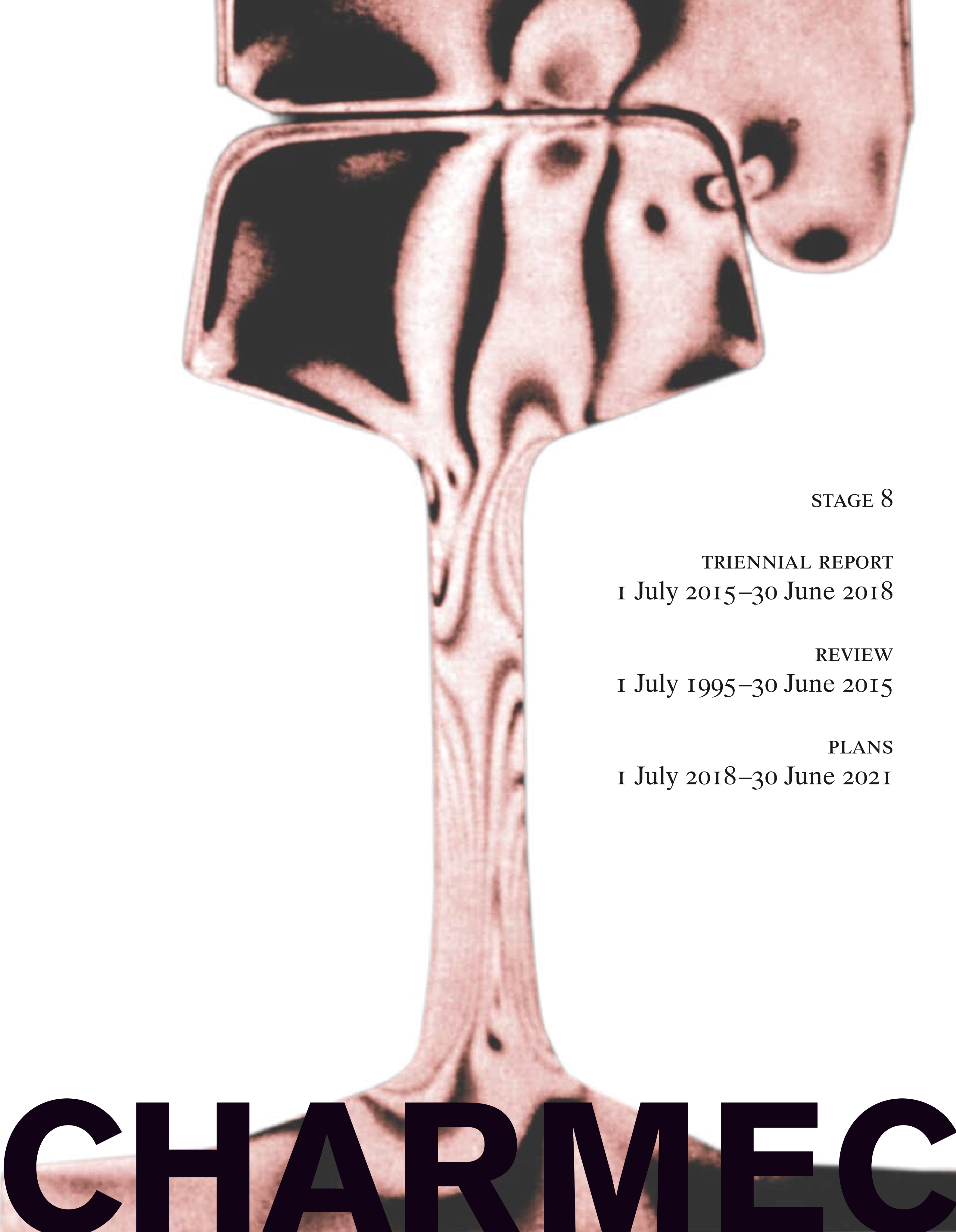

STAGE 8

TRIENNIAL REPORT
1 July 2015–30 June 2018

REVIEW
1 July 1995–30 June 2015

PLANS
1 July 2018–30 June 2021

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 8 (1 July 2015 – 30 June 2018) 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 80–82 display an overview of all 112 projects that have been (or are being) carried out within CHARMEC, but only the 28 projects running during Stage 8 are accounted for in detail. Some results from the period 1 July 2018 – 31 January 2019 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 January 2019
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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EU6. HIPERWHEEL – Development of an innovative high-performance railway wheelset

EU7. INFRASTAR – Improving railway infrastructure productivity by sustainable two-material rail development

EU8. ERS – Euro Rolling Silently

EU9. EURNEX – European Rail Research Network of Excellence

EU10. INNOTRACK – Innovative Track Systems

EU11. QCITY – Quiet City Transport

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REFLECTIONS FROM THE DIRECTOR

Today, the railway sector sees a combination of large possibilities and major challenges all over the world, and rail transportation increases on a network that in many cases was designed for conditions prevailing a hundred years ago. In general, the situation should be welcomed since a shift of transportation from road and air to train is one of the most efficient means of combating congestion and emissions. However, it implies challenges for all actors in the railway sector where increased operation increases the risk of component deterioration and system breakdown. This must be handled at the same time as there is less time available for maintenance work on tracks and vehicles. Also, margins for error are diminishing since traffic disruptions now swiftly spread through the network and affect ever more passenger and freight transports.

In this situation it is 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.

How does the above relate to railway mechanics, a topic that has been around since the 1850's? Has this subject become obsolete? No, in fact it is becoming more relevant than ever since the paradigm shift makes the need for predictions obvious. In the same manner as it is not acceptable only to deal with breakdowns of an industrial assembly line when they happen, it is now more evident than ever that failures of the railway system have to be prevented and not only mitigated when they occur. This calls for in-depth knowledge and ability to predict how the railway system deteriorates so that mitigating actions can be employed before traffic disruptions occur. Here numerical simulations have a key role. With less time available for field tests and handling of larger consequences of malfunctioning equipment, the need for 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 (and also provides them with new and more fancy names).

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 put in the hard and dedicated work that is 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 eleven partners during Stage 8 (including Lucchini) have been involved since 1995, and another four 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, see page 116 in the previous Triennial Report.

The annual budget for the three years of Stage 8 (1 July 2015 – 30 June 2018) has been MSEK 26.0 (about MEUR 2.6), see page 76. Three parties have provided funding: Chalmers University of Technology, Trafikverket, and an Industrial Interests Group comprising 10 partners. Substantial funding also was provided by EU. In total, 21 ordinary research projects, 5 EU projects and 2 development projects were carried out within the six programme areas during Stage 8,

- Interaction of Train and Track
- Vibrations and Noise
- Materials and Maintenance
- Systems for Monitoring and Operation
- Parallel EU Projects
- Parallel Special Projects

At Chalmers, 38 people (project leaders, academic supervisors, doctoral students and senior researchers) from 3 departments (out of a total of 13 at Chalmers, see page 83), have been involved. They published 96 scientific papers in international journals and conference proceedings and 17 EU deliverables during Stage 8 (including those in print). Eight Licentiate degrees and four PhD degrees were conferred during Stage 8.

A total of 60 Licentiate degrees and 45 PhD degrees in railway mechanics have been awarded up to June 2018 at Chalmers, see page 62. More than 110 partners (industries, universities, institutes, public agencies, consultancies) from 18 countries have been involved in our European projects during Stage 8.

CHARMEC endeavours to combine academic excellence and industrial relevance while generating first rate research and skilled PhDs. 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 not the least 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 internationalisation 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 *			

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

The approximate exchange rate (December 2018) is 1 MSEK = 0.10 MEUR

* After Board Meeting on 23 November 2018

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), 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 (now Bombardier Transportation Sweden) 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 AB (later Interfleet Technology AB, now SNC-Lavalin) 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.
From Stage 8, voestalpine are represented by their two companies voestalpine Schienen GmbH and voestalpine VAE GmbH. The contract for Stage 8 was signed by Stefan Bengtsson, new President of Chalmers University from 1 August 2015, on 1 October 2015. For a brief outline of CHARMEC's Stage 9 (1 July 2018 – 30 June 2021), see page 79. 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 8 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 – an international train manufacturer with Swedish headquarters in Västerås

Faiveley Transport – an international manufacturer of braking systems with Swedish headquarters in Landskrona

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

Interfleet Technology / SNC-Lavalin – 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 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 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 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 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 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

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 as members of the Board of the Competence Centre CHARMEC at the end of Stage 8 (decision dated 2017-07-10) :

Ingemar Frej (chair)	Trafikverket
Rikard Bolmsvik	Abetong
Fredrik Holmberg	Bombardier Transportation
Fredrik Blennow	Faiveley Transport
Bengt Fors	Green Cargo
Erik Kihlberg	Lucchini Sweden
Susanne Rymell	SJ
Sven-Ivar Karlsson	SNC-Lavalin
Tilo Reuter	SweMaint
Björn Drakenberg	voestalpine Metal Engineering
Sebastian Stichel	Royal Institute of Technology (KTH)
Per Lövsund	Chalmers

Tomas Ramstedt of Sweco (previously at Banverket / Trafikverket), who entered as chairman of the CHARMEC Board on 1 January 2009, resigned as chairman on 31 December 2011 and was then succeeded by Annika Renfors of Trafikverket. Björn Paulsson had held this position since the start of CHARMEC on 1 July 1995. Tomas Ramstedt left Trafikverket on 28 February 2011, but stayed on the CHARMEC Board until 30 June 2012. Annika Renfors resigned as member and chairperson on 30 June 2015 and was then succeeded by Ingemar Frej of Trafikverket.

On 1 January 2017, Martin Schilke of SNC-Lavalin was succeeded by Sven-Ivar Karlsson. At the start of Stage 8, it was decided that Robert Lagnebäck of SLL Trafikfövaltningen should continue as Board member since it was assumed that SLL would continue as partner in CHARMEC. However, SLL later decided to leave CHARMEC and Robert Lagnebäck left the Board on 31 December 2016. Fredrik Holmberg of Bombardier Transportation Sweden succeeded Jakob Wingren on 1 July 2017. The decisions on these changes by President Stefan Bengtsson are dated 2016-12-06 and 2017-07-10, respectively.

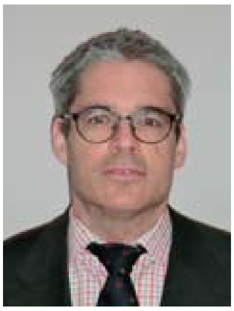
Roger Lundén, now Professor in Railway Mechanics at the Chalmers Department of Mechanics and Maritime Sciences, was appointed Director of CHARMEC from 1 April 1997. He then succeeded the Centre's first Director, Bengt Åkesson, who is now Professor Emeritus of Solid Mechanics. From 1 October 2012, Docent (now Professor) Anders Ekberg succeeded Roger Lundén as Director (decision by President Karin Markides dated 2012-08-29).

BOARD MEMBERS

The Board of CHARMEC at its meeting on 7 February 2019 at Chalmers. From the left:

Anders Ekberg of Chalmers Mechanics and Maritime Sciences (Director of CHARMEC); ***Sven-Ivar Karlsson*** of SNC-Lavalin (Stages 8+9); ***Roger Lundén*** of Chalmers Mechanics and Maritime Sciences (Director of CHARMEC 1997–2012); ***Roger Deuce*** of Bombardier Transportation in Germany (Stage 9); ***Susanne Rymell*** of SJ (Stages 6+7+8+9); ***Björn Drakenberg*** of voestalpine Metal Engineering (Stages 7+8+9); ***Tilo Reuter*** of SweMaint (Stages 8+9); ***Markus Gardbring*** of Green Cargo (Stage 9); ***Per Lövsund*** of Chalmers (Stages 6+7+8+9); ***Rikard Bolmsvik*** of Abetong (Stages 5+6+7+8+9); ***Ingemar Frej*** of Trafikverket (Chairperson, Stages 8+9)

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



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

Fredrik Blennow of
Faiveley Transport
(Stages 8+9)

Martin Schilke of
Interfleet Technology /
SNC-Lavalin
(Stages 7+8)

Jakob Wingren
of Bombardier
Transportation Sweden
(Stages 7+8)

Fredrik Holmberg
of Bombardier
Transportation Sweden
(Stage 8)

QUALITY ASSESSMENT AND KNOWLEDGE TRANSFER

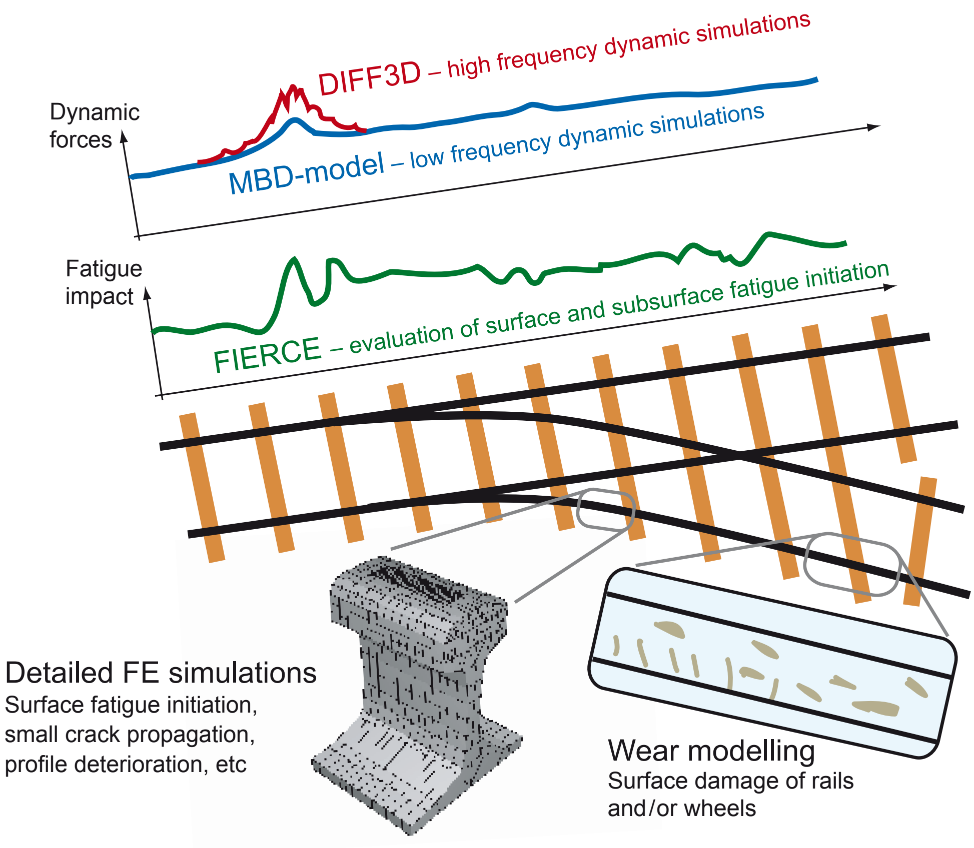
In our opinion, an assessment of the quality and quantity of the results and effects achieved by a Competence Centre like CHARMEC should take the following points into consideration:

- 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 (see page 62)
- 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

During Stage 8, 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 orientation and summarizing at seminars, and through informative reports and the handing over of test results and computer programs. 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.



Integration of research results from the CHARMEC projects where our programs DIFF3D and FIERCE have been used

PROGRAMME AREAS CHARMEC STAGE 8

According to the Principal Agreement for Stage 8, 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 program areas for Stage 8 are the same as those during Stages 3, 4, 5, 6 and 7.

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 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 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 8

Research at the Centre during Stage 8 (1 July 2015 – 30 June 2018) has been carried out as planned. The Board of CHARMEC met as follows:

28 September	2015	7 February	2017
25 November	2015	9 May	2017
8 February	2016	25 September	2017
12 May	2016	29 November	2017
27 September	2016	20 February	2018
23 November	2016	22 May	2018

Detailed minutes were recorded at all meetings. Early decisions were made concerning the content and funding of projects carried over from Stage 7 and of new projects started during Stage 8. 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 8. 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

When selecting new projects to be run by CHARMEC, the Board has 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 Stage 8, 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 and 8. 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) Noise and vibrations.

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 8, CHARMEC has received financial support from the areas Energy, Materials and Transport.

The staff attached to the Centre during Stage 8 both at Chalmers (23 project leaders/principal advisers/senior researchers and 15 PhD students), at Trafikverket, and in the Industrial Interests Group, have been actively involved. Generally CHARMEC projects have reference groups, see page 69. 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.

Eight licentiate theses and four PhD dissertations in railway mechanics were presented by CHARMEC's doctoral candidates during Stage 8, see page 62. In addition, 39 articles were published (or accepted for publication) in international scientific journals with a referee system, 57 papers were published in the proceedings of international conferences with a referee system, 17 EU reports were delivered, 6 research reports were edited in our own series of research publications, 7 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 1–7, four seminars (two if not held at Chalmers) 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 120 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 8 comprised more than 110 organizations in 18 countries; see under projects EU14 – EU18. We also cooperate with railway bodies in Australia, Canada, China, India, Japan, South Africa and the USA.

PROJECTS AND RESULTS

In contrast to previous reports, the present Triennial Report only contains details on those projects (they are 28) which have been active during the stage accounted for. A list of all 122 projects run by CHARMEC during the years 1995-2018 is given on pages 80–82. The publications listed under the projects have not previously been registered in CHARMEC's Biennial and Triennial Reports 1 July 1995–30 June 2015 (Stages 1, 2, 3, 4, 5, 6 and 7), 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 8, 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 projects EU15, EU16 and EU17 belong to the Horizon 2020 Programme whereas EU18 is part of the Shift2Rail Research and Innovation Action. It should be noted that external access to EU documents supplied by us and others is often limited. The abbreviation S2R for Shift2Rail is used in some of the budgets.

The departments where the 28 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.

As for the project budgets presented for Stage 9, these include the sums allocated by the Board up until the meeting on 23 November 2018. The abbreviation LicEng for the doctoral candidates stands for the intermediate academic degree Licentiate of Engineering.

SUMMARY OF … (cont'd)

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 570 such articles and contributions have been published internationally so far. A total of 60 Licentiate degrees and 45 PhD degrees in railway mechanics have been awarded at Chalmers up to June 2018, see page 62.

During Stage 8 the presentations from the partners were:

Ingemar Frej (at Chalmers)	Trafikverket	28 Sept 2015
Mikael Åhlén (in Stockholm Bromma)	Interfleet	25 Nov 2015
Jakob Wingren (at Chalmers)	Bombardier	8 Febr 2016
Ralf Grahn and Anders Dahlstrand (in Solna)	Trafikverket	12 May 2016
Per Uneklint (at Chalmers)	Trafikverket	27 Sept 2016
Rikard Bolmsvik (in Vislanda)	Abetong	23 Nov 2016
Rikard Bolmsvik (at Chalmers)	Abetong	7 Febr 2017
Kari Arbelius (in Gothenburg)	SweMaint	9 May 2017
Erik Kihlberg (at Chalmers)	Lucchini	25 Sept 2017
Susanne Rymell (in Solna)	SJ	29 Nov 2017
Dan Cedergårdh (at Chalmers)	Trafikverket	20 Febr 2018
Johan Malm (in Landskrona)	Faiveley	22 May 2018

TS8. INTEGRATED TRACK DYNAMICS

Integrerad spårdynamik
Integrierte Gleisdynamik
Dynamique intégrée de la voie

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 – 2018-06-30 (– 2021-06-30)
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 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 (*Abetong + Trafikverket*)

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 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 board of the International Journal of Rail Transportation.

Jens Nielsen chaired the organization committee for the Nordic Seminar on Railway Technology at Chalmers in June 2018, see page 73. He is a member of the organization committee for the international symposium on Vehicle System Dynamics at Chalmers in August 2019. Papers submitted for the book Noise and Vibration Mitigation for Rail Transportation Systems, which includes contributions presented at IWRN12 in Terrigal (Australia) in September 2016, have been reviewed by him. He evaluated abstracts for the IAVSD symposium in Rockhampton (Australia) in August 2017. He was invited as external expert in railway noise to the Go-Leise workshop in Ittigen (Switzerland) in June 2016. The objective of the Schweizerische Bundesbahnen (SBB) project Go-Leise is to reduce railway noise, while considering LCC, safety and vibrations.

The work in project TS8 also includes the planning, preparation, support and follow-up of research proposals. Examples are the newly launched projects TS19 and TS20 and also contributions to the EU project proposal In2Track-2 on differential track settlement in transition zones and on multicriterion track optimization.

On request by Trafikverket, bending moments in concrete sleepers have been specified in collaboration with Abetong. Based on field measurements and simulations performed in previous CHARMEC projects, characteristic bending moments for traffic with axle load 25 tonnes have been defined. Load cases involving both impact loads generated by out-of-round wheels and poor distributions of ballast support have been considered in new simulations.

Jens Nielsen gave his annual lecture 'Introduction to train–track dynamics' at NBIU (Nordisk Banteknisk Ingenjörsutbildning) in Tällberg in September 2015, 2016 and 2017. For his inauguration lecture as research professor in railway dynamics, see page 70.

Andreas Carlberger, Anders Frid, Peter Torstensson, Björn Pålsson and Jens Nielsen: Numerical prediction of rail corrugation growth on curves, *Proceedings 19th Nordic Seminar on Railway Technology*, Luleå (Sweden) September 2016 (Summary and PowerPoint presentation)

David Anderson, Pierre-Etienne Gautier, Masanobu Iida, James Nelson, David Thompson, Thorsten Tielkes, David Towers, Paul de Vos and Jens Nielsen (editors): Noise and Vibration Mitigation for Rail Transportation Systems, *Proceedings 12th International Workshop on Railway Noise (IWRN12)*, Terrigal (Australia) September 2016, *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 139, 2018, 780 pp

Jens Nielsen, Eric Augis and Florian Biebl: Reproducibility of railway noise measurements – influence of weather and test site conditions. In Noise and Vibration Mitigation for Rail Transportation Systems, *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 139, 2018, pp 167–179

Rikard Bolmsvik and Jens Nielsen: Karakteristiska böjmoment i sliper för trafik med axellast 25 ton (Characteristic bending moments in sleepers for traffic with axle load 25 tonnes; in Swedish), Research Report 2016:03, *Chalmers Applied Mechanics*, Gothenburg 2016, 24 pp

Andreas Carlberger, Peter Torstensson, Jens Nielsen and Anders Frid: An iterative methodology for the prediction of dynamic vehicle–track interaction and long-term periodic rail wear, *IMechE Journal of Rail and Rapid Transit*, vol 232, no F6, 2018, pp 1718-1730

Peter Torstensson and Jens Nielsen: Impact noise generated at railway crossings, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

TS14. MULTICRITERION OPTIMIZATION OF TRACK PROPERTIES

Multikriterieoptimering av spåregenskaper
Mehrfaches Kriterium für Optimierung der Gleiseigenschaften
Critère multiple pour l'optimisation des propriétés de la voie

Project leader and supervisor	Professor Thomas Abrahamsson, Mechanics and Maritime Sciences / Division of Dynamics
Assistant supervisor	Professor Jens Nielsen, Mechanics and Maritime Sciences
Doctoral candidate	Mr Sadegh Rahrovani (from 2011-03-01; Lic Eng February 2014; PhD March 2016)
Period	2011-03-01–2017-12-31
Chalmers budget (excluding university basic resources)	Stage 6: KSEK 1 800 Stage 7: KSEK 2 775 Stage 8: KSEK 1 170
Industrial interests in-kind budget	Stage 6: KSEK 200 Stage 7: KSEK 360 Stage 8: KSEK 360 (*Abetong*)

For a photo of Thomas Abrahamsson and Sadegh Rahrovani, see previous Triennial Report on page 23

System identification of structures based on measured response data plays a key role in improving reliability based structural design. However, the experimental limitations of in situ tests and uncertainties regarding required model complexity together with the inverse nature of system identification give rise to a number of challenging issues. Common examples of these issues in spatially varying parameter identification problems are poor modelling or ill-conditioning problems that are created due to inappropriate discretization of the parameter field. Even with a proper discretization, the large number of uncertain parameters associated with these problems makes the standard optimization or sampling techniques computationally cumbersome and also more prone to the so-called 'curse of dimensionality' problem.

An in-depth study of such modelling and computational issues was made in project TS14 for finding appropriate methods to treat them in a railway ballast stiffness-field property identification, and for doing test planning of in situ experimental conditions. This is achieved by utilizing a recently proposed Bayesian approach, known as enhanced 'Bayesian Updating with Structural Reliability Methods', through feasibility studies. By interpreting the Bayesian system identification problem as an equivalent reliability problem, this approach opens up the possibility to employ well-developed rare-event samplers, such as subset simulation, to efficiently draw samples from the posterior probability distribution in high-dimensional inference problems.

Another topic of the present work was to develop a time integration scheme for fast simulation of large finite element models with spatially localized non-linear or stochastic properties. This is a prerequisite for the ballast-sleeper load characterization problem, in which the local non-linear/uncertain properties of the spatially varying ballast bed (along the sleeper length) is of major concern. Briefly stated, the developed integration scheme computes the system response based on the solution of an underlying linear system augmented with a low-rank non-linear pseudo-force vector that accommodates the local non-linearity and uncertainty effects. This is achieved through an efficient correction-prediction method.

The integration scheme presented here is combined with a developed modal reduction method, which is enhanced to take into account the effect of pseudo-forces in its modal dominancy analysis. It has been successfully applied to the studied moving-load simulation problem where the sleeper response statistics is required for estimating the risk of failure. The problem of detecting non-minimality in modal reduction of systems with multiple or very close eigenvalues (as in the studied railway track structure with large clusters of neighbouring eigenvalues) is described and two methods to circumvent this problem are proposed. The reduction method is enhanced to effectively treat systems under moving loads or distributed loading, by incorporating information from structural properties of the input force matrix into the modal dominancy analysis.

