Materials Physics
Microstructure Physics
Nano and Biophysics
Subatomic, High Energy and Plasma Physics

SPACE, EARTH AND ENVIRONMENT
Astronomy and Plasma Physics
Energy Technology
Geoscience and Remote Sensing
Onsala Space Observatory
Physical Resource Theory

TECHNOLOGY MANAGEMENT AND ECONOMICS
Entrepreneurship and Strategy
Environmental Systems Analysis
Innovation and R&D Management
Science, Technology and Society
Service Management and Logistics
Supply and Operations Management

RESEARCH CENTRES
In total 63 centres in the following areas:
- Built Environment (13 centres)
- Energy (6 centres)
- Graphene and other 2D-materials (2 centres)
- Health Engineering (6 centres)
- Information and Communication Technology (6 centres)
- Materials Science (8 centres)
- Nano Science (5 centres)
- Production (5 centres)
- Transport (10 centres)
- Quantum Technology (1 centre)
- Sustainable Development (1 centre)

Educational programmes

ENGINEERING FOUNDATION PROGRAMME
Engineering preparatory year

BACHELOR'S STUDIES
30 bachelor's programmes (in Swedish) in engineering, science, shipping and architecture

MASTER'S STUDIES
Architecture and Civil Engineering
Automation and Mechatronics
Biotechnology and Chemical Engineering
Civil Engineering
Computer Engineering
Electrical Engineering
Engineering for Sustainable Development
Engineering Physics, Mathematics
Industrial Engineering and Management
Information Engineering
Mechanical and Industrial Design Engineering
Maritime Management
Technology and Learning

MASTER'S PROGRAMMES
39 international programmes (in English)

LICENTIATE AND PHD PROGRAMMES
32 graduate schools, each organised within a department or common to a number of departments and with a corresponding research

CONTINUING AND PROFESSIONAL STUDIES
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MOOC – Massive Open Online Courses

Areas of Advance

Chalmers has profiled its research activities around six Areas of Advance (Swedish: Styrkeområden). CHARMEC is presently active the area Transport

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Health Engineering

Information and Communication Technology

Materials Science

Production

Transport

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