In a continuation of project TS14, an implementation of probabilistic response on top of the DIFF (CHARMEC's in-house program) functionality has been made and reported (see below). The reference group for the project had members from Abetong, Dr Plica Ingenieure in Munich (Germany) and Trafikverket. The research plan for project TS14 is dated 2010-05-30.

Sadegh Rahrovani: Structural reliability and identification with stochastic simulation – application to railway mechanics, Doctoral Dissertation, *Chalmers Applied Mechanics*, Gothenburg March 2016, 120 pp (Summary and five appended papers. Also listed in the previous Triennial Report)

Thomas Abrahamsson and Sadegh Rahrovani: optDIFF User's Guide – A MATLAB App for railway design with focus on risk and reliability, Research Report 2018:01, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2018, 18 pp

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

Förbättrad tillgänglighet och minskad livscykelkostnad för spårväxlar
Verbesserte Verfügbarkeit und verminderte Lebenszykluskosten für Gleisweichen
Amélioration de la disponibilité et réduction des coûts du cycle de vie des aiguillages

Project leader and supervisor	Professor Jens Nielsen, Mechanics and Maritime Sciences/ Division of Dynamics
Assistant supervisors	Professor Elena Kabo, Mechanics and Maritime Sciences, and Dr Peter Torstensson, VTI (see page 74)
Doctoral candidate	Ms Xin Li (from 2012-01-09; Lic Eng November 2014)
Period	2011-07-01 – 2018-06-30 (– 2019-09-30)
Chalmers budget (excluding university basic resources)	Stage 6: kSEK 725 Stage 7: kSEK 2 704 Stage 8: kSEK 1 757 Stage 9: kSEK 200
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)*

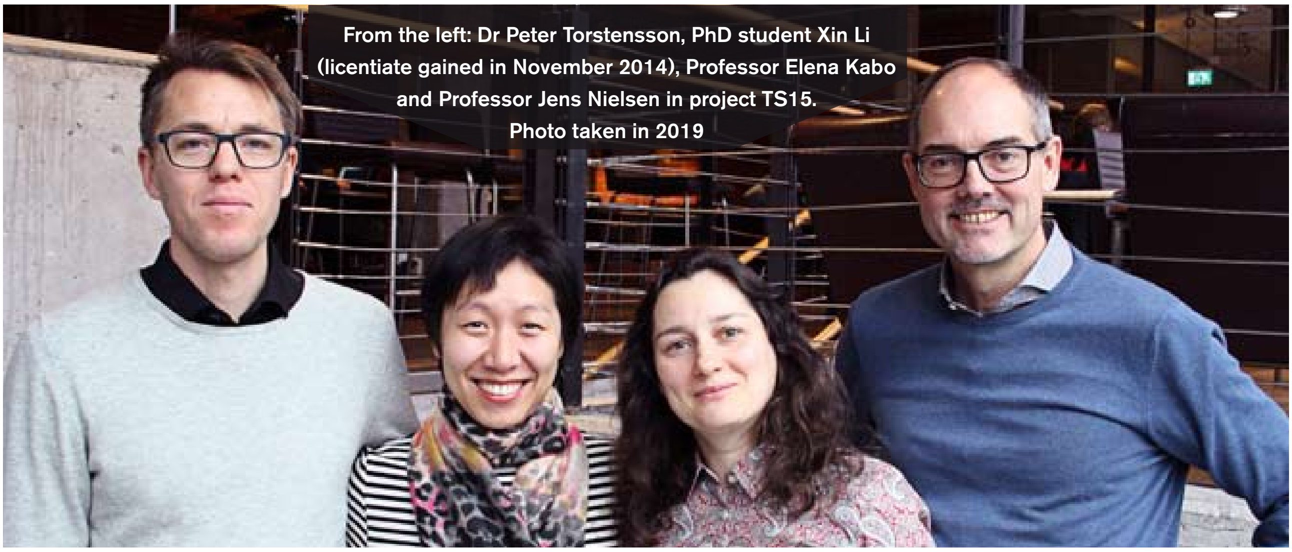
The project is mainly financed by Trafikverket via LTU (through CHARMEC's budget)

The aim of this project is 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 knowledge of parameters affecting track geometry degradation caused by the settlement of ballast and soil should be increased. Product development of S&C, based on optimal use of resilient elements and leading to lower dynamic forces and improved geometric stability, is supported. Models of dynamic interaction between vehicle and S&C, and finite element (FE) calculations of stresses and strains in relevant S&C components and ballast/soil, are being used to predict wheel–rail contact forces and track geometry degradation. Distributions of load parameters such as amount of wear of wheel profiles and variations in train speed, axle load and wheel–rail friction are considered. The methodology developed in INNOTRACK (our project EU10) and project TS13 has been applied.

A model for simulation of high-frequency dynamic vehicle–track interaction in a railway crossing was developed. Here the vertical 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 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 in 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 VAE. The variation in three-dimensional contact geometry of crossing rail, wing rail and wheel is described by use of linear surface elements.

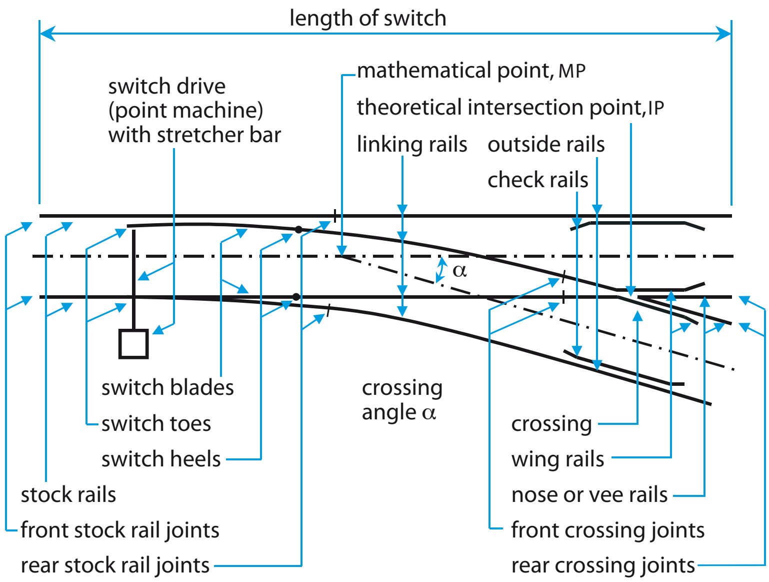
In each time step of the contact detection algorithm, the lateral position of the wheelset centre is prescribed but the contact positions on wheel and rail are not, allowing for an accurate prediction of the wheel transition between wing rail and crossing rail. It has been shown that the magnitude of the impact load is influenced more by the wheel–rail contact geometry than by the selection of rail pad stiffness.

A parameter study has been performed to investigate the influence of sleeper bottom width, rail pad stiffness and implementation of under sleeper pads (USP, see photo on


From the left: Dr Peter Torstensson, PhD student Xin Li (licentiate gained in November 2014), 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 α = 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"



page 56) on the variation in static track stiffness at rail level, maximum wheel–rail contact force and load transferred to the track bed. Based on the investigated design space for the crossing panel and the calculated maximum values of the selected dynamic responses, it was found that (1) implementing USP and/or reducing rail pad stiffness will result in a reduced variation in static track stiffness in the crossing panel, (2) reducing rail pad stiffness and implementing USP leads to a moderate reduction of the maximum wheel–rail contact force at the crossing, and (3) the most effective mitigation measures to reduce sleeper–ballast contact pressure are an implementation of USP and an increase of the sleeper bottom width. It is thus 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 mitigate the risk of differential track settlement by lowering the sleeper–ballast contact pressure. The research plan for project TS15 is dated 2010-09-06.

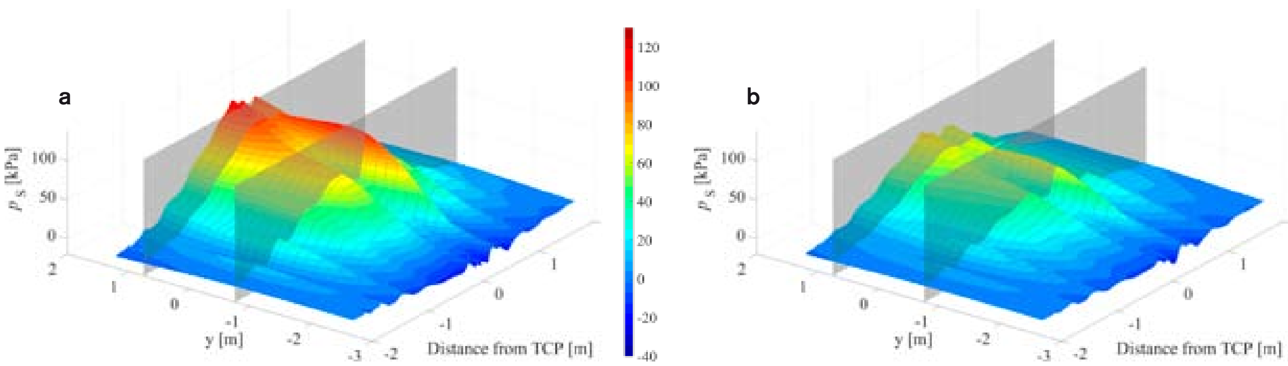
The reference group for the present project and a parallel project at LTU has members from Abetong, voestalpine VAE, Vossloh Nordic and Trafikverket. Project TS15 is continuously being presented and discussed during the biannual workshops with participants from University of Leoben (Austria), voestalpine VAE, voestalpine Schienen and CHARMEC, see page 71. Xin Li has been on parental leave and has worked on a part-time basis during parts of Stage 8.

Xin Li, Magnus Ekh and Jens Nielsen: Three-dimensional modelling of differential railway track settlement using a cycle domain constitutive model, *International Journal for Numerical and Analytical Methods in Geomechanics*, vol 40, no 12, 2016, pp 1758-1770

Xin Li, Peter Torstensson and Jens Nielsen: Simulation of vertical dynamic vehicle–track interaction in a railway crossing using Green's functions, *Journal of Sound and Vibration*, vol 410, 2017, pp 318-329 (also listed under project TS16)

Jens Nielsen and Xin Li: Railway track geometry degradation due to differential settlement of ballast/subgrade – numerical prediction by an iterative procedure, *Journal of Sound and Vibration*, vol 412, 2018, pp 441-456 (also listed under projects EU16 and SP26)

Xin Li, Jens Nielsen and Peter Torstensson: Simulation of wheel–rail impact loads and measures to reduce track settlement in railway crossings (submitted for international publication)



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)

TS16. TIME-DOMAIN MODEL OF RAILWAY BRAKING NOISE

Tidsdomänmodell av järnvägsbuller från bromsning
Zeitbereichsmodell der Eisenbahnbremsgeräusche
Modèle en domaine temporel du bruit au freinage ferroviaire

Project leader	Dr Peter Torstensson, Assistant Professor (Swedish: forskarassistent), Mechanics and Maritime Sciences/ Division of Dynamics
Doctoral candidate	None (only senior researcher in this project)
Period	2013-01-01 – 2017-11-30
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 900 Stage 8: KSEK 1 209
Industrial interests in-kind budget	Stage 7: KSEK 100 + 200 + 50 + 50 + 50 Stage 8: KSEK 100 + 200 + 50 + 0 + 0 *(Bombardier Transportation + Faiveley Transport + Lucchini Sweden + SL + Trafikverket)*

For a photo of Peter Torstensson, see page 16

The EU commission has identified the shift from road traffic to other modes of transportation (i e, railway and waterway) as an important strategy to cut the EU's emission of greenhouse gases. As railway tracks are operated throughout the 24 hours and often are built in densely populated areas, the solving of noise issues is crucial in order to gain people's acceptance for the expected future expansion of railway traffic.

In project TS16, a model to simulate braking noise has been developed. Besides providing a deeper understanding of this complex phenomenon, the present simulation tool can be applied in the search for a design solution to the noise problem.

As mentioned in the previous Triennial Report, a computational framework for efficient time-domain simulation of dynamic multibody systems labelled RAVEN (RAil VEhicle Noise) has been developed and validated against our existing model DIFF (by Jens Nielsen) for the case of dynamic vehicle – track interaction. To account for three-dimensional non-Hertzian and non-steady wheel – rail contact, the implementation of Kalker's variational method in project VB12 is applied. RAVEN's functionality was further utilized in project EU16 where RAVEN was combined with TWINS (Track Wheel Interaction Noise Software) to investigate the radiation of impact noise at railway crossings.

At Polytechnic University of Valencia (Spain), a frequency-domain model for complex linear stability analysis of railway tread brakes was developed in a collaboration between Peter Torstensson and Professor Luis Baeza. Here, inertial effects due to wheel rotation as well as damping provided by tangential wheel – rail contact forces were accounted for. The brake block–wheel contact was modelled by use of kinematic constraint equations. At a later stage a flexible rail, implemented by Dr Juan Giner Navarro of Polytechnic University of Valencia, that relied on the so-called Moving Element Method, was introduced.

The model for prediction of brake squeal was found able to capture the dominant unstable eigenmodes of the wheel–brake system in Lucchini's test rig in Surahammar, see page 58. For the case of curve squeal, a further verification of the current frequency-domain model was achieved by a comparison against the existing time-domain model developed in project VB10. Both models predict similar squeal frequencies for a large parameter space in terms of wheel – rail friction coefficients and wheelset yaw angles.

The joint reference group of projects TS16, VB11 and VB12 had members from Bombardier Transportation (in Germany, Sweden and Switzerland), Faiveley Transport, SL, SNC-Lavalin and Trafikverket. The research plan for project TS16 is dated 2012-09-06.

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 (also listed under project MU31)

Astrid Pieringer, Peter Torstensson, Juan Giner Navarro and Luis Baeza: Investigation of railway curve squeal using a combination of frequency- and time-domain models, *Proceedings 12th International Workshop on Railway Noise (IWRN12)*, Terrigal (Australia) September 2016, 8 pp (also listed under project VB12)

Xin Li, Peter Torstensson and Jens Nielsen: Simulation of vertical dynamic vehicle–track interaction in a railway crossing using Green's functions, *Journal of Sound and Vibration*, vol 410, 2017, pp 318-329 (also listed under project TS15)

Peter Torstensson, Giacomo Squicciarini, Matthias Krüger, Jens Nielsen and David Thompson: Hybrid model for prediction of impact noise generated at railway crossings. In David Anderson et al (editors): Noise and Vibration Mitigation for Rail Transportation Systems, *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 139, 2018, pp 759-769 (revised article from workshop *IWRN12*. Also listed under project EU16)

Astrid Pieringer, Peter Torstensson, Juan Giner and Luis Baeza: Investigation of railway curve squeal using a combination of frequency- and time-domain models, *ibidem*, pp 83-95 (revised article from workshop *IWRN12.* Also listed under project VB12)

Andreas Carlberger, Peter Torstensson, Jens Nielsen and Anders Frid: An iterative methodology for the prediction of dynamic vehicle–track interaction and long-term periodic rail wear, *IMechE Journal of Rail and Rapid Transit*, vol 232, 2018, pp 1718-1730

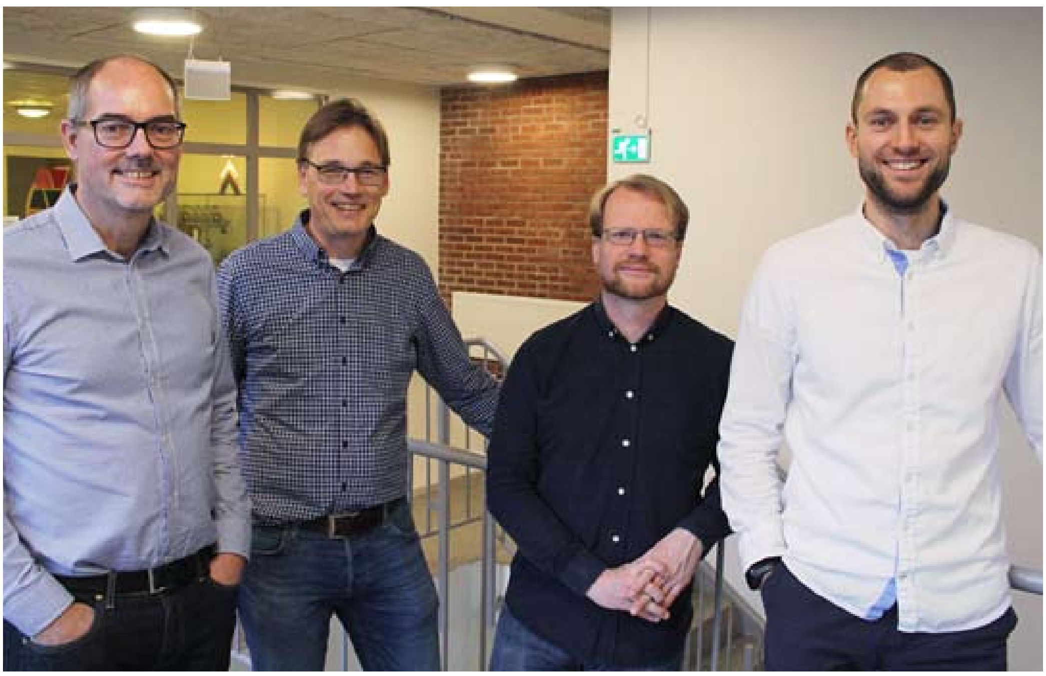
TS17. OPTIMIZATION OF MATERIALS IN TRACK SWITCHES

Optimering av material i spårväxlar
Optimierung von Werkstoffen in Eisenbahnweichen
Optimisation des matériaux pour les aiguillages de voies ferrées

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 Björn Pålsson, Senior Lecturer, Mechanics and Maritime Sciences
Doctoral candidate	Mr Rostyslav Skrypnyk (from 2015-05-26; Lic Eng June 2018)
Period	2015-05-27 – 2018-06-30 (– 2020-05-31)
Chalmers budget (excluding university basic resources)	Stage 7: ksek 150 Stage 8: ksek 2200 (+ 1090 in S2R) Stage 9: ksek 650 (+ 1000 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)*

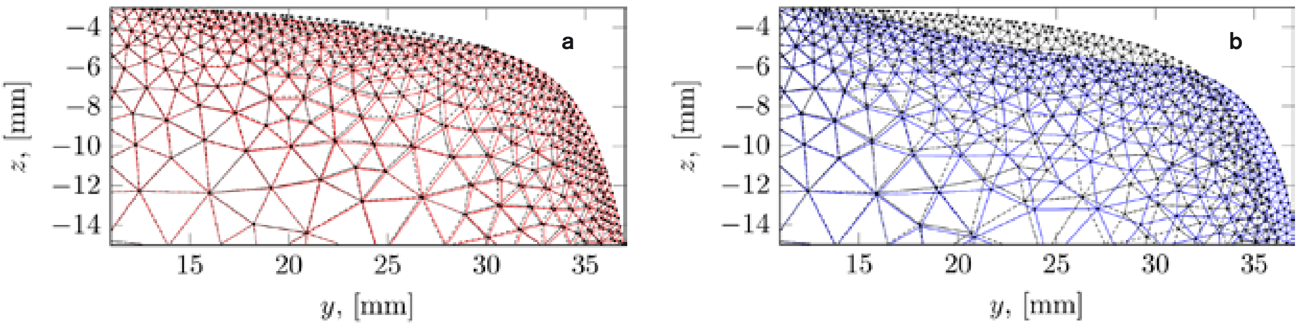
The project aims at increasing the understanding of the long-term degradation and damage modes of different crossing materials. Guidelines for selection of crossing material will be developed, where the selected material should produce a crossing that for a given traffic scenario is stable in geometry and has a long service life and a low life cycle cost. The methodology, developed in INNOTRACK (our project EU10), for prediction of rail profile degradation in track switches by integrating several cross-disciplinary numerical models and tools, is being applied and extended. Robustness and computational efficiency of the methodology is improved by formulating meta-models using, for example, Response Surface Modelling. The models are calibrated and validated versus damaged rail profiles measured in the field. A better understanding of required production tolerances and maintenance action limits considering rail profile degradation will be established.

For a given set of wheel and rail profiles, and based on a prescribed range of relative lateral displacements between wheel and rail and on three different magnitudes of the contact force, samples of contact load data have been calculated using a parameterized FE model in ABAQUS and accounting for plastic deformations. Based on the Hertz solution for contact problems, a meta-model of the wheel–rail contact has been formulated by replacing the constants and material parameters in the Hertzian solution with coefficients that are obtained by calibration against results from the sample simulations in ABAQUS. In terms of maximum contact pressure and contact patch size, the hypothesis that curvatures of wheel and rail within the contact area can be assumed constant in the FE simulations has been verified. This means that it is acceptable to work with simplified wheel/rail geometry in each iteration step of the calculation of long-term rail profile degradation. The reduction of computation time when using the meta-model instead of the FE model for new load cases is significant.



From the left: Professor Jens Nielsen, Professor Magnus Ekh, Senior Lecturer Björn Pålsson and PhD student Rostyslav Skrypnyk (licentiate gained in June 2018) in project TS17

TS17. (cont'd)



Calculated plastic deformation (without scaling) of rail profile in project TS17 for rail grades R350HT (a) and Mn13 (b) after 150 load sequences (41 400 wheel passages). Dashed black lines show undeformed mesh

Based on work in project TS13, a model of three-dimensional dynamic interaction between a vehicle and the crossing panel has been developed and used to assemble a load collective for a crossing. This collective accounts 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 condition, the load collective provides information about the distribution of locations and magnitudes of the high-frequency impact loads generated on the crossing. It is concluded that the first contact between wheel and nominal crossing rail is made over a relatively narrow zone and that most of the initial contacts occur at about half a metre after the theoretical intersection point (see figure on page 17). The maximum contact force occurs later than the initial contact with 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 0.8 MGT. The rolled manganese steel deformed about 3.5 times more than the R350HT, see figures above.

A numerical tool for the calculation of rail wear using FASTSIM and the Archard model has also been developed. Because of the lack of material data, accumulated wear after 0.8 MGT of traffic was simulated for the manganese steel only. 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 2% of the predicted plastic deformation.

Project TS17 has continuously been presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine VAE, voestalpine Schienen and CHARMEC, see page 71. Rostyslav Skrypnyk presented his licentiate thesis (see below) at a seminar on 7 June 2018 with Dr Matin Sh Sichani of TÜV Sweden introducing the discussion. The research plan of project TS17 is dated 2015-06-04.

Rostyslav Skrypnyk, Jim Brouzoulis, Magnus Ekh and Jens Nielsen: Simulation of material degradation in track switches, *Proceedings 19th Nordic Seminar on Railway Technology*, Luleå (Sweden) September 2016 (Summary and PowerPoint presentation)

Rostyslav Skrypnyk, Björn Pålsson, Jens Nielsen and Magnus Ekh: Metamodel for elasto-plastic wheel–rail contact with application to damage in a railway crossing, *Proceedings 25th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2017)*, Rockhampton (Australia) August 2017, 6 pp

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* (in printing)

Rostyslav Skrypnyk: Towards simulation-based optimisation of materials in railway crossings, Licentiate Thesis, *Chalmers Mechanics and Maritime Sciences*, Gothenburg June 2018, 72 pp (Summary and two appended papers)

Rostyslav Skrypnyk, Magnus Ekh, Jens Nielsen and Björn Pålsson: Simulation of plasticity and wear in railway crossings, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

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 (submitted for international publication)

Rostyslav Skrypnyk, Magnus Ekh, Jens Nielsen and Björn Pålsson: Simulation of damage in railway crossings – a comparison of R350HT and rolled Mn13, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 902-907

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
Numerische Simulationen der Degradierung von Zug und Gleis als Basis für RAMS- und LCC-Analysen
Simulations numériques de la dégradation de train et voie comme base pour des analyses RAMS et LCC

Project leader	Dr Björn Pålsson, Senior Lecturer, Mechanics and Maritime Sciences / Division of Dynamics
Doctoral candidate	None (only senior researcher in this project)
Period	2014-03-01 – 2018-06-30 (– 2021-06-30)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 000 Stage 8: KSEK 780 (+ 191 in S2R) Stage 9: KSEK 200 (+ 800 in S2R)
Industrial interests in-kind budget	Stage 7: KSEK 15 + 50 + 100 Stage 8: KSEK 0 + 0 + 0 Stage 9: KSEK 0 + 0 + 0 *(SL + Trafikverket + ÅF)*

For a photo of Björn Pålsson, see page 19

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 ultimate 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 developed methods 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. Identified sub-tasks include the characterization of traffic scenarios using statistical methods and the creation of load collectives which are representative for the traffic scenario at hand.

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 the 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.

In the next stages, the models are being used to investigate the relation between crossing geometry quality and sleeper-ballast contact pressures and for the calculation of settlements. This simulation framework has been developed as part of a greater effort within the EU project In2Track (our EU17) to develop a so-called Whole System Model.

The parameterized S&C model has also been applied in project EU17 to develop embedded sensor concepts for condition monitoring. The study showed that when a wheel passes over a crossing, the vertical impact load and the resulting vertical crossing acceleration are mostly proportional to the speed of the passing wheelset and the crossing dip angle where the latter is determined by the crossing geometry. It is thus proposed that if the maximum vertical acceleration and maximum displacement of crossings in traffic are recorded over time together with the speed of passing vehicles, it should be possible to determine the status of a given crossing in terms of settlements and crossing geometry degradation from these data.

In order to achieve a better qualitative understanding of the geometric constraints posed on crossing geometries in traffic under the passage of a variety of wheel profile shapes, an analytical model for the interaction between a set of wheel profile shapes and a given crossing geometry has been derived. The model demonstrates that the greater the spread in the geometry of passing wheel profiles, the greater the longitudinal inclinations of wing rail and crossing nose and thus also the dip angles will have to be, if all wheel profiles should make an orderly crossing transition from wing rail to crossing nose. Increased dip angles lead to increased impact loads as wheels pass over the crossing. There is thus a trade-off between the magnitude of geometric variation of wheel profiles that can be allowed in traffic and the impact loading at crossings.

Björn Pålsson: Robust evaluation of rail damage and track forces using representative load collectives, *Proceedings 24th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2015)*, Graz (Austria) August 2015, 10 pp (also listed in the previous Triennial Report)

Björn Pålsson: Kinematic principles in switches & crossings, *Proceedings 19th Nordic Seminar on Railway Technology*, Luleå (Sweden) September 2016 (Summary and PowerPoint presentation)

Björn Pålsson: A linear wheel-crossing interaction model, *IMechE Journal of Rail and Rapid Transit*, vol 232, no 10, 2018, pp 2431-2443

Björn Pålsson: Condition monitoring in crossing panels using embedded sensors, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

See also Deliverables in projects EU16 and EU17

TS19. DESIGN CRITERIA FOR SLAB TRACK STRUCTURES

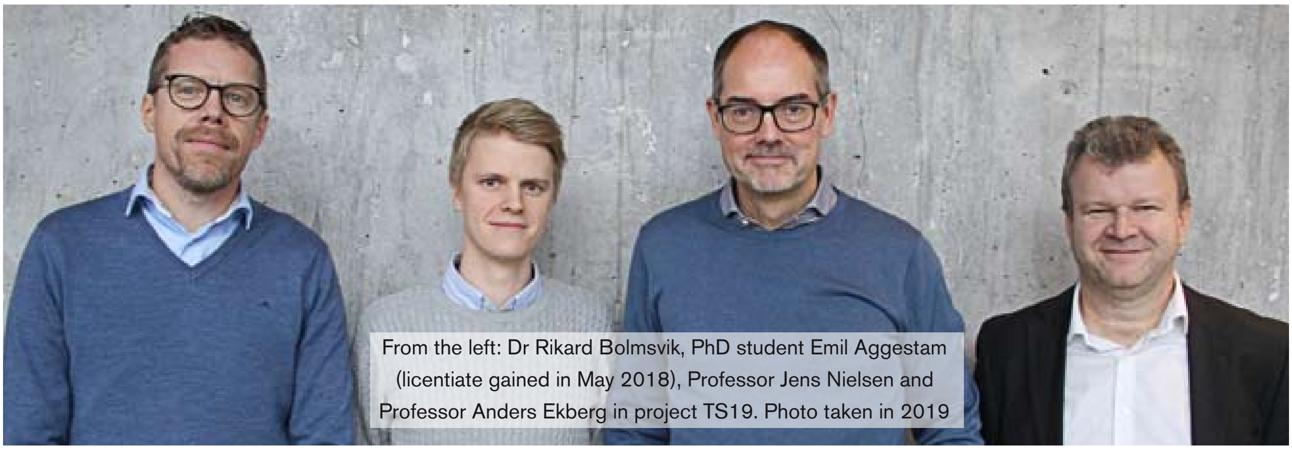
Designkriterier för ballastfria spår
Auslegungskriterien für schotterlose Gleise
Critères de conception de voies ferrées sans ballast

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)
Period	2016-07-01 – 2018-06-30 (– 2021-06-30)
Chalmers budget (excluding university basic resources)	Stage 8: KSEK 1 760 (+ 145 in S2R) Stage 9: KSEK 1 640 (+ 1 565 in S2R)
Industrial interests in-kind budget	Stage 8: KSEK 0 Stage 9: KSEK 200 *(Abetong)*

According to technical specifications issued by Trafikverket, the construction of future high-speed lines in Sweden may be based on slab track design. 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 is being studied using a generic model that includes a three-dimensional description of the slab track structure on a Winkler-type foundation. The influence of stiffness gradients and differential settlements in the supporting foundation along and across the slab are being investigated and transition zones between different track forms studied. Strength and fatigue life of the design is analysed considering high-frequency impact loads due to wheel/rail irregularities, temperature variations and crack propagation. Different slab track designs available on the market will be compared with conventional ballasted track designs to obtain an optimum performance under Swedish climate conditions at a low life cycle cost. Project TS19 runs in parallel with work in the EU programme Shift2Rail.

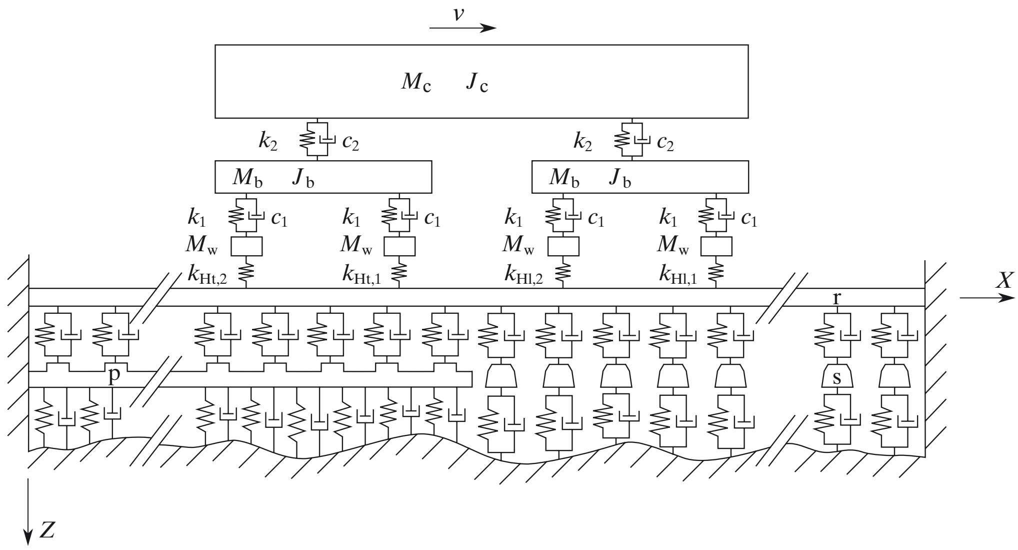
A generic two-dimensional model of dynamic interaction between vehicle and slab track has been implemented in the in-house computer program DIFF (from project TS8), and procedures to assess the performance of the track have been derived. The vehicle model is a mass–spring–damper model of the car body and two bogies, while the track model is an FE model including a discretely supported rail on a continuous or decoupled concrete panel which rests on a Winkler foundation, see figure. It has been concluded that the influence of a foundation stiffness gradient on the magnitude of the maximum wheel–rail contact force is dependent on the vehicle speed due to the rail seat passing frequency and the excitation of the fundamental vehicle-track system resonance. Geometric rail imperfections may have a large impact on the wheel–rail contact force and the bending moment in the concrete panels. A thicker roadbed distributes the load on the foundation over a longer distance, while a lower rail pad stiffness reduces the bending moment 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 in transition zones. Investigated design variables include rail pad stiffness and sleeper spacing. Transition zones of different lengths and character have been analysed, and the robustness of the optimized transition zone has been assessed by introducing selected track irregularities. By using an optimum distribution of rail pad stiffness and sleeper spacing in the transition zone, the wheel–rail contact force and also 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,



From the left: Dr Rikard Bolmsvik, PhD student Emil Aggestam (licentiate gained in May 2018), Professor Jens Nielsen and Professor Anders Ekberg in project TS19. Photo taken in 2019

TS 19. (cont'd)



Track and vehicle models used in simulations in project TS19. Track model contains rail (r), panel (p) and sleepers (s) that are modelled as beam elements

Sleepers and panel are supported by a Winkler foundation where the prescribed (possibly random) variation in stiffness is indicated by the irregular level of the ground surface

whereas a longer transition zone may be required to minimize dynamic vehicle responses, e g, ride comfort.

Emil Aggestam presented his licentiate thesis (see below) at a seminar on 25 May 2018 where Professor Mats Berg of KTH introduced the discussion. The joint reference group for projects TS19 and VB13 has members from Abetong, Trafikverket and Bombardier Transportation. The research plan of project TS19 is dated 2016-11-18.

Emil Aggestam and Jens Nielsen: Dynamic interaction between vehicle and slab track – influence of track design parameters, *Proceedings 25th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2017)*, Rockhampton (Australia) August 2017, 6 pp

Niklas Sved: A parameterized three-dimensional finite element model of a slab track for simulation of dynamic vehicle-track interaction, MSc Thesis 2018:1, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2018, 71 pp

Emil Aggestam, Jens Nielsen and Rikard Bolmsvik: Simulation of vertical dynamic vehicle–track interaction using a two-dimensional slab track model, *Vehicle System Dynamics*, vol 56, no 11, 2018, pp 1633-1657

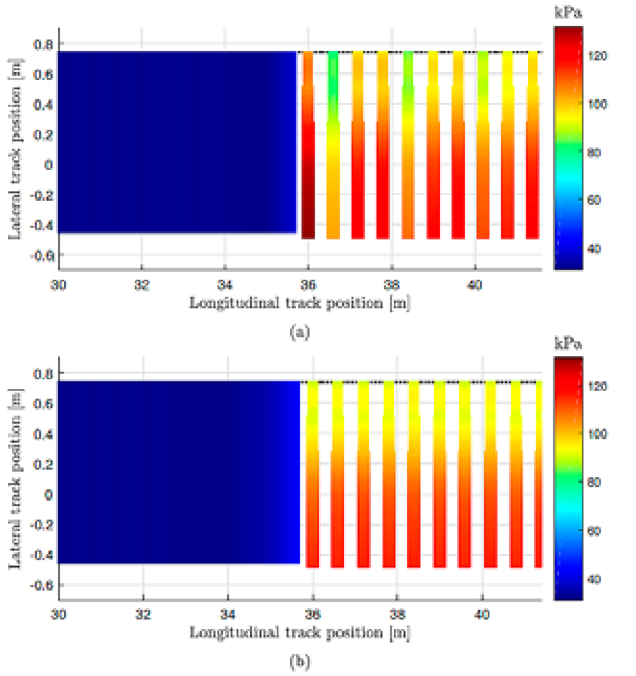
Emil Aggestam: Simulation of vertical dynamic interaction between railway vehicle and slab track, Licentiate Thesis, *Chalmers Mechanics and Maritime Sciences*, Gothenburg May 2018, 97 pp (Summary and three appended papers)

Emil Aggestam and Jens Nielsen: Optimisation of transition zones between different railway track forms using a genetic algorithm, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

Emil Aggestam, Jens Nielsen, Andreas Andersson and Martin Li: Multi-objective optimisation of transition zones between different railway track forms, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 1-6

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

An existing slab track. Photo by Slab Track Austria



Calculated distribution of maximum pressure between sleeper/panel and foundation in project TS19 for (a) nominal track and (b) track that has been optimized to minimize maximum pressure between sleeper/panel and foundation. The horizontal lines indicate the symmetry lines of the track, while the rail is located along the lateral track position $Y = 0$ m

TS20. WHEEL TREAD DAMAGE – IDENTIFICATION AND EFFECTS

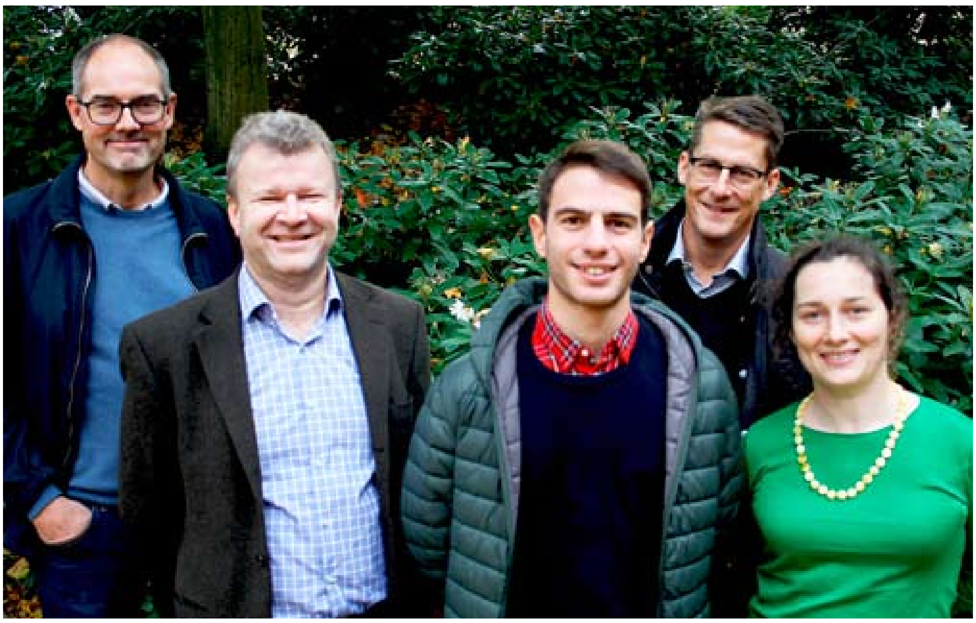
Löpbaneskador på hjul – identifiering och konsekvenser
Schäden an Radlaufflächen – Identifizierung und Konsequenzen
Dommages sur bande de roulement de roues
– identification et consequences

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, MSc (from 2018-02-01)
Period	2018-02-01 – 2018-06-30 (– 2023-01-31)
Chalmers budget (excluding university basic resources)	Stage 8: kSEK 400 (+ 301 in S2R) Stage 9: kSEK 1 300 (+ 1 565 in S2R)
Industrial interests in-kind budget	Stage 8: kSEK 0 + 0 + 0 + 0 Stage 9: kSEK 200 + 100 + 100 + 100 *(Bombardier Transportation + Faiveley Transport + Green Cargo + Lucchini Sweden)*

Wheel tread damage leads to 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). To limit the risk of a catastrophic failure of the running gear, 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 will start by deriving load spectra resulting from different types of tread damage. In a second stage, the dynamic interaction between the wheel and the railway track is studied in order to establish stress time histories resulting from the prescribed loads as based on field measurements and simulation studies. Subsequently, models to assess damage of critical components are developed such that fatigue stress spectra can be obtained for the running gear. The influence of wheel tread irregularities and their lateral position with respect to the running band is taken into account. Eventually, the fatigue damage caused by different tread defects and operational conditions, in particular train speed and track stiffness, will be investigated.

Initial work has been performed to increase the understanding of models for dynamic vehicle–track interaction and of how to integrate results from the commercial FE software ABAQUS with the in-house software RAVEN (RAil VEhicle Noise, see project TS16), which has also been used in projects MU31 and TS15. Some FE models of train wheels have been developed and used in modal and steady-state dynamic analyses. The Green's functions and the convolution integral approach applied in RAVEN have been studied and implemented in a MATLAB script that can compute the dynamic behaviour of systems, setting out from transfer functions obtained from the FE analysis.

Damaged wheel tread surfaces have been scanned at two different Swedish workshops (SweMaint in Gothenburg and Bombardier Transportation in Luleå) using a 3D laser equipment. The data were extracted and post-processed using commercial CAD software. A 3D FE model of a wheelset will be established, and its displacement and stress



From the left: Professor Jens Nielsen, Professor Anders Ekberg, PhD student Michele Maglio, Docent Tore Vernersson and Professor Elena Kabo in project TS20

TS20. (cont'd)

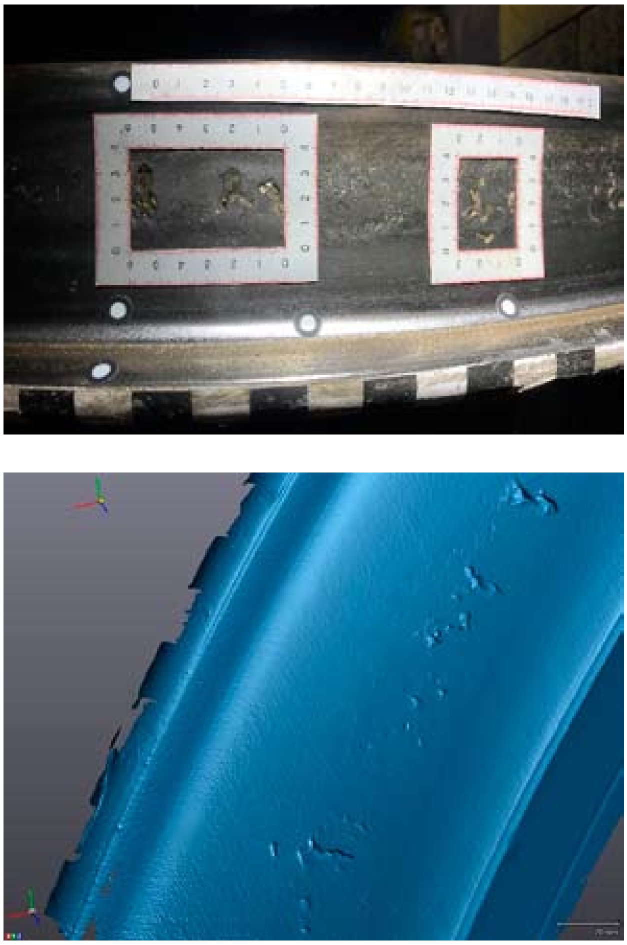
Michele Maglio scanning a wheel tread in the Luleå workshop and Tore Vernersson applying reflective points on the running surface of a wheel. Photos by Tore Vernersson and Michele Maglio

transfer functions will be extracted at several locations. For given types of wheel tread damage, the subsequent analyses using the Green's function approach in RAVEN will be used to calculate wheel–rail contact forces and to identify the wheelset positions with maximum stress where the risk of fatigue damage is the highest.

Based on the tread surfaces scanned in Luleå as input to the simulation model, the calculated maximum wheel–rail contact forces will be compared to those extracted from field tests performed by Trafikverket in April 2018. Efforts are being made to instrument an axle for estimating wheel – rail contact loads as part of a co-operation with Lucchini RS and SJ. To this end, a leading axle of a double-decker X40 train is instrumented with Lucchini's Smartset® devices in order to acquire in-field data regarding axle bending load spectra. This information together with measurements of actual wheel tread damage and the aforementioned dynamic modelling will be key to developing new knowledge on how tread damage influences load spectra for trains in revenue traffic.

For the joint reference group, see under project MU22. The research plan for project TS20 is dated 2017-09-15. For Elena Kabo's inauguration lecture as research professor, see page 70.

Michele Maglio and Elena Kabo: Thermomechanical analyses of discrete defect repair process for rails, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation. Also listed under project EU16)



Severely damaged wheel tread with large RCF clusters scanned in Luleå (top) and a post processed wheel tread obtained using the software VXElements (bottom). Photo / picture by Michele Maglio

VB11. ABATEMENT OF CURVE SQUEAL NOISE FROM TRAINS

Reduktion av kurvskrikljud från tåg
Verminderung des Quietschens von Zügen in Kurven
Réduction du grincement ferroviaire dans les courbes

Project leaders and supervisors	Professor Wolfgang Kropp and Dr Astrid Pieringer, Assistant Professor (Swedish: forskarassistent), Architecture and Civil Engineering / Division of Applied Acoustics
Doctoral candidates	Mr Ragnar Vidarsson, MSc (2011-01-15 – 2011-06-30) Mr Ivan Zenzerovic (2012-06-01 – 2015-12-31 and 2017-03-01 – 2018-01-31; Lic Eng December 2014; PhD January 2018)
Period	2011-01-01 – 2018-01-01
Chalmers budget (excluding university basic resources)	Stage 6: kSEK 490 Stage 7: kSEK 2 775 Stage 8: kSEK 1 900
Industrial interests in-kind budget	Stage 6: kSEK 200 + 0 + 0 + 0 Stage 7: kSEK 100 + 15 + 25 + 50 Stage 8: kSEK 100 + 15 + 0 + 0 *(Bombardier Transportation + Interfleet Technology/SNC-Lavalin + SL + Trafikverket)*

Curve squeal is a highly disturbing tonal sound generated by railway cars, metros and trams when they negotiate a sharp curve. For curves with a radius of 200 m and below, curve squeal noise is common. In addition, such tight curves are situated mainly in urban areas where many people live close to the tracks. The noise is also a comfort issue for the passengers inside the vehicles.

Curve squeal noise is commonly attributed to self-excited vibrations of the railway wheel, which are induced either by stick/slip behaviour due to lateral creepage of the wheel tyre on the top of the rail or by contact on the wheel flange. Practical measures to reduce the noise are increased wheel damping and applied friction modifiers. However, it is desirable to gain a fundamental understanding of the mechanisms and causes of squeal in order to find, if possible, appropriate vehicle and track designs to avoid or abate the generation of squeal noise. For this purpose, it is advantageous to predict not only the likelihood of squeal noise but also its amplitude. Project VB11 was divided into four parts: (i) a further extension of the time-domain model developed in project VB10, (ii) an experimental validation of the model, (iii) an extensive study to identify the essential parameters (and their complex interaction) responsible for curve squeal, and (iv) an investigation of the potential to reduce curve squeal by design changes to track and wheel.

Aiming at an engineering model for curve squeal, the time-domain model for curve squeal developed in project VB10 has now been modified and extended with a computationally efficient tangential point-contact model instead of the tangential part of Kalker's variational method (TANG) used in project VB10. The new model considers the contact variables in a global manner, but has the drawback of being steady-state. This stands in contrast to Kalker's variational contact model, which is a transient model that discretizes the contact into elements. In the present project, the regularized friction curve and the contact stiffness in the point-contact model are derived in a stringent way in relation to Kalker's model, see figure on page 29. In this way, the point-contact model is able to describe the transition of contact conditions from full stick to full slip. A validation of the tangential point-contact model against Kalker's transient variational contact model revealed that the former performs well up to at least 5 kHz. Calculations using the squeal model based on point-contact are typically 2–3 times faster than those based on the original model from project VB10.

The step towards a full engineering model was completed by implementing a simple model for sound radiation from the railway wheel taken from the literature, which was validated against results from an in-house Boundary Element code.

Studies of kinematic parameters related to the vehicle's curving performance (lateral creepage and wheel/rail contact position and friction) were performed using the proposed engineering model for squeal. Friction and kinematic parameters were found to have a significant influence on squeal occurrence and amplitudes. The influence

From the left: Dr (now Assistant Professor) Astrid Pieringer, Professor Wolfgang Kropp and PhD student Ivan Zenzerovic (doctorate earned in January 2018) in projects VB11, VB12 and VB13. Photo taken in 2012

VB11. (cont'd)

of the wheel modal damping was also investigated. Results indicate that an increase of only the damping of the wheel mode excited in squeal might not help. Another mode may then be excited in squeal. The amount of modal damping to prevent squeal was found to be relatively low and easily achievable.

Research has continued towards a more detailed modelling of the wheel–rail contact including the contact angle and spin creepage. To include spin creepage in the point-contact model, a family of regularized friction curves have been precomputed using Kalker's variational method for each contact location (defining the contact area's shape and size) and friction coefficient value. The results of the extended point-contact model are in good agreement with results obtained from Kalker's variational method.

A parameter study with the model showed that the contact angle has a significant influence on curve squeal amplitudes and frequencies, which confirms the hypothesis that the contact angle influences the geometric coupling which is responsible for squeal. Spin creepage only influences curve squeal amplitudes, and the influence of the contact angle is dominant over the influence of spin creepage. Further, the squeal model was extended to two-point wheel–rail contact. This extension enables the evaluation of squeal on outer wheels in curves where two-point contact between wheel and rail may occur. In the studied cases, severe squeal with a frequency of 3.2 kHz was obtained. Further studies have shown that the two-point-contact case cannot be simplified to one-point-contact cases.

Ivan Zenzerovic successfully defended his doctoral dissertation in public on 19 January 2018. The faculty-appointed external examiner of the dissertation was Professor David J Thompson from ISVR at the University of Southampton in the UK. Under the supervision of Astrid Pieringer, the Master's students Arthur Aglat and Jannik Theyssen designed a test rig for squeal noise, see page 75, and made theoretical predictions of the rig using Ivan Zenzerovic's one-point-contact model. The costs of the rig (about 500 kSEK) are an investment by Chalmers Applied Acoustics in future work with squeal noise abatement.

The joint reference group for projects VB11, VB12 and TS16 had members from Bombardier Transportation (in Germany, Sweden and Switzerland), Faiveley Transport, SNC-Lavalin, SL Technology and Trafikverket. The research plan for project VB11 is dated 2010-05-15.

Arthur Aglat and Jannik Theyssen: Design of a test rig for railway curve squealing noise, MSc Thesis BOMX02-17-86, *Chalmers Applied Acoustics*, Gothenburg 2017, 72 pp (and 1 annex 52 pp). The authors received the 2018 Swedtrain award for Best Master's Thesis in Railway Technology, see page 74

Ivan Zenzerovic: Time-domain modelling of curve squeal: a fast model for one- and two-point wheel/rail contact, Doctoral Dissertation, *Chalmers Applied Acoustics*, Gothenburg January 2018, 216 pp (Monograph and four appended papers)

Ivan Zenzerovic, Wolfgang Kropp and Astrid Pieringer: Influence of spin creepage and contact angle on curve squeal: A numerical approach, *Journal of Sound and Vibration*, vol 419, 2018, pp 268-280

Ivan Zenzerovic, Wolfgang Kropp and Astrid Pieringer: Time-domain investigation of curve squeal in the presence of two wheel/rail contact points (submitted for international publication)

Vibrations and noise – Vibrationer och buller (VB) – Schwingungen und Geräusche – Vibrations et bruit

VB12. HIGH-FREQUENCY WHEEL–RAIL INTERACTION

Samverkan tåg–spår vid höga frekvenser
Wechselwirkung von Rad und Schiene bei hohen Frequenzen
Interaction roue–rail à hautes fréquences

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 concerns 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 concerns squeal noise generated by tangential interaction. In the completed doctoral project VB10, a model was developed for the combined vertical and tangential wheel–rail interaction, which is valid in the frequency range relevant for noise generation (from approximately 100 Hz to 5 kHz). Project VB12 is a continuation of VB10 and focuses on different aspects of high-frequency wheel–rail interaction. The aim is to further develop, apply and validate the current simulation model, e g, for excitation by wheel flats and for curve squeal. The work in the parallel doctoral project VB11 has been supported.

The simulation model from project VB10, which includes a three-dimensional (3D) non-Hertzian contact model, was adapted to excitation by wheel flats. To investigate the level of model complexity needed for the dynamic wheel–rail interaction due to wheel flats, the results obtained using a two-dimensional (2D) non-Hertzian contact model or,

VB12. (cont'd)

Project leader	Dr Astrid Pieringer, Assistant Professor (Swedish: forskarassistent), Architecture and Civil Engineering / Division of Applied Acoustics
Doctoral candidate	None (only senior researcher in this project)
Period	2012-01-01 – 2018-06-30 (– 2021-06-30)
Chalmers budget (excluding university basic resources)	Stage 7: see below Stage 8: see below Stage 9: see below
Industrial interests in-kind budget	Stage 7: KSEK 100 + 15 + 25 + 50 Stage 8: KSEK 100 + 15 + 0 + 0 Stage 9: KSEK 100 + 20 + 0 + 0 *(Bombardier Transportation + Interfleet Technology/SNC-Lavalin + SL + Trafikverket)*

This post-doc project is 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

alternatively, a single non-linear Hertzian contact spring, were compared. The simulation model for impact forces due to wheel flats gave similar results for the 2D model and the Hertzian spring in comparison to the 3D contact model. In the case of the Hertzian spring, it was, however, important to use the precalculated vertical wheel centre trajectory as relative displacement input. If instead the wheel profile deviation was used, large errors occurred.

From December 2012 to April 2013, Astrid Pieringer stayed at Universidad Politécnica de Valencia in Spain for co-operation with Professor Luis Baeza and his group in the field of wheel–rail interaction. She implemented a model of a rotating flexible wheel developed by Luis Baeza and his group in the prediction model for curve squeal from project VB10. In addition, a simplified approach where the rotating wheel is replaced by a stationary wheel with a moving load was implemented. These models were applied to numerically investigate whether the wheel rotation has effects on curve squeal. Simulation results for different friction coefficients and values of lateral creepage showed that the two approaches for the rotating wheel gave almost identical results for the considered rolling speed of 50 km/h. Furthermore, it could be concluded that using a stationary wheel is sufficiently accurate both for capturing the tendency to squeal and for predicting the resulting lateral forces.

As a first step towards the validation of the time-domain model for squeal noise prediction in projects VB10 and VB12, the model has been compared to a model for linear complex stability analysis in the frequency domain developed by Peter Torstensson in project TS16. The same sub-models have been implemented in both squeal models. They are a rail model based on a mathematical description applying Eulerian co-ordinates (developed by Juan Giner Navarro in Valencia) and a model of a rotating wheel (Luis Baeza). Results from both models are similar in terms of the instability range in the parameter space and the predicted squeal frequencies. For most of the investigated cases, the main squeal frequency identified in the time-domain approach corresponds to the eigenvalue with the largest magnitude of the positive real-part obtained from the linear stability analysis. An experimental validation of the time-domain model for curve squeal in projects VB10 and VB11 will be carried out on a newly developed test rig, see page 75.

In collaboration with Loïc Grau from the engineering office Acouphen in France, the influence of the ground/structure interaction on the calculation of the vertical force at the wheel–rail contact has been studied. Here, the model for vertical wheel/rail interaction from projects VB10 and VB12 has been combined with an analytical model of the ground/structure interaction developed by Loïc Grau. In order to facilitate the coupling of the models, the rail model has been replaced by a series of springs. This simplified approach is only reasonable at low frequencies. Numerical results from the combined model showed that the influence of slab and ground on the dynamic wheel–rail contact forces increases for thinner slabs and softer grounds, but is generally of secondary importance. Deviations in contact force did not exceed 2 dB for frequencies up to 200 Hz. The project is currently suspended since Astrid Pieringer carries out a 14-month research project at DB Systemtechnik GmbH in Munich (Germany), see page 74. Work in project VB12 will be resumed in August 2019. For the joint reference group, see under project VB11.

Astrid Pieringer, Peter Torstensson, Juan Giner and Luis Baeza: Investigation of railway curve squeal using a combination of frequency- and time-domain models, *Proceedings 12th International Workshop on Railway Noise (IWRN12)*, Terrigal (Australia) September 2016, 8 pp (also listed under project TS16)

Loïc Grau, Astrid Pieringer, Bernard Laulagnet and Wolfgang Kropp: Influence of the ground/structure interaction on the calculation of the force at the wheel/rail contact, *Proceedings Internoise 2016*, Hamburg (Germany) August 2016, pp 2086-2097

Astrid Pieringer, Peter Torstensson, Juan Giner and Luis Baeza: Investigation of railway curve squeal using a combination of frequency- and time-domain models. In David Anderson et al (editors): Noise and Vibration Mitigation for Rail Transportation Systems, *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 139, 2018, pp 83–95 (revised article from workshop *IWRN12*. Also listed under project TS16)

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

Prediktering och reduktion av buller från fordon på ballastfria spår
Prognose und Minderung der Geräusche von Fahrzeugen auf schotterlosen Gleisen
Prédiction et atténuation du bruit de véhicules sur voies ferrées sans ballast

Project leaders and supervisors	Professor Wolfgang Kropp and Dr Astrid Pieringer, Assistant Professor (Swedish: forskarassistent), Architecture and Civil Engineering / Division of Applied Acoustics
Doctoral candidate	Mr Jannik Theyssen, MSc (from 2017-08-28)
Period	2017-08-28 – 2018-06-30 (– 2022-08-31)
Chalmers budget (excluding university basic resources)	Stage 8: kSEK 833 Stage 9: kSEK 1 967 (+ 1 190 in S2R)
Industrial interests in-kind budget	Stage 8: kSEK 0 + 0 Stage 9: kSEK 100 + 100 *(Abetong + Bombardier Transportation)*

For a photo of Jannik Theyssen, see page 74

Rolling noise from high-speed trains may call for costly measures along the tracks. It is thus important to be able to predict this noise with high accuracy already in the planning phase. As a prediction tool for noise propagation outdoors, Nord 2000 is used in Scandinavia but also the European prediction model CNOSSOS can be applied here. However, these models are entirely dependent on a realistic input for source characterization, which today is not available for rolling noise on slab tracks in different operational conditions. Thus, the overall objective of project VB13 is to develop a method for accurate prediction of high-speed rail rolling noise on slab tracks and to identify cost-effective and sustainable measures for its reduction. The time-domain model for rolling noise on ballasted track developed in project VB10 will be extended and adapted to slab track. This model will be applied to study the impact of different track parameters and designs on the noise generation and to provide realistic source data for, e g, Nord 2000. Measures aiming at the reduction of the generation, the radiation and the propagation of rolling noise will be identified and evaluated. Finally, the project will provide guidelines for sustainable and cost-effective noise reduction measures on slab tracks. The project is carried out in co-operation with project TS19 "Design criteria for slab track structures", see page 22.

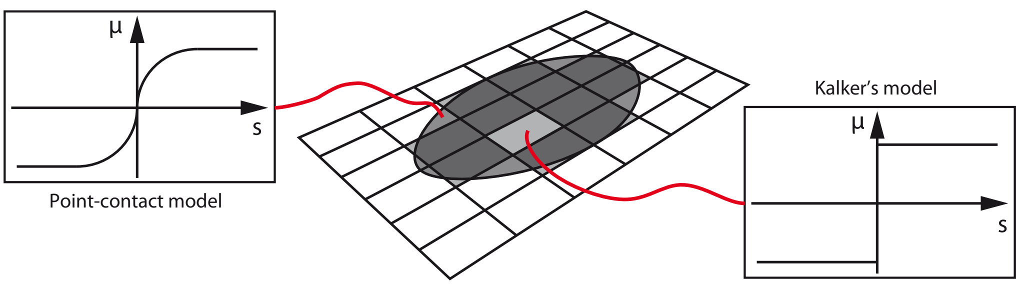
A model based on the Waveguide Finite Element (WFE) method has been developed to provide information about the dynamic behaviour of the slab. This method makes possible a reduction of the three-dimensional geometry to two dimensions by assuming wave propagation along the rail, enabling the simulation of large structures. The WFE model has been extended with a Boundary Element Model that likewise uses the WFE approach to calculate the radiation from the track as shown in the work "A waveguide finite element and boundary element approach to calculating the sound radiated by railway and tram rails" by C-M Nilsson et al (JSV, 2009, vol 321, nos 3-5, pp 813-836).

The dynamic response of the wheel is calculated according to the procedure presented in project VB10. A modal superposition of the wheel modes leads to a detailed description of the vibration and serves as the basis for the sound radiation calculation. In project VB11 a so-called half-space Boundary Element Method was successfully used to calculate the sound radiation from a train wheel and this method is planned to be used also in project VB13. An arbitrary ground impedance can be specified.

The joint reference group for projects TS19 and VB13 has members from Abetong, Trafikverket and Bombardier Transportation. The research plan for project VB13 is dated 2016-02-08.

Jannik Theyssen, Wolfgang Kropp and Astrid Pieringer: An efficient simulation model for the dynamic behaviour of slab tracks at high frequencies, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

Method used in project VB11 for obtaining a so-called regularized friction curve between wheel and rail in the point-contact model including information about contact area and spin



MU22. IMPROVED CRITERION FOR SURFACE INITIATED RCF

Förbättrat kriterium för ytinitierad rullkontaktutmattning
Verbessertes Kriterium für oberflächeninitiierte Rollkontaktermüdung
Critère amélioré de la fatigue due au contact roulant initiée en surface

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 – 2018-06-30 (– 2021-06-30)
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 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 50 + 100 + 50 *(Bombardier Transportation + Lucchini Sweden + SweMaint)*

Several CHARMEC projects have been (and are) related to rolling contact fatigue (RCF). The project MU22 aims at developing and improving engineering criteria for RCF prediction, and also to facilitate operational implementation of derived knowledge and predictive capabilities etc. Examples of applications are operational monitoring related to RCF, operational mitigation of RCF, and inclusion of RCF deterioration in LCC and RAMS analyses. The project also supports other CHARMEC projects (e g, MU31) dealing with RCF, and provides expertise to projects where RCF is of interest but not a core topic. The project includes interaction with research and industrial partners (within and outside CHARMEC) to uphold and develop a world leading competence in the field of RCF of railway wheels and rails.

A number of damage analyses and improvement studies have been conducted under the umbrella of project MU22. For example, Anders Ekberg has supported SweMaint in investigations of a fractured axle and LKAB in studies of wheel damage on the Iron Ore line. He has also supported Trafikverket with suggestions and comments to a revision of UIC Leaflet 712: Rail defects. Further, MU22 has provided comments and suggestions to Trafikverket's Technical System Standard for high-speed rail (TSS höghastighet). Co-operation on scientific papers has been carried out with Motohide Matsui at RTRI in Japan, Eric Magel at NRC in Canada, Peter Mutton at Monash University in Australia, and Ajay Kapoor at Swindon University in Australia, see below.

Anders Ekberg has participated in meetings of the International Scientific Committee for the UK research project Track to the Future in 2015, 2017 and 2018, see page 74. He acted as external examiner for the doctoral thesis "Reduction of rolling contact fatigue through the control of the wheel wear shape" by Ulrich Spangenberg at the University of Pretoria in RSA, and acted as a member of the grading committee at KTH on 2018-02-06 when Saeed Hossein Nia defended his doctoral thesis "On heavy-haul wheel damages using vehicle dynamics simulation". Elena Kabo acted as a member in the grading committees for

From the left: Professor Elena Kabo, Professor Anders Ekberg and (sitting) Professor Roger Lundén in project MU22

MU22. (cont'd)

Babette Dirks' doctoral thesis "Simulation and measurement of wheel on rail fatigue and wear" on 2015-06-02 and for Matin Sichani's doctoral thesis "On efficient modelling of wheel-rail contact in vehicle dynamics simulation" on 2016-02-24 at KTH in Stockholm. She had the same role for Matthias Asplund's doctoral thesis "Wayside condition monitoring for railway wheel profiles: applications and performance assessment" on 2016-12-15 at LTU in Luleå, and was a member of the doctoral committee at TU Delft 2018-06-04 when Zhen Yang defended his doctoral thesis "Numerical modelling of wheel-rail dynamic interactions with an explicit finite element method".

The MU22 project has presented CHARMEC's research on several occasions, both for CHARMEC partners and external parties. In more of a popular science context, Anders Ekberg and colleagues participated in Vetenskapsfestivalen in Gothenburg with presentations on structural integrity (2017) and on the railway as the "rolling process industry" (2018). Further, researchers in MU22 have been fairly frequently engaged by media to comment on railway issues, especially accidents and delays. Within project MU22, Elena Kabo and Anders Ekberg have supervised MSc theses and BSc projects, see below.

Anders Ekberg and Roger Lundén chaired sessions at the CM2015 conference and were selected as two of five guest editors for the special issue of the periodical Wear featuring papers from CM2015, see page 72. In addition to CM2015, MU22 researchers have participated and presented at the ICRI-RCF workshop (2016) and the IHHA2017 conference, see below. MU22 researchers were also heavily involved in the organization of the 20th Nordic Seminar on Railway Technology at Chalmers, including reviewing of abstracts and organizing an introductory course, see page 73. During the period being reported here, the joint reference group for projects MU22, MU31 and MU33 had members from Trafikverket, Bombardier Transportation (in Germany/Siegen and Sweden), Lucchini Sweden, SNC-Lavalin, KTH, SJ and SLL, and had meetings twice a year.

Anders Ekberg and Björn Paulsson: D-RAIL: konsten att inte spåra ur – en sammanfattning av de viktigaste resultaten från ett europeiskt forskningsprojekt (D-RAIL: The art of not derail – a summary of the most important results from a European research project; in Swedish), Research Report 2015:07, *Chalmers Applied Mechanics*, 21 pp (and 2 annexes 1+1 pp)

Stuart Grassie, Roger Lundén, Anders Ekberg, Mats Berg and Sebastian Stichel: Special edition of "Wear" to contain CM2015 proceedings (editorial), *Wear*, vols 366–367, 2016, pp 1–2

Anders Ekberg, Elena Kabo, Roger Lundén and Motohide Matsui: Stress gradient effects in surface initiated rolling contact fatigue of rails and wheels, *ibidem*, pp 188–193 (revised article from conference *CM2015*)

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

Eric Magel, Peter Mutton, Anders Ekberg and Ajay Kapoor: Rolling contact fatigue, wear and broken rail derailments, *ibidem*, pp 249–257 (revised article from conference *CM2015*)

Kalle Karttunen, Elena Kabo and Anders Ekberg: Estimation of gauge corner and flange root degradation from rail, wheel and track geometries, *ibidem*, pp 294–302 (revised article from conference *CM2015*)

Johan Ahlström, Elena Kabo and Anders Ekberg: Temperature-dependent evolution of the cyclic yield stress of railway wheel steels, *ibidem*, pp 378–382 (revised article from conference *CM2015*. Also listed under project MU30)

Niklas Olofsson: Design of experiments for validation of multiaxial high cycle fatigue criteria, MSc Thesis 2017:4, *Chalmers Applied Mechanics*, Gothenburg 2017, 50 pp (and 4 annexes 2+2+2+3 pp)

Michele Maglio: Finite element analysis of thermal fields during repair welding of discrete rail defects, MSc Thesis 2017:17, *Chalmers Applied Mechanics*, Gothenburg 2017, 49 pp (and 1 annex 4 pp. Also listed under project EU16)

Roger Deuce, Anders Ekberg and Elena Kabo: Mechanical deterioration of wheels and rails under winter conditions – mechanisms and consequences, *Proceedings 11th International Heavy Haul Association Conference (IHHA2017)*, Cape Town (RSA) September 2017, 8 pp

David Andersson, Frida Carlvik, Filip Kronvall-Bjelkengren and Oskar Vamling: Riskanalys för järnvägstransporter – en undersökning om förbättringsmöjlighet för tungkontrollkontakt och lastobalans med riskanalys som grund (Risk analysis for railway transportation – an investigation of improved possibilities for switch tongue control contact and load imbalance; in Swedish), BSc Thesis 2018:25, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2018, 48 pp (and 7 annexes 20 pp)

Elena Kabo and Anders Ekberg: Monitoring of track and running gear, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

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* (in printing)

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

MU28. MECHANICAL PERFORMANCE OF WHEEL AND RAIL MATERIALS

Mekaniska prestanda hos hjul- och rälmaterial
Mechanische Güte von Rad- und Schienenwerkstoffen
Performance mécanique des matériaux pour roues et rails

Project leader and supervisor	Professor Johan Ahlström, Industrial and Materials Science / Division of Engineering Materials
Assistant supervisors	Professor Christer Persson and Professor Magnus Ekh, Industrial and Materials Science
Doctoral candidate	Mr Dimitrios Nikas (from 2013-08-15; Lic Eng June 2016; PhD October 2018)
Period	2013-08-15 – 2018-06-30 (– 2018-10-15)
Chalmers budget (excluding university basic resources)	Stage 7: ksek 2200 Stage 8: ksek 2000 (+ 1283 in S2R) Stage 9: ksek 50 (+ 92 in S2R)
Industrial interests in-kind budget	Stage 7: ksek 100 + 50 + 50 + 200 Stage 8: ksek 100 + 50 + 0 + 200 Stage 9: ksek 30 + 20 + 0 + 50 *(Bombardier Transportation + Lucchini Sweden + Trafikverket + voestalpine)*

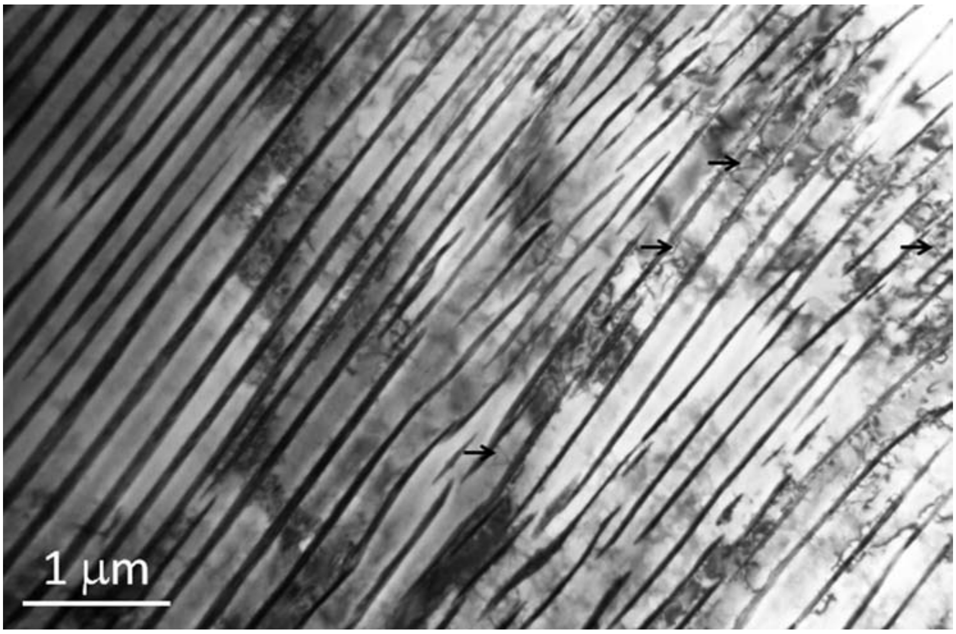
Materials used in wheels and rails are exposed to a complex combination of mechanical and thermal loadings. Understanding the behaviour under this exposure is essential in the design of the components as well as for tuning of traction and braking systems. In project MU28, material properties under realistic conditions have been examined by use of uniaxial and biaxial servohydraulic test frames with capability to perform cyclic mechanical tests at temperatures ranging from –70°C to 750°C. 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.

The first laboratory experiments included evaluation of room temperature hardness changes after exposure to medium and high temperatures from 250°C to 700°C for the ER8T wheel steel, both in its initial state and when prestrained. An increased hardness was observed in the material after exposure to temperatures around 300°C. After heat treatment at higher temperatures, a decreased hardness instead appeared. It was found that cyclically prestrained material softens with about 30% after annealing at 600°C. Microstructural evaluation showed that spheroidization of the pearlite started to become visible at 450°C for the undeformed ER8T material and at around 400°C for the prestrained material and that it correlates with the measured change in hardness.

Uniaxial low cycle fatigue (LCF) experiments at elevated temperatures were made with the wheel steel ER7T that is frequently used in block-braked wheels. The cyclic hardening and softening observed after elevated temperature exposure agreed with the static hardening and softening observed for the ER8T material. Additional LCF experiments with hold times showed a rapid recovery in mechanical behaviour after the hold time. Only the very first cycle after each hold time deviates to a remarkable degree; thereafter stresses lie within a few percent of the stabilized stress-strain loop before the hold time. Initial hold times show less viscous behaviour compared to hold times after cyclic deformation. In another set of stress-controlled high temperature LCF tests, strain rates were varied to further characterize the viscoplastic behaviour, and a mean stress was added to examine ratchetting at different temperatures. These experimental findings help with the calibration of the material model that is developed in the parallel project

From the left: Jens Karlström, Reinhard Pippan, Christer Persson, Ru Peng, Dimitrios Nikas, Johan Ahlström and Håkan Johansson after the doctoral examination in project MU28 on 18 October 2018

MU28. (cont'd)



Early example in project MU28 of observed initial microstructure in test bars of the fully pearlitic R260 rail steel. Alternating ferrite and cementite lamellae are seen. Black arrows show dislocation structures in the ferrite. Average size of a pearlitic colony was 8 μm and the interlamellar spacing was around 230 nm. Test bars were later biaxially deformed (imitating shear strain in the surface layer of rails in field) and the material´s decreased lamellar thickness, higher dislocation density and increased hardness were measured. Standard grinding, electropolishing and etching were used to prepare specimens for investigation in a JEOL 2000FX TEM at 200 kV

MU32. Initial biaxial testing of ER7T wheel steels at the elevated temperatures 200 – 400°C showed an increased strain hardening on out-of-phase loading as compared to uniaxial in-phase loading.

Another study using Electron BackScattered Diffraction (EBSD) technique was done for the material ER8T to examine the degradation of the pearlitic microstructure with respect to temperature and grain orientation. Pearlite colonies appear to have orientation gradients presumably both from predeformation and from initial formation of the pearlite, while ferrite grains have a more uniform orientation. Spheroidized pearlite colonies appear to have lost their initial orientation gradients and obtained a more uniform orientation after spheroidization. A higher annealing temperature introduces more subgrain boundaries in the material, mostly in the pearlite colonies.

In collaboration with project MU34, deformed material produced by torsion straining of test bars under parallel static compression was compared with deformed surface layers from used rails. The materials were examined using microhardness and Scanning Electron Microscopy (SEM). In collaboration with Risø DTU in Denmark, a closer examination of the material deformed in the laboratory was done using Transmission Electron Microscopy (TEM) in order to provide a more detailed understanding of material microstructure development during plastic straining. In the analysis of the TEM images, dislocation density was measured and found to increase with increasing strain. Using models of boundary and dislocation strengthening, a good agreement with measured strength via the microhardness technique was achieved.

Dimitrios Nikas successfully defended his doctoral dissertation (see below) on 18 October 2018 with Professor Reinhard Pippan from University of Leoben in Austria as the faculty-appointed external examiner. Members of the grading committee (see photo) were Professor Jens Bergström of Karlstad University, Professor Ru Peng of Linköping University and Docent Håkan Johansson of Chalmers. The joint reference group for projects MU28, MU29, MU30 and MU32 had members from Trafikverket, Bombardier Transportation (in Germany/Siegen and Sweden), Lucchini Sweden, SNC-Lavalin, SJ and SL. Project MU28 has also been presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen and voestalpine VAE, see page 71. The research plan for project MU28 is dated 2013-03-23.

Dimitrios Nikas, Johan Ahlström and Amir Malakizadi: Mechanical properties and fatigue behaviour of railway wheel steels as influenced by mechanical and thermal loading, *Wear*, vols 366-367, 2016, pp 407–415 (also listed under project MU30)

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, 012 1035, 7 pp (also listed under projects MU30 and MU34)

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, no 1, 2018, pp 12-21 (also listed under projects MU30 and MU34)

Dimitrios Nikas: Influence of combined thermal and mechanical loadings on pearlitic steel microstructure in railway wheels and rails, Doctoral Dissertation, *Chalmers Industrial and Materials Science*, Gothenburg October 2018, 110 pp (Summary and five appended papers)

MU29. DAMAGE IN WHEEL AND RAIL MATERIALS

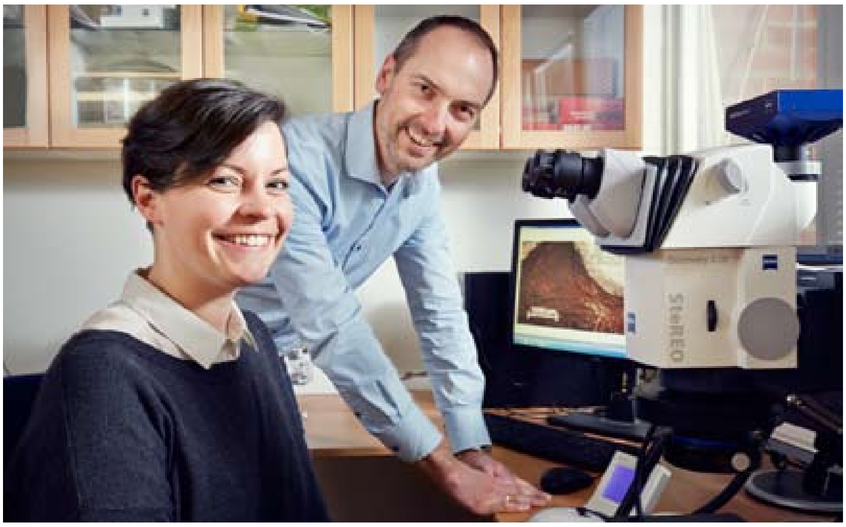
Skador i hjul- och rälmaterial
Schäden in Rad- und Schienenwerkstoffen
Endommagements des matériaux des roues et rails

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)
Period	2014-02-10 – 2018-06-30 (– 2019-06-30)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 1570 Stage 8: kSEK 2400 (+ 678 in S2R) Stage 9: kSEK 300 (+ 737 in S2R)
Industrial interests in-kind budget	Stage 7: kSEK 100+15+50+50+200 Stage 8: kSEK 100 + 15 + 50 + 0+200 Stage 9: kSEK 50 + 15 + 50 + 0+50 *(Bombardier Transportation + Interfleet Technology/SNC-Lavalin + Lucchini Sweden + Trafikverket + voestalpine)*

Cracks in wheel and rail components affect both costs and reliability of the railway system and an understanding of the mechanisms of crack initiation and crack propagation is therefore crucial. This includes both how climatic conditions alter the friction between crack faces and the influence of the material properties. In project MU29, field samples have been studied and laboratory experiments done better to understand crack initiation and crack growth. Using a biaxial testing machine with a climate chamber, cracks are being propagated under realistic loading conditions and at varying climatic conditions. The findings will help when formulating, calibrating and verifying suitable numerical models for crack initiation and crack propagation within parallel CHARMEC projects.

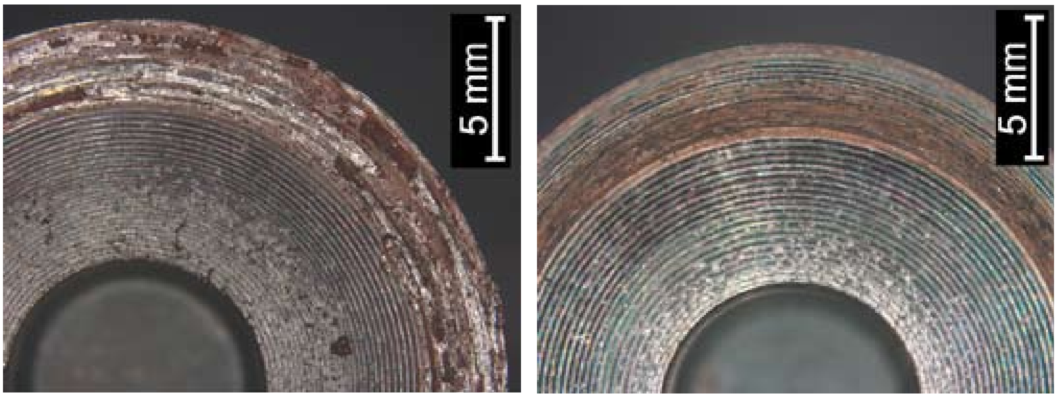
An X-ray radiography study was performed on a rail section with a squat (see project MU31) taken from the field. The aim was to observe the network of cracks associated to the squat and to investigate the ability of radiography and image analysis to detect crack extension and crack geometry. Combining the exposures from a range of angles using geometrical reconstruction, a method was developed to try to render a 3D representation of the complete and complex crack network. Metallographic sectioning was later carried out to determine the accuracy of prediction of the geometrical reconstruction. A 3D reconstruction was obtained and comparisons to the metallographic sectioning showed accurate geometry at medium depths, though the crack tip was not visible due to limitations of the radiography in terms of detecting tightly closed cracks. Also, the actual crack extended farther laterally than what could be detected from the 3D reconstruction. The conclusion from the investigation is that the method is not sufficiently reliable for field measurements when judging whether a rail section needs to be replaced, as it is non-precise in estimating the crack extension. In case the cracks are too tightly closed, or oriented in an unfavourable angle for detection, the method might thus fail to detect or misjudge the extension of the crack network.

Further characterization studies on the squat crack network were done using optical, stereo and scanning electron microscopy to measure global geometry and local topology. The different methods to geometrically describe the squat crack network proved to be complementary to one another; observations made using one method could sometimes explain the limitations and shortcomings of others. It was found that a combination of the methods could provide an accurate description of the network geometry.



PhD student Casey Jessop (licentiate gained in March 2017) and her supervisor Docent (now Professor) Johan Ahlström in project MU29. A squat sample is being examined in a stereo microscope, see also photo on page 39. Photo taken in 2016

MU29. (cont'd)



Result of experiments in project MU29 with friction between pearlitic steel surfaces mimicking the situation occurring between the two rubbing surfaces of a rolling contact fatigue crack. The calculated average friction coefficient was 0.68 and 0.40, respectively, for the dry (left) and wet (right) case. From CM2018 paper below

Damage initiation experiments were carried out using our biaxial testing machine for 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. Residual stress measurements by X-ray diffraction were continued on field samples and test bars to be used for fatigue testing. As expected, the main effect of initial thermal damage on the test bars was a decrease of the fatigue life. The stress evolution was similar for all tests performed with the same constant strain amplitude. Failure occurred at the level of the WEL and at the extensometer indents for the test bars with and without WEL spots, respectively.

A general trend observed in the residual stress analysis of rails subjected to laser heating experiments is the presence of high tensile stresses just outside the WEL spot and compressive stresses in the bulk material. This variation was more pronounced in new rails but with a scatter between the different samples. Electropolishing is required to remove the texture from grinding in the topmost layer, since the X-ray method only gathers information from the topmost 5–10 microns. Anyhow, the trend remains the same after electropolishing of the rail sections.

Experiments to investigate crack face friction between two R260 rail steel surfaces in different combinations of compression and torsional loading were performed (see figure), and complements done under different climatic conditions are planned for. A literature study showed that little similar work had been reported. Suitable test specimens and a temperature cabinet were designed. Crack face friction at ambient temperature was found to be direction dependent, especially for low axial compressive loads. The results will further be used for analysis of fatigue experiments with biaxial loading. Crack propagation experiments using different test bar geometries and loading conditions are planned.

X-ray tomography experiments were performed in collaboratory work with Technical University of Denmark (DTU) to identify void formation and coalescence in the centre of test bars subjected to tension until the appearance of necking. The test bars with internal voids will be used in biaxial fatigue tests with the aim being to propagate an internal crack in shear (cf stud/squat crack propagation). During spring 2018, Casey Jessop was supported by an EU InterReg project which enabled further tomography and synchrotron studies of void and crack formation in rail steels in collaboration with DTU.

Casey Jessop gained her licentiate degree after a seminar 2017-03-03 on her thesis (see below) with Dr Kamellia Dalaei of ESAB Sverige AB acting as discussion leader. For the joint reference group, see under project MU28. The research plan for project MU29 is dated 2013-03-23.

Casey Jessop: Damage and thermally induced defects in railway materials, Licentiate Thesis, *Chalmers Materials and Manufacturing Technology*, Gothenburg March 2016, 37 pp (Summary and two appended papers)

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 (also listed under project MU30)

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 (LCF8)*, Dresden (Germany) June 2017, DVM Berlin 2017, pp 275–280 (also listed under project MU30)

Casey Jessop, Johan Ahlström, Lars Hammar, Søren Fæster and Hilmar Danielsen: 3D characterization of RCF crack networks, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

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 (also listed under project MU30)

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

Modellering av egenskaper och skador i hjul- och rälmaterial
Modellierung von Eigenschaften und Schäden in Rad- und Schienenwerkstoffen
Modélisation des propriétés et endommagements des matériaux des roues et rails

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	2013-04-01 – 2018-06-30 (– 2021-06-30)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 1 290 Stage 8: kSEK 1 275 (+ 229 in S2R) Stage 9: kSEK 450 (+ 1 800 in S2R)
Industrial interests in-kind budget	Stage 7: kSEK 50 + 15 + 50 + 50 + 200 Stage 8: kSEK 50 + 15 + 50 + 0 + 200 Stage 9: kSEK 50 + 15 + 50 + 0 + 150 *(Bombardier Transportation + Interfleet Technology / SNC-Lavalin + Lucchini Sweden + Trafikverket + voestalpine)*

For a photo of Johan Ahlström, see page 40

This senior research project was started as a complement to the doctoral projects MU28 and MU29. An important part of project MU30 is the modelling of combined mechanical and thermal damage in the surface layer of wheels and rails in order better to understand crack initiation. Another key ingredient is to help interpret the experimental results from projects MU28 and MU29 and implement these in numerical models of suitable complexity for the problems at hand. Accurate yet efficient material models are crucial for simulation of material deformation and of crack formation and growth.

The thermal damage in the wheel/rail surface layer because of repeated slipping due to, for example, malfunctioning WSP devices has been studied. The observed localized discontinuities in material strength and large stress gradients are supposed to form potential initiation sites for RCF (rolling contact fatigue) cluster cracks and also squat-type cracks. Our calculated residual stress fields and altered material properties after thermal loadings are intended as a starting condition for crack modelling. In collaboration with project MU31, simulations of thermally induced squat-like cracks and crack clusters were done with a simplified phase transformation model. The results shed light on reasons for initiation of cracks close to a White Etching Layer (WEL); especially off-centre contact passages resulted in extensive fatigue damage.

A collaboration with project MU32 was started to improve the full model of phase transformation and thermal damage developed in projects MU23 and MU30 and to enable more accurate strength and stress predictions. The Fortran code used for the FE simulation in ABAQUS was transferred to a UMAT subroutine, combined with advanced material constitutive models. During the MU30 project, the biaxial test rig was specified, purchased, installed and used for predeformation, biaxial testing and friction studies. The test results are judged to be crucial for the understanding of material behaviour in rails and wheels.

New tools for analysis of experimental results have been launched. An analysis program (MATLAB script) was developed to convert test data into a more condensed format by part-wise polynomial description of the hysteresis loops and to use these parameterized data to estimate the degree of microplasticity. Also, the program was developed further to handle tests with hold times, and to compensate for thermal strains due to adiabatic heating on plastic deformation during the test. Finally, the script was developed to analyse cyclic flow stress development, needed for fatigue damage evaluation in collaboration with project MU22. One result is that hold times do not have a large effect on continued cycling and that there is a rather large influence of temperature on cyclic hardening and softening. Different strain amplitudes exhibit similar response to elevated temperature. This leads to the conclusion that the single most important factor to consider for an RCF criterion is the temperature during deformation.

During the MU30 project, a new collaboration with the Technical University of Denmark (DTU) was established. Part of the effort was to co-supervise a doctoral student at DTU, Somrita Dhar, who stayed for a three months period at Chalmers during spring 2018 and did biaxial fatigue experiments on materials from crossing noses made of manganese steels, and on pearlitic material. The fatigued material is now analysed by use of Transmission Electron Microscopy (TEM). Johan Ahlström was co-supervisor of two EU InterReg projects supporting Somrita Dahr's work on measuring residual stresses in crossing noses. The co-operation with DTU has improved the possibilities for in-depth characterization of deformed surface layers of rails using X-ray tomography, TEM and synchrotron. For the joint reference group, see under project MU28. The research plan for project MU30 is dated 2013-03-23.

MU30. (cont'd)

Johan Ahlström: Residual stresses generated by repeated local heating events – Modelling of possible mechanisms for crack initiation, *Wear*, vols 366–367, 2016, pp 180–187

Johan Ahlström, Elena Kabo and Anders Ekberg: Temperature-dependent evolution of the cyclic yield stress of railway wheel steels, *ibidem*, pp 378–382 (also listed under project MU22)

Dimitrios Nikas, Johan Ahlström and Amir Malakizadi: Mechanical properties and fatigue behaviour of railway wheel steels as influenced by mechanical and thermal loading, *ibidem*, pp 407–415 (also listed under project MU28)

Casey Jessop, Johan Ahlström, Lars Hammar, Søren Fæster and Hilmar Danielsen: 3D characterization of rolling contact fatigue crack networks, *ibidem*, pp 392–400 (also listed under project MU29)

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 project MU29)

Ali Esmaeili, Mandeep Singh Walia, Kazuyuki Handa, Katsuyoshi Ikeuchi, Magnus Ekh, Tore Vernersson and Johan Ahlström: A methodology to predict thermomechanical cracking of railway wheel treads – From experiments to numerical predictions, *International Journal of Fatigue*, vol 105, 2017, pp 71–85 (also listed under projects MU32 and SD10)

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, 012 1035, 7 pp (also listed under projects MU28 and MU34)

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, no 2018, pp 12–21 (also listed under projects MU28 and MU34)

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*, vols 130-131, 2018, pp 122–132 (also listed under project MU34)

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 (also listed under project MU31)

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 (also listed under project MU29)

Participants in 20th Nordic Seminar on Railway Technology at Chalmers on 12–13 June 2018, see page 73

MU31. SQUATS IN RAILS AND RCF CLUSTERS ON WHEELS

Squats på räler och lokala sprickanhopningar på hjul
Squats auf Schienen und Nester von RCF auf Rädern
Squats et défauts de fatigue de roulement en colonie

Project leader and supervisor	Professor Elena Kabo, Mechanics and Maritime Sciences / Division of Dynamics
Assistant supervisors	Professor Fredrik Larsson, Industrial and Materials Science, and Professor Anders Ekberg and Dr Peter Torstensson, Assistant Professor, Mechanics and Maritime Sciences
Doctoral candidate	Mr Robin Andersson (from 2013-04-08; Lic Eng June 2015; PhD June 2018)
Period	2013-04-08 – 2018-06-30
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 2325 Stage 8: KSEK 2307 (+ 1076 in S2R)
Industrial interests in-kind budget	Stage 7: KSEK 50 + 100 + 200 + 300 Stage 8: KSEK 50 + 100 + 0 + 300 *(Bombardier Transportation + Green Cargo + Trafikverket + voestalpine)*

Squats in rails and rolling contact fatigue (RCF) clusters that emanate from isolated defects on the wheel surface are starting to reach epidemic proportions in Europe including Sweden. The problem is exacerbated by the ongoing introduction of more aggressive operational patterns (higher loads, higher acceleration, heavier braking etc). Despite significant research efforts, for instance in the INNOTRACK project (our EU10), there is still a fundamental lack of knowledge of underlying mechanisms, influencing factors and (cost) efficient mitigation measures. Project MU31 aimed to forward the understanding of the phenomena of squats (and studs) and RCF clusters through numerical simulations. This has been carried out in connection to other projects both within CHARMEC (e g, projects MU28–30 and MU32–33) and internationally (both at industrial partners and at universities/research institutes/infrastructure managers).

Project MU31 set out from, and continuously compared results against, operational experiences. Focusing on understanding and quantifying the phenomena, the project has incorporated detailed studies of the parametric influence of operational parameters on plastic deformation, crack formation and crack growth from local defects. Increased dynamic loads and contact stresses due to surface irregularities etc have been considered. The 3D computational framework for mapping dynamic contact stresses in a wheel–rail contact onto a finite element (FE) model (created in the commercial software ABAQUS) has been developed based on our previously developed 2D computational framework. The major change is that wheel–rail contact conditions in 3D are now fully supported in the dynamic vehicle–track interaction analysis and that 3D contact stresses are mapped onto a 3D FE model.

The continued focus in the project was on 3D modelling of surface-breaking circular cracks in the railhead and evaluation of stress intensity factors (SIFs) by the extended FE method XFEM using ABAQUS. The analysis of this squat-like crack loaded by Hertzian contact pressure resulted in calculated negative mode I SIFs. To mitigate these non-physical results, several new approaches have been studied. They employ a comparison of analytical asymptotic expres-

From the left: Elias Kassa, Fredrik Larsson, Elena Kabo, Robin Andersson, Richard Stock, Rickard Nilsson, Peter Torstensson, Johan Ahlström and Anders Ekberg after the doctoral examination in project MU31 on 8 June 2018

MU31. (cont'd)

Typical squat-like defect found on a metro line rail in Stockholm (Sweden). Two distinct lobes are visible. Also note the V-shaped surface breaking crack and the slight widening of the running band. Photo by Robin Andersson

Typical rolling contact fatigue (RCF) cluster on a wheel tread. Photo by Robin Andersson

sions of the displacement and stress fields around the crack front against displacements obtained by FE analysis. The quality of the different approaches has been evaluated for simple (handbook) problems as well as for the squat crack. The new method for FE based SIF evaluation was validated against cases in different crack deformation modes and it has shown both efficiency and convergence and has yielded more accurate results than those obtained from the ABAQUS internal SIF evaluation technique. Different operational scenarios in relation to RCF cracks in railheads have been investigated.

A study on the influence of White Etching Layers (WELS) on stud and RCF cluster initiation was performed. A WEL of a specific size under the effect of a wheel passage was investigated and WELS on both rails and wheels were considered. Effects of high and low axle loads as well as high and low friction were investigated by a 3D FE analysis using ABAQUS. Here, material phase transformation is modelled by use of ABAQUS' Fortran subroutines and the resulting damage is assessed by the Jiang-Sehitoglu fatigue parameter. Both the bulk material and the interface between the martensite and pearlite structures are investigated. The results showed that WELS produce relatively high compressive stresses. The friction coefficient seems to be an influential parameter regarding crack initiation also in the presence of a WEL. The crack initiation criterion alone does not seem to explain why stud cracks tend to grow across rather than along the rail.

The MU31 project was completed with Robin Andersson's successful defence in public of his doctoral dissertation on 8 June 2018. The faculty-appointed external examiner of the dissertation was Dr Richard Stock from the company LINMAG GmbH in Vancouver (Canada). Members of the grading committee (see photo) were Professor Elias Kassa of NTNU in Trondheim, Norway, and Dr Rickard Nilsson of SLL in Stockholm. Robin Andersson has now returned to consultant work at ÅF in Gothenburg.

For the joint reference group, see under project MU22. Project MU31 was continuously presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen and VAE, and CHARMEC, see page 71. The research plan for project MU31 is dated 2013-04-04. The present project had support from Elena Kabo and Anders Ekberg also through project MU22.

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 (also listed under project TS16)

Robin Andersson, Fredrik Larsson, Elena Kabo and Anders Ekberg: Stress intensity factor evaluation for rolling contact fatigue cracks, *Proceedings 30th Nordic Seminar on Computational Mechanics (NSCM-30)*, Kgs Lyngby (Denmark) October 2017, 2 pp

Robin Andersson: Squat defects and rolling contact fatigue clusters – Numerical investigations of rail and wheel deterioration mechanisms, Doctoral Dissertation, *Chalmers Industrial and Materials Science*, Gothenburg June 2018, 167 pp (Summary and six appended papers)

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 (also listed under project MU30)

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

MU32. MODELLING OF THERMOMECHANICALLY LOADED RAIL AND WHEEL STEELS

Modellering av termomekaniskt belastade stål i räler och hjul
Modellierung von thermomechanisch beanspruchten Stählen in Schienen und Rädern
Modélisation des aciers sous chargement thérmomecanique dans les rails et les roues

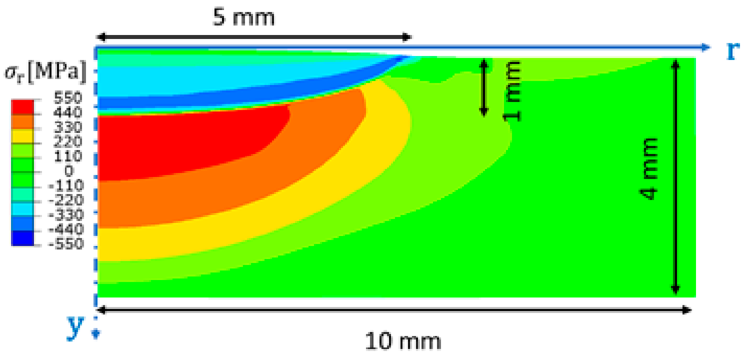
Project leader and supervisor	Professor Magnus Ekh, Industrial and Materials Science / Division of Material and Computational Mechanics
Assistant supervisors	Docent Tore Vernersson, Mechanics and Maritime Sciences, and Professor Johan Ahlström, Industrial and Materials Science
Doctoral candidate	Mr Ali Esmaeili (from 2013-12-13; Lic Eng December 2016; PhD January 2019)
Period	2013-12-13 – 2018-06-30 (– 2019-01-30)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1470 Stage 8: KSEK 2200 (+ 965 in S2R) Stage 9: KSEK 240 (+ 180 in S2R)
Industrial interests in-kind budget	Stage 7: KSEK 100+100+100+50+200 Stage 8: KSEK 100+100+100+0+200 Stage 9: KSEK 0+30+30+0+50 *(Bombardier Transportation + Faiveley Transport + Lucchini Sweden + Trafikverket + voestalpine)*

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. At the same time the temperature may increase due to frictional heat generated between wheel and rail or between wheel and brake blocks at tread braking, and this further complicates the loading situation. Additional material response types and deterioration phenomena may come into play. The main goal of project MU32 has been to improve modelling of the cyclic behaviour of wheel and rail materials subjected to mechanical and thermal loadings. The work has been conducted in close collaboration with project MU28 where experiments have been performed on pearlitic steels at elevated and varying temperatures for uniaxial as well as compression–torsional loading. The present project also interacted with project SD10 where the rolling contact between wheel and rail is simulated with focus on the impact on RCF (rolling contact fatigue) from the temperature increase due to tread braking.

Thermal cracking of railway wheel treads has been investigated, using a combined experimental and numerical approach, in collaboration with a research group at Railway Technical Research Institute (RTRI) in Tokyo (Japan). The experimental results at RTRI were produced from controlled brake rig tests of repeated stop braking cycles of a

PhD student Ali Esmaeili (in white) together with (from the left) Professor Johan Ahlström, Docent Tore Vernersson and Professor Magnus Ekh

MU32. (cont'd)



Residual radial stresses in the wheel (as calculated in a local rotationally symmetric model) after two sequential wheel flat loadings with tensile radial stresses being obtained where the pearlite has transformed to tempered martensite

railway wheel in rolling contact with a so-called rail-wheel, see photo on page 49. The test conditions were numerically analysed by us using finite element (FE) simulations of the wheel–rail and brake block–wheel interaction which account for the thermomechanical loading of the wheel tread. The simulations were performed utilizing a material model for the wheel that was calibrated against isothermal (up to 625 °C) experimental data for cyclic loading and relaxation (low strain rates) as well as against data from high strain rate tests.

Material behaviour at wheel flat formation has also been studied. Wheel flats are formed during short term local heating events such as when a railway wheelset skids along the rail. The consequent temperature increase can be severe and may result in phase transformations in pearlitic rail and wheel steels. The differences in thermal expansion, density and mechanical properties of the phases result in residual stresses and cause thermal damage in rail and wheel steels. Research work building on previous work in projects MU2, MU3, MU23 and MU30 has been conducted to enhance modelling of the phase transformation kinetics combined with cyclic plasticity of the phases. A sequential (uncoupled) thermal and mechanical FE analysis has been performed to compute residual stresses near the wheel–rail contact after being subjected to two sequential wheel flat loadings, see figure.

Ali Esmaeili presented his licentiate thesis (see below) at a seminar on 16 December 2016 with Professor Mathias Wallin from Lund University introducing the discussion. Project MU32 was concluded with Ali Esmaeili's successful defence in public of his doctoral dissertation (see below) on 10 January 2019. Here Dr David Fletcher from the Department of Mechanical Engineering at the University of Sheffield in the UK acted as the faculty-appointed external examiner. The joint reference group for projects MU28, MU29, MU30, MU32 and MU34 has members from Bombardier Germany, Lucchini Sweden, voestalpine Schienen, Trafikverket and SJ. The research plan for project MU32 is dated 2013-12-13.

Mandeep Singh Walia, Ali Esmaeili, Tore Vernersson and Roger Lundén: Thermomechanical capacity of wheel treads at stop braking: A parametric study, *International Journal of Fatigue*, vol 113, 2018, pp 407-415 (also listed under project SD10)

Ali Esmaeili, Mandeep Singh Walia, Kazuyuki Handa, Katsuyoshi Ikeuchi, Magnus Ekh, Tore Vernersson and Johan Ahlström: A methodology to predict thermomechanical cracking of railway wheel treads – From experiments to numerical predictions, *International Journal of Fatigue*, vol 105, 2017, pp 71-85 (also listed under projects MU30 and SD10)

Ali Esmaeili: Modelling of cyclic and viscous behaviour of pearlitic steels – Application to tread braked railway wheels, Licentiate Thesis, *Chalmers Materials and Manufacturing Technology*, Gothenburg December 2016, 68 pp (Summary and three appended papers)

Ali Esmaeili, Magnus Ekh, Tore Vernersson and Johan Ahlström: Modelling of thermomechanically loaded rail and wheel pearlitic steels, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

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

Ali Esmaeili: Modelling of cyclic and viscous behaviour of thermomechanically loaded pearlitic steels – Application to tread braked railway wheels, Doctoral Dissertation, *Chalmers Industrial and Materials Science*, Gothenburg January 2019, 147 pp (Summary and five appended papers)

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

Simulering av spricktillväxt i räl under rullkontaktutmattning
Simulation von Risswachstum in Schienen unter Rollkontaktermüdung
Simulation de la propagation de fissure dans les rails sous fatigue de contact de roulement

Project leader and supervisor	Professor Fredrik Larsson, Industrial and Materials Science / Division of Material and Computational Mechanics
Assistant supervisors	Professor Anders Ekberg, Mechanics and Maritime Sciences, and Professor Kenneth Runesson, Industrial and Materials Science
Doctoral candidate	Mr Dimosthenis Floros (from 2014-01-15; Lic Eng November 2016; PhD January 2019)
Period	2014-01-15 – 2018-06-30 (– 2019-01-30)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 1 350 Stage 8: kSEK 2 000 (+ 1 156 in S2R) Stage 9: kSEK 200 (+ 219 in S2R)
Industrial interests in-kind budget	Stage 7: kSEK 50 + 50 + 200 Stage 8: kSEK 0 + 0 + 200 Stage 9: kSEK 0 + 0 + 100 *(SL + Trafikverket + voestalpine)*

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

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 railway steel where large inelastic deformations develop. The 3D geometry of the cracks, the compressive stress/strain field with rotating principal directions, the interaction between adjacent cracks (crack shielding) and material anisotropy are points that complicate 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 (e g, MU17, MU20 and MU22) for establishing reliable criteria for crack propagation. More specifically, project MU33 aimed at the development of a numerical tool for qualitative and quantitative assessment of the evolution of RCF cracks accounting for various parameters such as crack geometry, rolling contact conditions, anisotropy, large inelastic deformations and wear rates. In the previous 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 work concerned the suitability of different fatigue crack models. In an introductory study, a 3D numerical model of cracked tubular specimens subjected to tension and torsion was analysed to study the effect of (static or variable) torsion on crack growth. Numerical simulations of crack growth in combined tension/torsion show the key role of plastic deformations in suppressing crack growth in the presence of static torsion. These results are in agreement with the behaviour observed in experiments as described in the literature.

The suitability of a large set of fatigue crack growth criteria with respect to fatigue crack growth direction (and kinking) has been evaluated for a set of benchmark problems. Criteria based on LEFM as well as more elaborate criteria for elastoplastic fracture mechanics have been considered. Reported 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 evaluate the suitability of these criteria under relevant RCF conditions pertinent to railway traffic, twin disc experiments have been considered.

Dimosthenis Floros presented his licentiate thesis at a seminar on 25 November 2016 (see below) where Professor Bo Alfredsson from the Royal Institute of Technology (KTH) in Stockholm was invited as discussion leader. Project

MU33. (cont'd)

MU33 was concluded with Dimosthenis Floros' successful defence in public of his doctoral dissertation (see below) on 18 January 2019. Here Professor Bo Alfredsson again took part and now acted as the faculty-appointed external examiner.

For the joint reference group, see under project MU22. Project MU33 was also continuously presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen, voestalpine VAE and CHARMEC, see page 71. The research plan for project MU33 is dated 2014-04-03.

Dimosthenis Floros, Anders Ekberg and Kenneth Runesson: A numerical investigation of elastoplastic deformation of cracks in tubular specimens subjected to combined torsional and axial loading, *International Journal of Fatigue*, vol 91, Part 1, 2016, pp 171-182

Dimosthenis Floros, Fredrik Larsson and Kenneth Runesson: Computation of material forces based on a gradient enhanced mixed variational formulation, *Proceedings 29th Nordic Seminar on Computational Mechanics (NSCM-29)*, Gothenburg (Sweden) October 2016, 4 pp

Dimosthenis Floros: The effect of inelastic deformation on crack loading, Licentiate Thesis, *Chalmers Applied Mechanics*, Gothenburg November 2016, 93 pp (Summary and two appended papers)

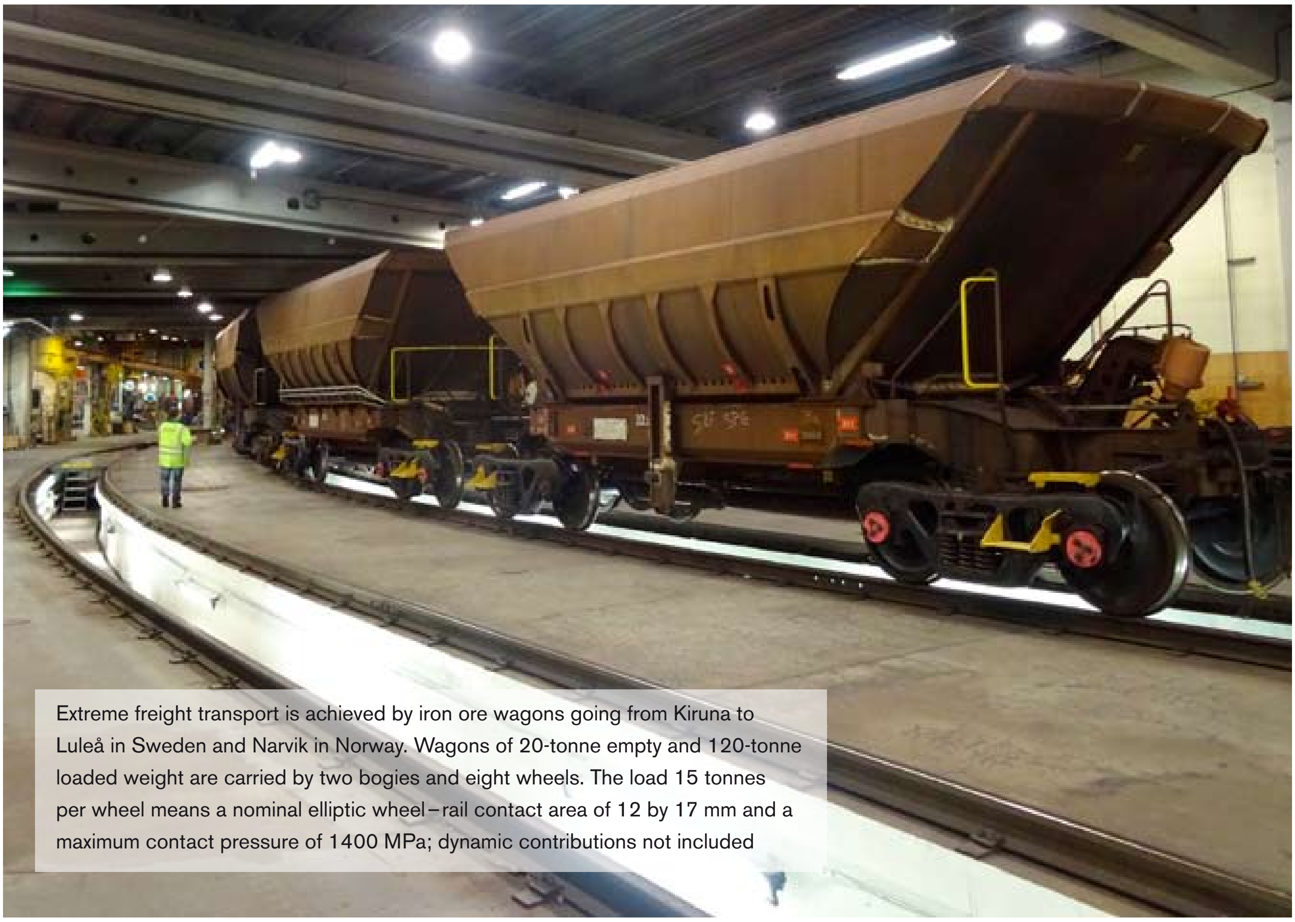
Dimosthenis Floros, Fredrik Larsson and Kenneth Runesson: Computation of configurational forces for gradient-enhanced inelasticity, *Proceedings XIV International Conference on Computational Plasticity – Fundamentals and Applications (COMPLAS 2017)*, Barcelona (Spain) September 2017 (abstract and oral presentation)

Dimosthenis Floros, Fredrik Larsson, Anders Ekberg and Kenneth Runesson: Evaluation of mixed mode crack growth criteria, *Proceedings 30th Nordic Seminar on Computational Mechanics (NSCM-30)*, Kgs Lyngby (Denmark) October 2017, pp 62-65

Dimosthenis Floros, Fredrik Larsson and Kenneth Runesson: On configurational forces for gradient-enhanced inelasticity, *Computational Mechanics*, vol 61, no 4, 2018, pp 409-432

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

Dimosthenis Floros: Finite element procedures for crack path prediction in multi-axial fatigue, Doctoral Dissertation, *Chalmers Industrial and Materials Science*, Gothenburg January 2019, 146 pp (Summary and five appended papers)



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

MU34. INFLUENCE OF ANISOTROPY ON ROLLING CONTACT FATIGUE CRACKS

Inverkan av anisotropi på utmattningsprickor under rullkontakt
Einfluss von Anisotropie auf Ermüdungsrisse unter Rollkontakt
Influence de l´anisotropie sur les fissures en fatigue de contact de roulement

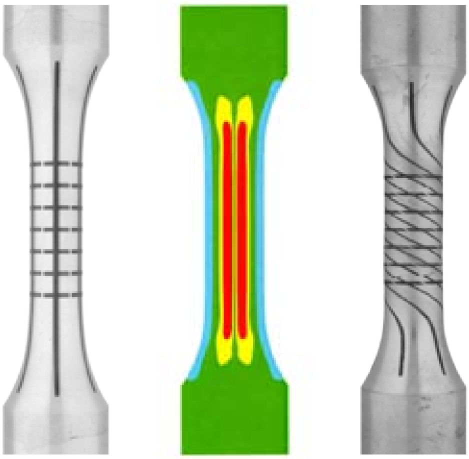
Project leader and supervisor	Professor Magnus Ekh, Industrial and Materials Science / Division of Material and Computational Mechanics
Assistant supervisor	Professor Johan Ahlström, Industrial and Materials Science
Doctoral candidate	Mr Knut Andreas Meyer (from 2015-05-18; Lic Eng October 2017)
Period	2015-05-18 – 2018-06-30 (– 2020-05-31)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 150 Stage 8: KSEK 2500 (+ 1 181 in S2R) Stage 9: KSEK 500 (+ 1 254 in S2R)
Industrial interests in-kind budget	Stage 7: KSEK 25 + 50 + 110 Stage 8: KSEK 0 + 0 + 110 Stage 9: KSEK 0 + 0 + 200 *(SL + Trafikverket + voestalpine)*

From the left: Professor Magnus Ekh, Professor Johan Ahlström and PhD student Knut Andreas Meyer (licentiate gained in October 2017) standing at the biaxial testing machine used in project MU34

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 a rail or wheel material. Microhardness and 3D head check crack geometry analyses of the surface layer of a rail (from field) were conducted in project MU24 and the modelling of anisotropic evolution and response of highly deformed pearlitic steel was developed in project MU19.

The modelling was validated against wire-drawing results from the literature as well as against high-pressure torsion tests and micropillar tests performed at Erich Schmid Institute in Leoben (Austria). A new biaxial axial-torsion testing machine at Chalmers Industrial and Materials Science (formerly Materials and Manufacturing Technology) makes it possible to perform laboratory tests on rail and wheel materials in more realistic loading conditions than earlier. Aims of project MU34 have been (i) to find ways to produce anisotropy (by predeformation) of the rail material similar to what is found in rails in field, (ii) to determine the multiaxial cyclic behaviour of rail steel in the biaxial testing machine, (iii) to utilize and further develop cyclic material models from, e g, project MU19, that take anisotropy into account, and (iv) to analyse crack initiation and formulate crack initiation criteria. The ultimate goal is to increase the understanding of the role of the microstruc-

MU34. (cont'd)



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

ture development in different rail materials subjected to realistic traffic loading conditions.

A method for producing a material with the same properties as 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. It was concluded that the resulting material closely resembles what is found in used R260 rails at a depth between 50 and 100 µm below the surface. In order to model this behaviour, existing theoretical frameworks of large strain plasticity and kinematic hardening have been evaluated and new ones proposed.

The advantage with the predeformation method developed in the present project 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. This has been used to characterize the yielding behaviour at different depths in the rail. As expected, it was found that both the size of the yield surface and the degree of anisotropy 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.

Knut Andreas Meyer presented his licentiate thesis (see below) at a seminar on 6 October 2017 where Professor Andreas Menzel from TU Dortmund University introduced the discussion. For the joint reference group, see under project MU32. Furthermore, project MU34 is continuously being presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen, voestalpine VAE and CHARMEC, see page 71. The research plan for project MU34 is dated 2014-01-30.

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

Knut Andreas Meyer: Modeling and experimental characterization of pearlitic rail steels subjected to large biaxial strains, Licentiate Thesis, *Chalmers Industrial and Material Science*, Gothenburg September 2017, 66 pp (Summary and three appended papers)

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, 012 1035, 7 pp (also listed under projects MU28 and MU30)

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 (also listed under project MU30)

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, 2018, pp 12–21 (also listed under projects MU28 and MU 30)

Knut Andreas Meyer, Johan Ahlström and Magnus Ekh: Investigation of material properties of the surface layer of rails, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

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

Chalmers Johanneberg campus

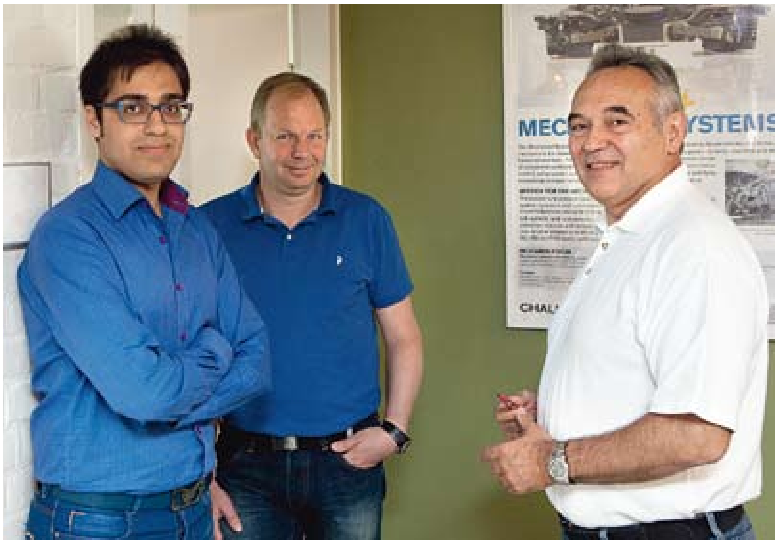
SD9. MULTIOBJECTIVE OPTIMIZATION OF BOGIE SYSTEM AND VIBRATION CONTROL

Flermålsoptimering av boggisystem och vibrationskontroll
Optimierung von Drehgestellsystem unter mehrfacher Zielsetzung und Schwingungskontrolle
Optimisation par objectifs multiples du système de bogie et contrôle des vibrations

Project leader and supervisor	Professor Viktor Berbyuk, Mechanics and Maritime Sciences/ Division of Dynamics
Assistant supervisor	Professor Mikael Enelund, Mechanics and Maritime Sciences
Doctoral candidate	Mr Milad Mousavi (from 2011-11-01; Lic Eng June 2014; PhD September 2016)
Period	2011-07-01 – 2017-06-30
Chalmers budget (excluding university basic resources)	Stage 6: kSEK 575 Stage 7: kSEK 2 790 Stage 8: kSEK 1 695
Industrial interests in-kind budget	Stage 6: kSEK 0 + 0 + 0 Stage 7: kSEK 200 + 15 + 50 Stage 8: kSEK 200 + 15 + 0 *(Bombardier Transportation + Interfleet Technology/SNC-Lavalin + Trafikverket)*

The project is financed by Family Ekman's Research Donation (through CHARMEC's budget), see page 68

With increasing requirements on the performance of railway vehicles, the demands on their bogies will also increase. Not only need the bogie be "stiff" enough to guarantee the stability of the running vehicle but it should also be "soft" enough to ensure comfort and minimize material wear and rolling contact fatigue of rails and wheels.



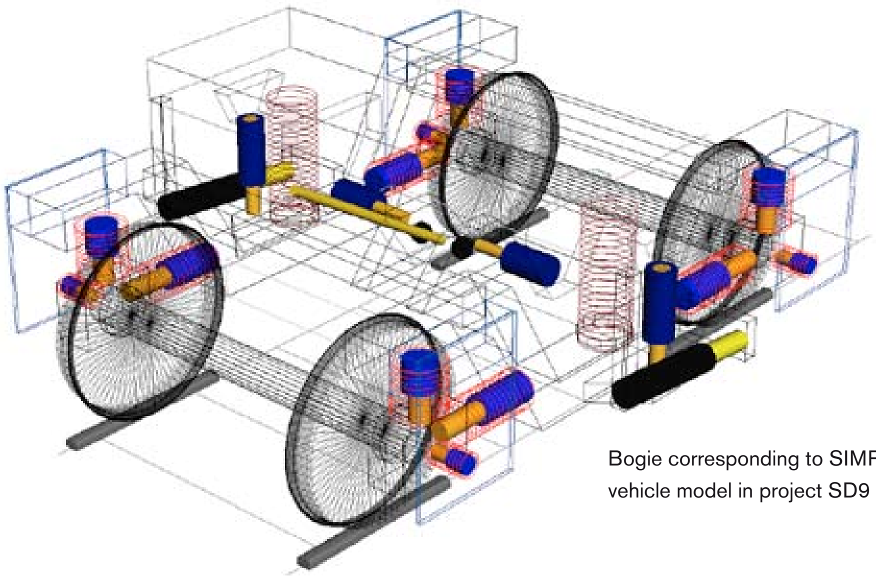
PhD student Milad Mousavi (left; doctorate earned in September 2016) and his supervisors Professor Viktor Berbyuk (right) and Professor Mikael Enelund from project SD9. Photo taken in 2012

These demands on bogies are becoming difficult to meet by use of traditional passive solutions, a situation which has led to an acceptance of active components. In project SD9, the focus has been on combined multiobjective optimization of the bogie system and on active vibration control. Main aims and objectives were (i) to formulate and solve multiobjective optimization problems for a multidimensional non-linear controlled dynamic system, which models the bogie of a modern railway vehicle with adaptronic components (sensors, actuators and controllers), (ii) to search for the optimal properties of the bogie system by identifying and analysing optimal design parameters, (iii) to study smart-material-based actuator and sensor technology to get an insight into the expected outcome of their application to bogie systems for high-speed railway vehicles, and (iv) to design adaptive strategies for optimal vibration control and system stability of the complete vehicle.

Two models of a high-speed train one-car vehicle with 26 and 50 degrees of freedom have been developed in MATLAB and in the multibody dynamics software SIMPACK, respectively. The complexity of the models is at a level making them suitable for the multiobjective optimization. Objective functions have been defined using existing railway standards and a global sensitivity analysis has been carried out to identify the design parameters that have the most important influences on the objective functions. After reference model assessments and system response analyses under different operational scenarios, the research was continued towards solving several multiobjective optimization problems for the railway vehicle model developed in SIMPACK.

Problems of multiobjective optimization of the bogie suspension with respect to safety (to boost speed on curves) and wear/comfort by use of the Pareto technique have been scrutinized. A target was to raise current train speeds up to those associated with a track plane acceleration of 1.5 m/s^2. The results were that, with the aid of the optimized values of design parameters, it will be possible to run the vehicle at higher speeds and shorten journey times as well as to reduce track access charges while guaranteeing a satisfactory level of safety, wear and ride comfort. Furthermore, the results of the wear/ride comfort optimization showed significant improvements in bogie dynamics behaviour. Effects of asymmetric suspension

SD9. (cont'd)



Bogie corresponding to SIMPACK vehicle model in project SD9

configurations on the dynamic behaviour of the vehicle have also been investigated and it was found that such configurations can significantly improve the performance of the vehicles on curves.

The efficiency of several semi-active control strategies as to safety, wear reduction and ride comfort has been scrutinized. Since track irregularities often reduce the controller performance, an active controller was designed which is robust against those irregularities. Sensors and electromechanical actuators will be employed to implement the active control scheme in a practical manner. Finally, a compensation technique has been proposed to attenuate the actuator dynamics effects and improve the active control efficiency.

The original SD9 project was concluded with Milad Mousavi's successful defence in public of his doctoral dissertation (see below) at Chalmers on 30 September 2016. The faculty-appointed external examiner of the dissertation was Professor José Luis Escalona from the University of Seville in Spain. The reference group for project SD9 had members from Bombardier Transportation, Interfleet Technology / SNC-Lavalin, Trafikverket, KTH Railway Group and Analytical Dynamics AB. The research plan for the project is dated 2011-04-28.

Project SD9 was prolonged by eight months (again financed by Family Ekman's Research Donation) for complementary work resulting in the Research Report 2017:01 (see below). Here, the acronym SAMO stands for Sensitivity Analysis and Multiobjective Optimization and is a computer code implemented in MATLAB to carry out a computationally efficient global sensitivity analysis and multiobjective optimization with many design applications. The current report was prepared to support SAMO users. Several case studies are considered including application of SAMO in a global sensitivity analysis of bogie dynamics with respect to suspension components. This demonstrates how SAMO can be used in a co-simulation environment with commercial multibody softwares like SIMPACK to solve complicated global sensitivity analysis and multiobjective optimization problems. The analysis is based on the multiplicative dimensional reduction method which significantly reduces the computational efforts required. Furthermore, a genetic algorithm is employed to carry out the multiobjective optimization. At the end of the report, the theories behind global sensitivity analysis and multiobjective optimization approaches used to develop SAMO are given.

Milad Mousavi and Viktor Berbyuk: Global sensitivity analysis of bogie dynamics with respect to suspension components, *Multibody System Dynamics*, vol 37, no 2, 2016, pp 145-174

Milad Mousavi, Viktor Berbyuk and Rickard Persson: Wear/comfort Pareto optimisation of bogie suspension, *Vehicle System Dynamics*, vol 54, no 8, 2016, pp 1053-1076

Milad Mousavi, T X Mei and Viktor Berbyuk: Robust control and actuator dynamics compensation for railway vehicles, *Vehicle System Dynamics*, vol 54, no 12, 2016, pp 1762-1784

Milad Mousavi and Viktor Berbyuk: Global sensitivity analysis and multiobjective optimization of bogie suspension, *Proceedings 24th International Congress on Theoretical and Applied Mechanics (ICTAM 2016)*, Montréal (Canada) August 2016, pp 2563-2564

Seyed Milad Mousavi Bideleh: Multiobjective optimisation and active control of bogie suspension, Doctoral Dissertation, *Chalmers Applied Mechanics*, Gothenburg September 2016, 173 pp (Summary and five appended papers)

Seyed Milad Mousavi Bideleh: Robustness analysis of bogie suspension components Pareto optimised values, *Vehicle System Dynamics*, vol 55, no 8, 2017, pp 1189-1205

Seyed Milad Mousavi Bideleh and Viktor Berbyuk: A computer code for sensitivity analysis and multiobjective optimization: SAMO Tutorial, Research Report 2017:01, *Chalmers Applied Mechanics*, Gothenburg 2017, 45 pp

SD10. ENHANCED MECHANICAL BRAKING SYSTEMS FOR MODERN TRAINS

Förbättrade mekaniska bromssystem för moderna tåg
Verbesserte mechanische Bremssysteme für moderne Züge
Systèmes de freinage améliorés pour des trains modernes

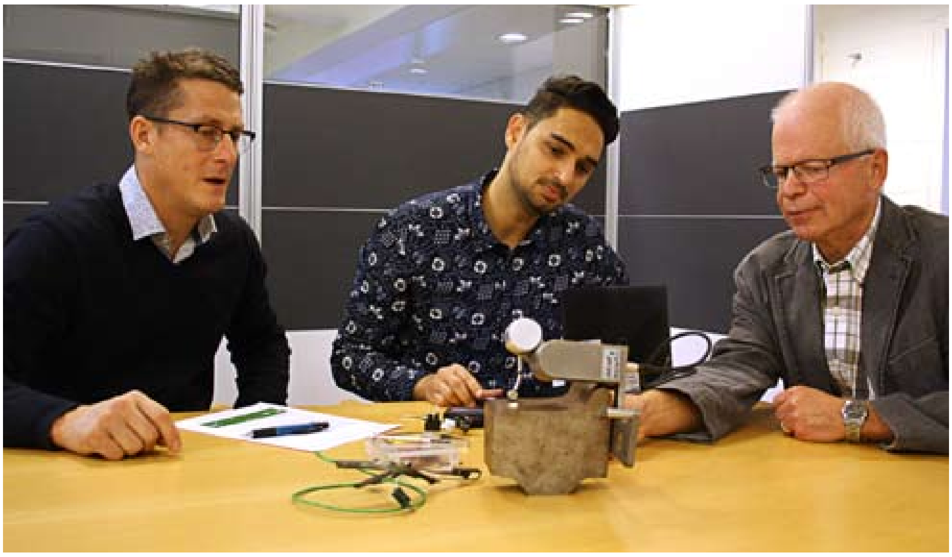
Project leader and supervisor	Docent Tore Vernersson, Mechanics and Maritime Sciences/ Division of Dynamics
Assistant supervisor	Professor Roger Lundén, Mechanics and Maritime Sciences
Doctoral candidate	Mr Mandeep Singh Walia, (from 2014-09-01; Lic Eng March 2017)
Period	2013-03-01 – 2018-06-30 (– 2019-08-31)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 1 565 Stage 8: kSEK 3900 Stage 9: kSEK 1935
Industrial interests in-kind budget	Stage 7: kSEK 100 + 200 + 0 + 15 + 100 + 50 Stage 8: kSEK 100 + 200 + 0 + 15 + 100 + 50 Stage 9: kSEK 50 + 300 + 130 + 50 + 100 + 62 *(Bombardier Transportation + Faiveley Transport + Green Cargo + Interfleet Technology/SNC-Lavalin + Lucchini Sweden + SweMaint)*

This is a combined doctoral and senior research project

Modern trains are often equipped with a computer-controlled braking system that flexibly can distribute 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 will be performed using mechanical brakes. The use of these can then range from the normal situation where they are 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 an analysis of what a broader use of tread brakes compared to disc brakes would imply considering the smaller investment at installation and the lower maintenance costs.

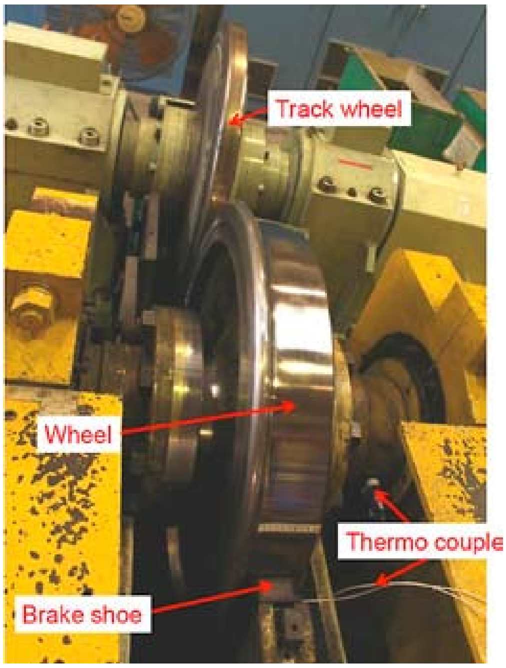
A study has been launched that continues the work of the previous project MU21 "Thermal impact on RCF of wheels" in order to establish a modelling framework for braking with respect to tread damage, see below. This work was performed in co-operation with project MU32 "Modelling of thermomechanically loaded rail and wheel steels" and together with the Railway Technical Research Institute (RTRI) in Tokyo (Japan). Brake rig rolling contact experiments performed at RTRI were used for verifying a numerical simulation tool that can account for the simultaneous thermal loads from tread braking and the impact from the mechanical rolling contact passages in the wheel–rail contact. The brake rig set-up at RTRI includes a so-called rail-wheel in contact with the tread braked wheel and also has the non-standard feature that tractive forces are transmitted between the two wheels in rolling contact (a consequence of having the inertia flywheels connected to the rail-wheel axle and not to the braked wheel, which is the traditional arrangement).

The rolling contact between wheel and rail was simulated with focus on impact on RCF (rolling contact fatigue)



PhD student Mandeep Singh Walia 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)

SD10. (cont'd)



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

from the temperature increase due to tread braking. To this end thermal cracking of railway wheel treads was studied in the RTRI brake rig tests for repeated stop braking cycles. Detailed detection of tread temperatures allowed for establishing the brake block/wheel interaction that is imperative for assessment of damage during braking. The test conditions were then numerically analysed using finite element (FE) simulations of the wheel–rail and brake block–wheel interaction that account for the thermomechanical loading of the wheel tread. The analyses were performed in the commercial FE package ABAQUS utilizing a material model calibrated for temperatures up to 625 °C as developed in project MU32. By combining the results from the brake rig and the simulation model, it was established that a plastic ratchetting type of fatigue criterion is suitable for life assessment of the thermal impact on RCF.

Building on the described work, a parametric study was formulated in order to investigate suitable limits for tread braking with respect to thermal impact on RCF. Here several braking scenarios were simulated in order to find such limits, investigating the influence of, e g, brake block materials, initial speeds, axle loads, initial temperatures and wheel geometry. It was found that the tread temperature in the vicinity of the wheel–rail rolling contact zone of the wheel tread is the main controlling parameter regarding life up to onset of tread cracking. Thus a limiting tread temperature could be established. When assessing tread braking temperatures it is imperative to account for local tread temperatures introduced, e g, by banded types of frictional contact between block and wheel and by thermoelastic interaction phenomena.

Brake wear and brake utilization have thus been investigated using combined field tests and numerical simulations. In this context, brake wear means both wear of the brake blocks and wear of the wheel treads as introduced by the application of the brakes. In-field measurements were performed on Roslagsbanan in Stockholm (Sweden) during the spring 2018 using low-cost wireless instruments allowing for simplified installation of measurement equipment. Here useful data could be collected for simulations / calibrations of brake temperatures and wear. A field study is planned with brake wear for a disc-braked vehicle.

Mandeep Singh Walia presented his licentiate thesis (see below) at a seminar on 20 March 2017 with Dr Daniel Thuresson of Vetec AB introducing the discussion. The reference group for project SD10 has members from Bombardier Transportation (in Siegen/Germany, Sweden and UK), Faiveley Transport and SNC-Lavalin.

Mandeep Singh Walia, Ali Esmaeili, Kazuyuki Handa, Tore Vernersson and Roger Lundén: Thermal impact on rolling contact fatigue of railway wheel treads and thermal capacity of wheels, *Proceedings EuroBrake 2016*, Milan (Italy) June 2016, 10 pp

Roger Lundén and Tore Vernersson: Mechanical braking systems – development and challenges (Keynote Lecture), *Proceedings 19th Nordic Seminar on Railway Technology*, Luleå (Sweden) September 2016 (Summary and PowerPoint presentation)

Katsuyoshi Ikeuchi, Kazuyuki Handa, Roger Lundén and Tore Vernersson: Wheel tread profile evolution for combined block braking and wheel-rail contact – results from dynamometer experiments, *Wear*, vols 366-367, 2016, pp 310-315 (revised article from conference *CM2015*)

Mandeep Singh Walia: Towards enhanced mechanical braking systems for trains – thermomechanical capacity of wheel treads at stop braking, Licentiate Thesis, *Chalmers Applied Mechanics*, Gothenburg March 2017, 97 pp (Summary and three appended papers)

Ali Esmaeili, Mandeep Singh Walia, Kazuyuki Handa, Katsuyoshi Ikeuchi, Magnus Ekh, Tore Vernersson and Johan Ahlström: A methodology to predict thermomechanical cracking of railway wheel treads – From experiments to numerical predictions, *International Journal of Fatigue*, vol 105, 2017, pp 71-85 (also listed under projects MU30 and MU32)

Roger Lundén and Tore Vernersson: Railway wheels and tread brakes (Keynote Lecture), *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

Mandeep Singh Walia: Wear of tread braked wheels and brake blocks, *ibidem* (Summary and PowerPoint presentation)

Mandeep Singh Walia, Ali Esmaeili, Tore Vernersson and Roger Lundén: Thermomechanical capacity of wheel treads at stop braking – a parametric study, *International Journal of Fatigue*, vol 113, 2018, pp 407-415 (also listed under project MU32)

Mandeep Singh Walia, Tore Vernersson, Roger Lundén, Fredrik Blennow and Markus Meinel: Temperatures and wear at railway tread braking: Field experiments and simulations, *Proceedings 11th International Conference on Contact Mechanics and Wear of Rail/ Wheel Systems (CM2018)*, Delft (The Netherlands) September 2018, pp 1029-1036

EU14. Capacity4Rail

Capacity4Rail – Capacity for Rail

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences/ Division of Dynamics
Co-workers	Professor Roger Lundén, Professor Elena Kabo, Professor Jens Nielsen, Senior Lecturer Björn Pålsson and Dr Peter Torstensson, all of Mechanics and Maritime Sciences, together with Dr Björn Paulsson, Mechanics and Maritime Sciences (and formerly of Trafikverket)
Period	2013-10-01 – 2017-09-30
Budget EU	kEUR 217 + 157
Budget CHARMEC	Stage 7: kSEK 300 Stage 8: kSEK 200

Capacity4Rail (SST.2013.2-2) was a "small or medium-scale focused research project" within the Seventh Framework Programme with a total budget of MEUR 15.6 of which MEUR 10.0 were the EU funding. Capacity4Rail aimed at paving the way for the future railway system, delivering coherent, demonstrated, innovative and sustainable solutions for track design, freight, operations, and advanced monitoring. The project Capacity4Rail was co-ordinated by the UIC and had 46 partners listed on www.capacity4rail.eu.

Capacity4Rail was divided into six subprojects: SP1 Infrastructure (led by SYSTRA), SP2 New concepts for freight (led by Trafikverket), SP3 Operations for enhanced capacity (led by Network Rail), SP4 Advanced monitoring (led by DB), SP5 Migration and vision to 2050 (led by DB), and SP6 Dissemination, exploitation and management (led by UIC). The subprojects were then divided into work packages. CHARMEC worked (number of Man-Months in parentheses) in WP1.1 Modular integrated design of new concepts for infrastructure (7.5 MM) and WP1.3 Switches & crossings (S&C) for future railways (11 MM), and as leader of WP4.1 Monitoring strategies and evaluation, Algorithms (6 MM).

In Deliverables D1.1.4 and D1.1.5, CHARMEC has contributed mainly to procedures on assessing how track upgrading affects deterioration of track and S&C. In addition, CHARMEC has provided summary sections and a description of the overall approach to structured upgrading. To aid implementation, Björn Paulsson and Anders Ekberg together with Lennart Elfgren of LTU have written a scientific paper on the most important aspects of track upgrading as learnt from the Deliverables, see below.

In Task 1.3.2 (Innovative designs minimizing S&C loads and material deterioration), CHARMEC developed a numerical approach for geometry optimization of S&C. Based on wheel–rail contact data from simulations of dynamic vehicle–track interaction, a post-processing toolbox for the prediction and graphical presentation of accumulated damage (in terms of wear and surface initiated rolling contact fatigue) has been developed and implemented. Short-term solutions for reducing loads and rail profile degradation in the switch panel including selections of rail profile and rail inclination, rail grade and friction management have been investigated. The influence of three sets of switch rail profiles with 60E1 or 60E2 profiles, and with or without a 60° chamfer along the front section of the switch rail, on accumulated damage was studied. The 60° chamfer leads to some increase of wear for traffic in the facing move but significantly less wear for traffic in the trailing move. The use of 60E2 profiles was found to reduce the maximum RCF (rolling contact fatigue) damage in both moves. The selection of rail grade R350HT instead of R260 leads to a large reduction in wear. However, the predicted influences of rail grade and friction management on RCF are uncertain due to the wide range of factors influencing RCF initiation, such as the important interaction between crack growth and wear. It was shown that both wear and RCF are reduced significantly by maintaining a low friction coefficient in the wheel–rail contact. These results are presented in Deliverables D13.2 and D13.3.

In WP4.1, CHARMEC co-ordinated the work, which included finalization of the Deliverables. In the research, CHARMEC focused on monitoring of track and running gear. In Deliverable 41.2, this resulted in an overview of which parameters that should (ideally) be measured and how they related to the status and deterioration of track and running gear. In D41.3 the study was continued and contrasted with current practices. Further, CHARMEC presented a description of how an overall identification and assessment (in terms of "costs" and "benefits" in a broad sense) of suitable monitoring strategies can be carried out. This approach was employed in all fields of monitoring discussed in WP4.1.

Jens Nielsen presented a paper on switch panel optimization at the CM2015 conference in Colorado Springs (USA) in August-September 2015. He participated in SP1.3 meetings in Huddersfield (UK) in September 2015, in Madrid in October 2015, in Luleå in February 2016, in Vienna in October 2016, and in Gothenburg in June 2017. Elena Kabo organized a joint meeting between the members of the Capacity4Rail SP4 project group together with Elin Jonsson and Arne Nissen of Trafikverket at Chalmers in July 2015 and she participated in a SP4 meeting in Lisbon (Portugal) in June 2017.

EU14. (cont'd)

CHARMEC researchers in EU projects during Stage 8. From the left: Anders Ekberg, Peter Torstensson, Lennart Josefson, Björn Pålsson, Roger Lundén, Jens Nielsen, Elena Kabo and Johan Ahlström. Photo taken in 2019

Björn Paulsson made a presentation at UIC Asia Pacific Workshop on Productivity Increase with Heavier and Longer Trains in St Petersburg (Russia) in May 2015 and a presentation to LKAB, Trafikverket and Jernbaneverket in Luleå in February 2017. Björn Paulsson and Anders Ekberg made a summary presentation for Trafikverket on the main infrastructure related results from Capacity4Rail in Stockholm in September 2017.

Björn Paulsson presented the main results on freight line upgrading at the hearing "Future logistics – focus on long-distance transports" in May 2017 at the Swedish Ministry of Enterprise and Innovation. This was followed up in June 2017 when Björn Paulsson and Anders Ekberg presented and discussed the work on a handbook for upgrading of railway freight lines in relation to the Ministry's work on a plan for long-distance freight transports. The discussion provided input to the Swedish parliament report no 2017/18:RFR16.

The final conference of Capacity4Rail was held in Madrid on 2017-09-21—22. Here Björn Paulsson led the presentation of SP4.

Jens Nielsen (editor): Innovative concepts and designs for resilient S&Cs (intermediate), Capacity4Rail Deliverable D13.2, 2016, 155 pp

Anders Ekberg (editor): Critical components and systems – current and future monitoring, Capacity4Rail Deliverable D41.1, 2016, 45 pp

Elena Kabo (editor): Monitoring-based deterioration prediction, Capacity4Rail Deliverable D41.2, 2016, 131 pp

Jens Nielsen, Björn Pålsson and Peter Torstensson: Switch panel design based on simulation of accumulated rail damage in a railway turnout, *Wear*, vols 366-367, 2016, pp 241–248

Elena Kabo (editor): Strategies for data collection and analysis, Capacity4Rail Deliverable D41.3, 2017, 71 pp

Björn Paulsson (editor): Upgrading of infrastructure in order to meet new operation and market demands, Capacity4Rail Deliverable D11.5, 2017, 209 pp

Björn Paulsson, Anders Ekberg and Lennart Elfgren: Efficient upgrading of freight railways, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

Björn Paulsson, Anders Ekberg and Lennart Elfgren: Upgrading of freight railways to meet operational and market demands, *Proceedings 7th Transport Research Arena TRA 2018*, Vienna (Austria) April 2018, 10 pp (DOI:10.5281/zenodo.1491480)

Elena Kabo and Anders Ekberg: Monitoring of track and running gear, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

EU15. WRIST

WRIST – Innovative Welding Processes for New Rail Infrastructures

Project leader	Professor Lennart Josefson, Industrial and Materials Sciences / Division of Material and Computational Mechanics
Co-workers	Dr Jim Brouzoulis, Mechanics and Maritime Sciences, and Mr Tomas Andersson, MSc, ÅF, and Mr Roeland Bisschop, MSc, and Mr Michele Maglio, MSc, both at Industrial and Materials Science
Period	2015-05-01 – 2018-06-30 (– 2019-01-31)
Budget EU	kEUR 417
Budget CHARMEC	Stage 8: kSEK 400 Stage 9: kSEK 0

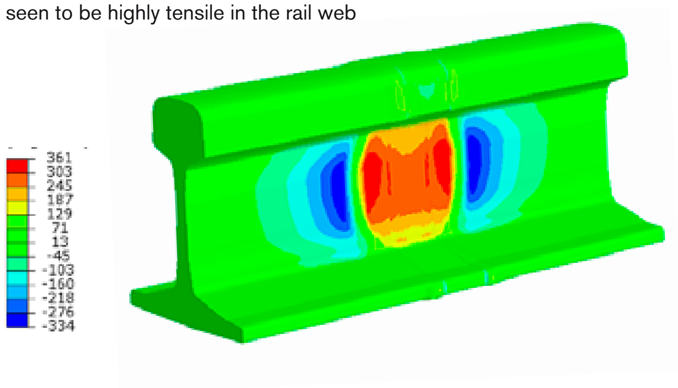
WRIST is a research project within the European Union's Horizon 2020 Programme with a total EU funded budget of MEUR 4.19, see www.wrist-project.eu. WRIST falls under the topic MG-8.1A-2014 – Smarter design, construction and maintenance. WRIST will develop and demonstrate two new joining processes for rails (orbital friction welding and aluminothermite welding) that will 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 is co-ordinated by the Belgian Welding Institute (BWI). In addition to Chalmers/CHARMEC, the eight partners are University of Huddersfield (UK), TU Delft (NL), ProRail (NL), Goldschmidt Thermite Group (Germany), DENYS (Belgium), JACKWELD (UK), ID2 BV (NL) and ARCTIC (France).

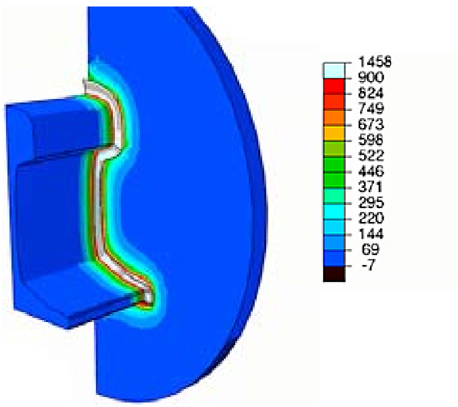
WRIST is divided into 9 work packages (CHARMEC's Man-Months in parentheses): WP1 Requirements analysis (–), WP2 Further development of the new aluminothermite welding process (1 MM), WP3 Further development of the new orbital friction welding method (1 MM), WP4 Finite element modelling of the welding processes (CHARMEC is WP-leader with 20 MM), WP5 Design of the intermediate component for orbital friction welding (2 MM), WP6 Weld quality optimization for conventional and bainitic rail steels (–), WP7 Metallurgical and geometrical characterization of the welds (–), WP8 Dissemination, sustainable impact and exploitation (3 MM), and WP9 Administrative and financial management (–). A kick-off meeting was held in Brussels on 20–21 May 2015, and a midterm review was held on 8 December 2016 also in Brussels. The project has been extended by 9 months due to problems with the manufacturing of the orbital friction welding machine.

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 variables friction coefficient, pressure and velocity, has been validated against a 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 rails has been simulated for the current design of the OFW machine. The model gives the temperature history in the rail and intermediate disc, whereby cooling rates can be determined and the final microstructure and the size of the HAZ can be estimated for different choices of process parameters. This work will continue when the final layout of the OFW machine is ready and the method can be tested in full scale.

As to the aluminothermite welding, a thermomechanical model of the full process has been developed. It includes preheating, tapping, pouring of molten material, applying a compressive force (forging) and shearing of excess material. The model has been verified using temperature measurements for the preheating and welding phases from

Calculated vertical residual stresses (MPa) for the aluminothermite welding where a forging pressure is applied shortly (2 minutes) after the weld metal´s tapping into the mould. Vertical stresses are seen to be highly tensile in the rail web





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

EU15. (cont'd)

a subsidiary to the partner Goldschmidt Thermite Group (GTG). Mechanical results, i e, the residual stress field, have been 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.

Ivar Wahlstedt: FE modeling of orbital friction welding, MSc Thesis 2016:43, *Chalmers Applied Mechanics*, Gothenburg 2016, 22 pp

Lennart Josefson and Jim Brouzoulis: Validated numerical FE-model of the orbital friction welding process, WRIST Deliverable 4.1, 2016, 17 pp

Lennart Josefson and Jim Brouzoulis: Validated numerical FE-model of the aluminothermic welding process, WRIST Deliverable 4.2, 2016, 16 pp

Jim Brouzoulis, Roeland Bisschop, Carolin Oddy and Lennart Josefson: Orbital friction welding of rails, *Proceedings 29th Nordic Seminar on Computational Mechanics (NSCM-29)*, Gothenburg October 2016, 4 pp

Håkan Ringius and Claes Thorsell: FE modeling of friction welding – thermo-mechanical simulations using ABAQUS, MSc Thesis 2017:06, *Chalmers Applied Mechanics*, Gothenburg 2017, 79 pp

Lennart Josefson, Roeland Bisschop, Michele Maglio, Jim Brouzoulis and Tomas Andersson: WRIST – Innovative welding processes for new rail infrastructure, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

Parallel EU projects – Parallella EU-projekt – Parallele EU-Projekte – Projets parallèles avec l´UE

EU16. In2Rail

In2Rail – Innovative Intelligent Rail

Project leader	Professor Anders Ekberg, Mechanics and Maritime Sciences / Division of Dynamics
Co-workers	Professor Roger Lundén, Professor Elena Kabo, Professor Jens Nielsen, Dr Peter Torstensson and Senior Lecturer Björn Pålsson, all of Mechanics and Maritime Sciences, together with Dr Eric Berggren, EBER Dynamics, and Dr Björn Paulsson, Mechanics and Maritime Sciences (and formerly Trafikverket)
Period	2015-05-01 – 2018-04-30
Budget EU	kEUR 502 + 129
Budget CHARMEC	Stage 8: kSEK 400

In2Rail (MG-2.1-2014) was a project within the European Union's Horizon 2020 Programme with an EU grant of MEUR 18.0. It was a so-called Shift2Rail Lighthouse project that "... is to set the foundations for a resilient, consistent, cost-efficient, high-capacity European network by delivering important building blocks that unlock the innovation potential that exists in the Shift2Rail Innovation Programmes (IP) 2 and 3". In2Rail was co-ordinated by Network Rail (UK) and had 53 additional partners listed on the project website www.in2rail.eu.

The 13 work packages (WP) in In2Rail were WP1 Project management, WP2 Innovative S&C solutions, WP3 Innovative track solutions, WP4 Bridges & tunnels, WP5 Commercial off the shelf monitoring, WP6 Maintenance strategies & execution, WP7 Intelligent Mobility Management (I2M) – System engineering, WP8 I2M – Integration layer, WP9 I2M – Nowcasting and forecasting, WP10 Intelligent AC power supply system, WP11 Smart metering for a railway distributed energy resource management system, WP12 Technical co-ordination and system integration, and WP13 Dissemination, communication and exploitation. Chalmers/CHARMEC was involved in WP2, WP3 and WP5. The formal In2Rail kick-off meeting was held in Brussels on 2015-05-07 and the project was finished on 2018-04-30.

CHARMEC's work in WP2 has focused on concepts for condition monitoring in crossings, switch rail maintenance and operational tolerances. An enhanced structural dynamics model of the crossing panel has been developed. To allow for the extraction of displacements, accelerations, local strain responses and a more realistic application of contact loads, the model features a crossing with solid finite elements. The model has been used to study crossing instrumentation concepts under static and dynamic loading.

A dynamic time-domain model of wheelset–track interaction for the assessment of different condition monitoring concepts at crossings under traffic loading has also been developed, and a parameter study has been performed to find a suitable instrumentation. This study shows that a wheel passing over a crossing generates a vertical impact load and a resulting vertical crossing acceleration that are mainly proportional to the crossing dip angle and the speed of the passing wheelset. For changes in track stiffness, on the other hand, it was found that these were mainly proportional to the vertical crossing displacement. It is therefore proposed

EU16. (cont'd)

that if the maximum vertical acceleration and maximum displacement of a crossing in traffic are logged over time together with traffic speed, it should be possible to determine the status of the crossing in terms of changes in track stiffness (e g, caused by settlements) and crossing geometry degradation (which gives a larger dip angle) from these data.

In WP3 our work was divided into three main categories: (i) optimized track solutions with focus on lateral stability of sleeper tracks and on transition zones, (ii) mitigation of impact noise at switches & crossings, and (iii) investigation of selected innovative repair methods.

Based on a statistical correlation analysis of annual peak temperature and number of track buckle events (sun kinks), it has been concluded that track buckling is strongly related to local variations in stress-free temperature (SFT) and lateral track resistance. A predictive model for track buckling (see page 61) has been established, and a Python script for generation of input data to the stability analysis solver in ABAQUS has been updated also to include local lateral track geometry faults. For different track configurations, the lateral stability of sleeper tracks has been investigated by performing numerical simulations of lateral track displacements at increased temperatures, see figure. Variations in ballast stiffness and track geometry deviations are interpreted in a manner (as equivalent temperature increases) that allows for a comparison to SFT and they have (where possible) been shown to correlate well with empirical experience.

Based on field measurements on the heavy haul line Malmbanan (Iron Ore Line) in northern Sweden and Norway, it was found that severe local irregularities in vertical track geometry often occur on track sections with a combination of low magnitude and high gradient of substructure stiffness. In August 2015, under sleeper pads (USP, see page 56) were installed on a 300 m test section of the Western Main Line near Lerum/Stenkullen in Sweden. Results from a continuous track stiffness measurement showed that the stiffness gradient was consistently low within the section of track fitted with USP. Also track geometry had been significantly improved since the track renewal. An iterative non-linear method for prediction of long-term track settlement and generation of voided sleepers has been developed. It accounts for the gap developing between sleeper bottom and ballast surface and considers the resulting load redistribution onto adjacent sleepers.

In collaboration with ISVR in the UK, a hybrid model for the prediction of impact noise at railway crossings has been developed. The hybrid model combines simulation of vertical wheel–rail contact force in the time-domain and prediction of sound pressure level using a linear frequency-domain model. Wheel structural flexibility and a discretely supported rail with space-variant beam properties are accounted for using moving Green's functions. Non-Hertzian normal wheel–rail contact is modelled. The time-domain and frequency-domain models are coupled based on the concept of an equivalent roughness spectrum. In collaboration with DB, ISVR and Vossloh-Cogifer, a measurement campaign was conducted on the Rhine-Alpine freight corridor in Germany. Measurements at two closely separated crossings included rail acceleration and impact noise generated during train pass-by, track decay rate, acoustic rail roughness and the three-dimensional contact geometry in the crossing panel. The collected measurement data have been used to calibrate the existing model for prediction of impact noise generated at railway crossings.

Based on a parameter study using the hybrid model, the crossing dip angle has been confirmed to significantly influence the generation of impact noise. An increase in crossing dip angle from 6 mrad to 24 mrad was found to correspond to an increase in radiated impact noise of about 11 dB(A). A significant influence of vehicle speed and wheel profile on the radiated noise was also detected.

A state-of-the-art study on existing and innovative methods for rail head welding repair as well as on welding simulation possibilities and features by use finite element simulations has been carried out. A simulation method was developed to evaluate the thermomechanical response during repair welding. The numerical model featured sequentially deposited weld beads and subsequent cooling. In particular, the residual stress field after cooling is of interest since it influences the subsequent risk of rolling contact fatigue.

A parametric study was carried out to evaluate the risk of surface initiated rolling contact fatigue (RCF) for high-speed trains. The results were interpreted in terms of RCF impact spectra and by using the T–gamma energy model. It was found that the two models result in similar tendencies. The development of RCF is dominated by the traction effort, but significant influences are also found for corrugation level, speed, axle load and unsprung mass.

Simulations showed that the corrugation wavelength on a reference curve of the Stockholm metro is mainly influenced by the vehicle speed and rail pad stiffness. The level of wheel–rail friction was found to be decisive for the potential corrugation growth. Furthermore, the rail geometry may have a significant influence on the corrugation growth rate.

In WP5 CHARMEC's work focused on thermal stresses with particular focus on the risk of track buckling. This included work on developing a new system for field measurement of the continuous variation of SFT of rails in collaboration

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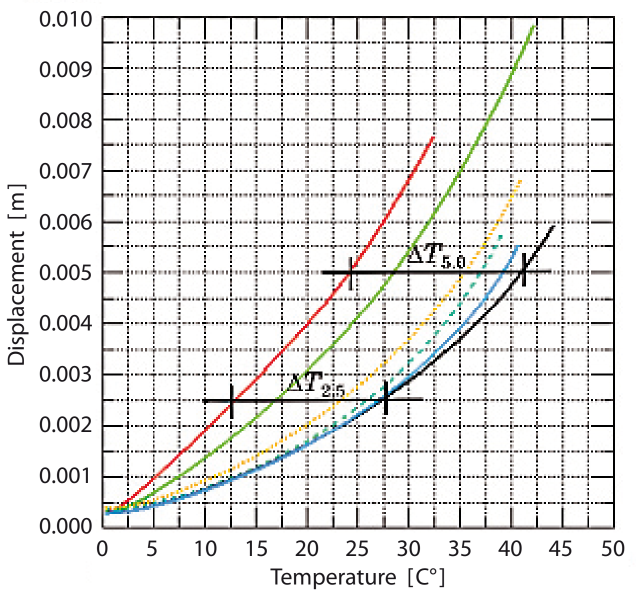


Definition of equivalent temperature increases corresponding to lateral rail deflections of 2.5 ($\Delta T_{2.5}$) and 5 mm ($\Delta T_{5.0}$) considering the question "How much less does the rail need to be heated to get the same lateral deflection?". From In2Rail Deliverable D5.3

with the company EBER Dynamics. In addition, studies of the mechanical characteristics of jointed tracks highlights the importance of when in the thermal cycle joint gaps are measured, i e, whether the gap is opening or closing. This knowledge was employed when a proposed methodology of using laser to measure joint gaps in jointed tracks was validated in a full-scale field test. Finally, work on characterizing the track resistance to track buckling in terms of equivalent temperatures was performed in WP5.

Anders Ekberg participated at the In2Rail Final conference in Vienna (Austria) on 19 April 2018 where he presented the parts of WP5 relating to thermal stress monitoring.

Stefan Kallander (editor): Investigation of repair methods and welding techniques, In2Rail Deliverable D3.1, 2017, 112 pp (and 2 annexes 49 + 63 pp)

Cedric Gallais (editor): Evaluation of solutions to decrease noise and vibration, In2Rail Deliverable D3.2, 2017, 143 pp (and 2 annexes 2 + 26 pp)

Dan Cedergårdh (editor): Evaluation of optimised track systems, In2Rail Deliverable D3.3, 2017, 304 pp

Federico Papa (editor): Methodology for thermal stress monitoring, In2Rail Deliverable D5.3, 2017, 117 pp

Margherita Lupi (editor), Report on technical validation of concepts, In2Rail Deliverable D5.4, 2018, 148 pp

Jens Nielsen and Xin Li: Railway track geometry degradation due to differential settlement of ballast/subgrade – numerical prediction by an iterative procedure, *Journal of Sound and Vibration*, vol 412, 2018, pp 441-456 (also listed under projects TS15 and SP26)

Peter Torstensson, Giacomo Squicciarini, Matthias Krüger, Jens Nielsen and David Thompson: Hybrid model for prediction of impact noise generated at railway crossings. In David Anderson et al (editors): Noise and Vibration Mitigation for Rail Transportation Systems, *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 139, 2018, pp 759-769 (revised article from workshop *IWRN12*. Also listed under project TS16)

Björn Pålsson: A linear wheel-crossing interaction model, *IMechE Journal of Rail and Rapid Transit* (in printing)

Matthias Germonpré, Jens Nielsen, Geert Degrande and Geert Lombaert: Contributions of longitudinal track unevenness and track stiffness variations to railway induced vibration, *Journal of Sound and Vibration* (in printing)

Jens Nielsen, Eric Berggren, Anders Hammar, Fredrik Jansson and Rikard Bolmsvik: Railway track geometry degradation – correlation between track stiffness gradient and differential settlement, *IMechE Journal of Rail and Rapid Transit* (in printing). Also listed under project SP26

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 (submitted for international publication)

Anders Ekberg, Roger Lundén, Jens Nielsen and Anders Ekberg: The influence of corrugation on frictional stress at the rail/wheel surface, *Proceedings Railways 2016 – The Third International Conference on Railway Technology*, Cagliari, Sardinia (Italy) April 2016, 14 pp

Roger Lundén, Jens Nielsen and Anders Ekberg: The influence of corrugation on tangential forces and rolling contact fatigue, *Proceedings 19th Nordic Seminar on Railway Technology*, Luleå (Sweden) September 2016 (Summary and PowerPoint presentation)

Jens Nielsen, Eric Berggren, Anders Hammar, Fredrik Jansson and Rikard Bolmsvik: Track geometry degradation on the Swedish heavy haul line – correlation between measured support stiffness gradients and differential settlement, *Proceedings 11th International Heavy Haul Association Conference (IHHA2017)*, Cape Town (RSA) September 2017, 8 pp

Jens Nielsen, Eric Berggren, Rikard Bolmsvik, Anders Hammar, Fredrik Jansson and Johan Lessner: Railway track superstructure: holistic optimization of design and maintenance for improved performance – guidelines and concluding technical report, Research Report 2017:05, *Chalmers Mechanics and Maritime Sciences*, Gothenburg 2017, 65 pp (also listed under project SP26)

Michele Maglio: Finite element analysis of thermal fields during repair welding of discrete rail defects, MSc Thesis 2017:17, *Chalmers Applied Mechanics*, 49 pp (and 1 annex 4 pp. Also listed under project MU22)

Björn Pålsson, Condition monitoring of crossing panels using embedded sensors, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

Michele Maglio and Elena Kabo: Thermomechanical analyses of discrete defect repair process for rails, *ibidem* (Summary and PowerPoint presentation. Also listed under project TS20)

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

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 – 2018-06-30 (– 2019-02-28)
Budget Trafikverket / EU	Stage 8: kSEK 8 007 Stage 9: kSEK 3 732
Budget CHARMEC	Stage 8: kSEK 640 Stage 9: kSEK 340

In2Track (S2R-CFM-IP3-01-2016) is 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 is Trafikverket, see shift2rail.org/in2track/. CHARMEC's Anders Ekberg is scientific–technical co-ordinator for the whole project In2Track.

The six work packages (WP) in In2Track are 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 is involved in WP2, WP3 and WP5 and assists in WP1. Our contributions to In2Track includes work from several parallel CHARMEC projects such as TS17, TS18, TS19, MU28, MU29, MU31, MU32, MU33 and MU34. The corresponding activities in In2Track are presented under these projects in the foregoing. Co-ordination activities are reported below.

In2Track officially started on 2016-09-01 and had a first co-ordination meeting on 2016-09-06–07 in Brussels where Anders Ekberg participated in his capacity as leader of WP3 and WP5 and as overall scientific–technical co-ordinator.

He has participated in steering committee / technical management team meetings with all WP leaders on 2016-12-07 in Brussels, on 2017-12-05 in Paris, and on 2018-05-29 in Madrid. Further, a meeting to plan the continuation of Shift2Rail was held in London on 2017-10-10. Joint Undertaking (JU) reviews were held on 2017-05-03 in Brussels where Anders Ekberg participated and presented WP3 and WP5, and on 2018-04-24 in Brussels.

An In2Track Midterm Event was held at the UIC headquarters in Paris on 2018-01-24. Anders Ekberg participated and presented research in WP3. For the meeting, CHARMEC had also carried out a mid-term review of all nine Technical Deliverables. Further, CHARMEC has reviewed all finalized reports.

Skeletons for all three Deliverables in WP3 were prepared by CHARMEC shortly after the kick-off and responsible partners were assigned to all sections. The work then continued in populating the skeletons. To co-ordinate these activities, technical meetings within WP2 and WP3 were held in Gothenburg on 2016-11-28–29, in London on 2017-05-10 (WP2) and 2017-05-11 (WP3), and in Paris on 2017-10-03–04 (WP2) and 2017-11-15 (WP3). From CHARMEC's side, at these meetings, Björn Pålsson and Anders Ekberg were responsible for WP2 and WP3, respectively.

Draft versions of the Technical Deliverables have been periodically compiled. Here CHARMEC has been responsible for D3.1 "Enhanced track structure – Status, key influencing parameters and prioritised areas of improvement" and D3.3 "Enhanced inspection, maintenance and operation of track", and we have contributed to D2.1 "Identifying and understanding core S&C issues", D2.2 "Enhanced switches and crossings – Enhanced S&C whole system analysis, design and virtual validation", D2.3 "Enhanced switches and crossings – Enhanced monitoring, operation, control and maintenance of S&C", and D3.2 "Enhanced track structure – Status, key influencing parameters and prioritised areas of improvement".

The work in In2Track will continue in In2Track-2. CHARMEC has provided input to Trafikverket for the drafting of the In2Track-2 project proposal, which was submitted during the spring 2018. The new project started in November 2018.

Anders Carolin (editor): Project management plans, In2Track Deliverable 1.1, 2016, 25 pp

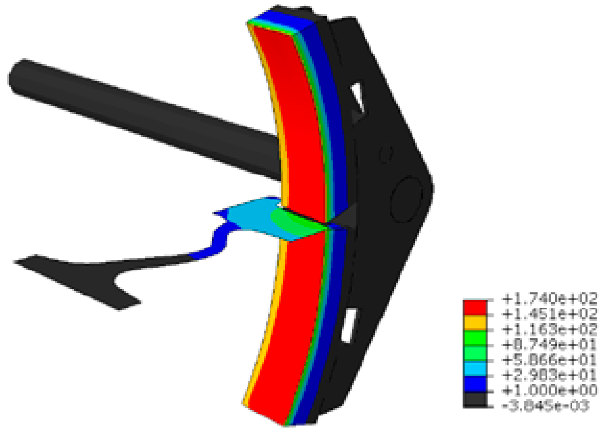
Anders Ekberg (editor): Quality assurance plan, In2Track Deliverable 5.1, 2016, 14 pp

Under Sleeper Pads
(courtesy Getzner Werkstoffe GmbH)

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 170

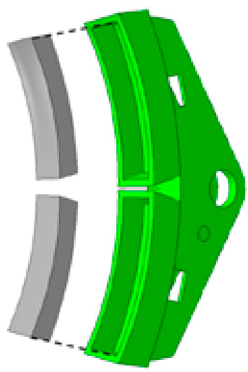


Example of simulation of natural de-icing of an organic composite brake block with holder for a short duration drag braking (30 kW for 5 min) with temperatures in °C. Original ice thickness was 5 mm. Black areas are still ice covered

The Fr8Rail project is part of the Shift2Rail Research and Innovation Action. It is co-ordinated by Trafikverket and has 18 European partners and a total budget of MEUR 7.8. In detail, the objectives are: (1) a 10 % reduction in the cost of freight transport measured by tonnes per km, (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. These objectives will be achieved by developing a number of vital areas within Fr8Rail. The eight work packages (WP) in the project are WP1 Business analytics, KPIs, top level requirements, WP2 Condition based and predictive maintenance, WP3 Telematics & electrification, WP4 Running gear, core and extended market wagons, WP5 Automatic coupling, WP6 High level system architecture and integration, WP7 Dissemination, and WP8 Project management. CHARMEC is involved in WP4. KPI stands for a Key Performance Index.

The CHARMEC contribution to the project is a study focusing on the performance of LL-type brake blocks. These blocks 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. Within the limited scope of Fr8Rail, the impact from introduction of LL blocks on the following selected areas is being investigated by us: (1) damage types affected by LL blocks, (2) wear of wheel treads, (3) rolling contact fatigue, and (4) winter problems in tread braking.

Reports from the UIC EuropeTrain project give detailed information on braking operation and wear of blocks and wheel treads for a total of 16 loops covering different parts of Europe with a total travelled distance of about 250 000 km. Acknowledging that such detailed information could not be acquired within the limited budget of the CHARMEC Fr8Rail project, an investigation of damage and wear was launched that builds entirely on data in the EuropeTrain reports. By reading numerical data from the reports into a response surface analysis tool, energy-related wear relations of treads and blocks could be established (wear is in the reports related to travelled distance). This information provides new insights into the characteristics of the different block types. The new LL blocks made from organic composite and sinter materials were found to wear at a considerably slower rate than cast iron brake blocks.
On the other hand they produce a higher degree of wheel tread wear that has a tendency to expand and to develop into hollow wear of the treads, which may introduce unstable running of vehicles. Brake blocks made from cast iron seem to have the same tendency for this type of detrimental wear pattern in a situation with an unloaded wagon but not with a loaded wagon. Tentative simulation efforts have been made to understand and possibly find mechanisms that are important for controlling these differences.



Proposed (and numerically investigated) novel type of brake block with organic composite material (here shown in gray) inserted into a shell of sinter material (green). From CHARMEC's contribution to Fr8Rail Deliverable D4.4

EU18. (cont'd)

Modelling of thermal impact on RCF (rolling contact fatigue) for freight-type axle loads has been executed by introducing a simplification to the modelling framework developed in projects SD10 and MU32 through introducing an a priori scheme for determining the wheel–rail normal contact pressure distribution. A parametric study of stop braking conditions at 22.5 tonne axle load confirms previous findings that 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 studied. A previously developed thermal model, originally established in project SD4, utilizing an axisymmetric representation for the wheel and a plane one for the brake blocks, has been enhanced by introducing a 3D representation of brake block and holder. This allows for detailed studies of temperatures on different surface parts of the system of block and holder for situations where ice-layers have previously built-up on the equipment. A parametric study reveals significant differences in behaviour for cast iron and sintered brake block materials 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.

Fr8Rail Deliverable D4.1: State of the Art, FR8-WP4-D-KTH/DLR/TVP-021-02, 2017-08-23, 188 pp (CHARMEC contributed to the chapter "Wheelsets")

Fr8Rail Deliverable D4.3: Running gear and wagon design concepts, FR8-WP4-D-ViF-023-03, 2018-03-20, 120 pp (CHARMEC contributed to the chapters "Braking design concepts" and "Wheelset concepts and wheel material development")

Fr8Rail Deliverable D4.4: Detailed running gear and wagon design concept (in preparation)

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

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 – 2018-06-30 (– 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)

From the left: Fredrik Jansson and Anders Hammar of Trafikverket, and Eric Berggren of EBER Dynamics in project SP26

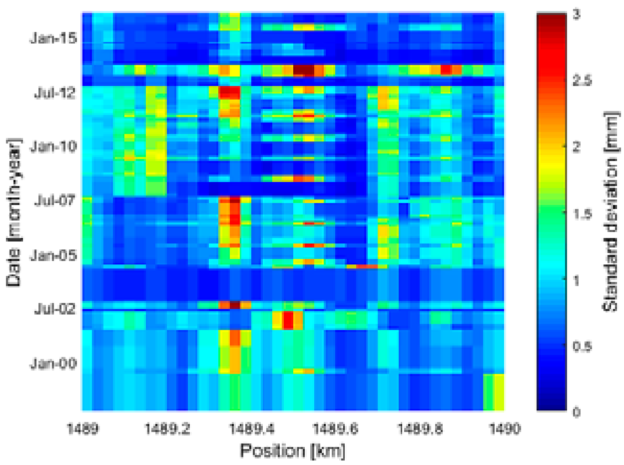
The environmental impact of railways should be reduced and, therefore, timber sleepers impregnated with creosote be replaced by concrete sleepers to reduce the emission of chemical products in the soil. In addition, concrete sleepers should be optimized to minimize material consumption and cost. A key issue here is to construct, maintain and guarantee appropriate support conditions for the sleepers. With known support conditions, sleepers can be optimized to a much higher degree than what is currently possible. 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. New knowledge can be obtained through physical measurement and numerical prediction of sleeper – ballast contact pressure and vertical track geometry degradation.

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. Both good and poor tracks (in terms of degradation rates) are included.

Using 20 years of track geometry car recordings on a section of the Iron Ore Line, vertical track geometry has here 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 figure). The upper layer of the subgrade on parts of the line is peat, while it is moraine in other places leading to a significant variation in the substructure's vertical stiffness. 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 found that recurrent severe local track irregularities often occur on track sections where there is a combination of a low magnitude and a high gradient in substructure stiffness. In such cases, tamping may not be a cost-efficient long-term solution to the problem. Instead upgrading of ballast and subgrade should be considered as an option.

It has been concluded that the method for stiffness measurement applied by us provides good information on the variation and distribution of track stiffness along the line



Longitudinal variation of vertical level (mean of swept standard deviation) measured on Malmbanan on some 60 occasions from September 1997 to February 2016. Wavelength interval 1–25 m. Track position km 1489 – 1490 (25 m segments)

SP26. (cont'd)

Thin film installed under a sleeper for measurement of sleeper–ballast contact pressure

and that it can be used as an efficient tool for the maintenance planning of a more robust railway track.

Based on a scanning device, a method has been developed to measure surface degradation of sleepers removed from track. Further, using a method developed in project TS14 with a thin film of piezoresistive material placed between sleeper and ballast (see figure), the distribution of contact pressure between sleeper and ballast has been measured for different types of traffic. Under sleeper pads (USP, see page 56) have been installed on a 300 m test section of the Western Main Line near Lerum. The test section can be used for a long-term assessment of sleeper and track geometry degradation with or 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 continued 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, i e, track with low magnitude or high gradient of substructure stiffness.

3. Application of a sleeper design where the bottom surface area under the two rail seats is maximized (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 assessment of performance of USP to improve load distribution and reduce contact stresses between sleeper and ballast.

The project description submitted to VINNOVA is dated 2013-06-25.

Jens Nielsen, Eric Berggren, Anders Hammar, Fredrik Jansson and Rikard Bolmsvik: Track geometry degradation on the Swedish heavy haul line – correlation between measured support stiffness gradients and differential settlement, *Proceedings 11th International Heavy Haul Association Conference (IHHA2017)*, Cape Town (RSA) September 2017, pp 542-549

Jens Nielsen, Eric Berggren, Anders Hammar, Fredrik Jansson and Rikard Bolmsvik: Railway track geometry degradation – correlation between track stiffness gradient and differential settlement, *IMechE Journal of Rail and Rapid Transport* (in printing). (Also listed under project EU16)

Eric Berggren and Jens Nielsen: Measurement of track stiffness irregularities – correlation between stiffness gradients and track geometry defects, *Proceedings Transportation Research Board (TRB) 97th Annual Meeting*, Washington DC (USA) January 2018, 11 pp

Jens Nielsen and Eric Berggren: Track geometry degradation and track stiffness on Swedish railway lines, Research Report 2017:02, *Chalmers Mechanics and Maritime Sciences*, Gothenburg November 2017, 117 pp

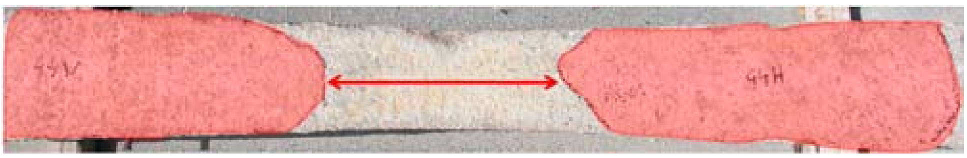
Jens Nielsen, Eric Berggren, Rikard Bolmsvik, Anders Hammar, Fredrik Jansson and Johan Lessner: Railway track superstructure: holistic optimization of design and maintenance for improved performance – guidelines and concluding technical report, Research Report 2017:05, *ibidem*, 65 pp (also listed under project EU16)

Jens Nielsen and Xin Li: Railway track geometry degradation due to differential settlement of ballast/subgrade – numerical prediction by an iterative procedure, *Journal of Sound and Vibration*, vol 412, 2018, pp 441-456 (also listed under projects TS15 and EU16)

Eric Berggren: A new measurement method to determine structural parameters of a railway track, *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

Jens Nielsen and Eric Berggren: Track geometry degradation on Malmbanan. Correlation between support stiffness gradient and differential settlement, *ibidem*

Johan Lessner: Measurements of contact pressure between sleeper and ballast, *ibidem*



Bottom surface of a sleeper removed from track with areas showing clear signs of ballast contact (red printing)

SP28. PREVENTION AND MITIGATION OF DERAILMENTS

Hindrad uppkomst och mildrad konsekvens av urspårningar

Project leader	Dr Björn Paulsson, Mechanics and Maritime Sciences (and formerly Trafikverket)
Period	2016-08-01 – 2018-06-30 (– 2018-12-31)
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)

This is a project under the Train Track Interaction Group (TTIG) at the UIC with the full name "Prevention and Mitigation of Derailments (PMD)". It aims at implementation of previous research and development projects by formulating the main results into an "International Railway Solution" (IRS). In particular, results from the D-RAIL project (our EU13) have been exploited.

The background to the project was the evaluation from the European Railway Agency (ERA) in 2005 that showed that costs for derailments increased. ERA's initiative for the long-term perspective was the EU project D-RAIL which highlighted that costs for derailments can be reduced by using modern monitoring equipment in a professional way. PMD is part of this effort. Other important projects that will contribute to PMD are the UIC projects HRMS (our SP25) and Axle Load Checkpoints (ALC).

The PMD project has created an Advisory Board that has had three meetings. The project has been presented to the UIC TTIG on four occasions and to the Freight Forum at UIC on two occasions. Draft versions of the IRS have been approved by all three groups. The IRS has also been scientifically reviewed by the University of Huddersfield in the UK and the Polytechnic University of Milan in Italy. Their comments have been processed and discussed at a dedicated meeting. A presentation to the ERA was given in Valencienne (France) in December 2017. According to routines at UIC, a new IRS has to be sent out for comments to the UIC members. This has now been carried out and the comments received from SNCF (France), RFI (Italy) and SBB (Switzerland) have been considered. An updated final draft with comments from the scientific review and the UIC review has now been compiled.

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 (cf the BSc thesis reported under project MU22) in order to work more proactively and adaptively. He also emphasized the importance of using university resources. This was presented at a public and televised hearing on 2018-06-07.

Björn Paulsson: Prevention and mitigation of derailments – A new International Railway Solution (Keynote Lecture), *Proceedings 20th Nordic Seminar on Railway Technology*, Gothenburg (Sweden) June 2018 (Summary and PowerPoint presentation)

Photo: Frida Hedberg, Aftonbladet Bild

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

ACADEMIC AWARDS

(up to June 2018)

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

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

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

Research Professors

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

Doctoral dissertations submitted by CHARMEC researchers during Stage 8

INTERNATIONAL CONFERENCES

During Stage 8 (and the months immediately following Stage 8) researchers from CHARMEC have participated in, and contributed to, the following major seminars, workshops, symposia, conferences and congresses:

The ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2015) in Boston MA (USA) 2-5 August 2015

The 24th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2015) in Graz (Austria) 17-21 August 2015

The 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015) in Colorado Springs CO (USA) 30 August – 3 September 2015

The 28th Nordic Seminar on Computational Mechanics (NSCM-28) in Tallinn (Estonia) 22-23 October 2015

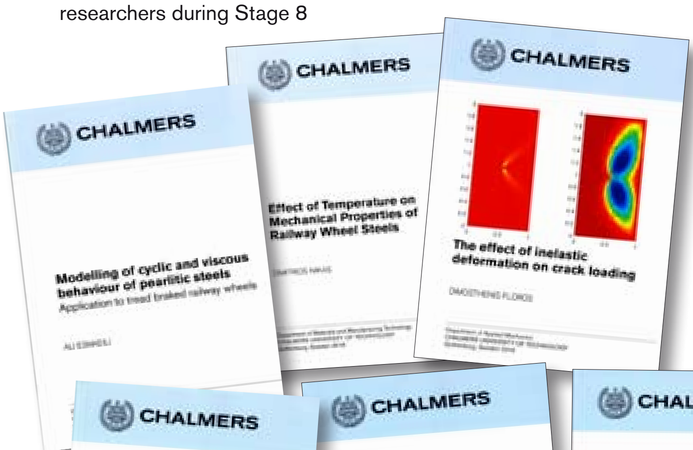
The 34th International Conference & Exposition on Structural Dynamics / International Modal Analysis Conference (IMAC XXXIV) in Orlando FL (USA) 25-28 January 2016

The 3rd International Conference on Railway Technology: Research, Development and Maintenance (Railways 2016) in Cagliari, Sardinia (Italy) 5-8 April 2016

The 5th Braking Technology Conference and Exhibition (EuroBrake 2016) in Milan (Italy) 13-15 June 2016

The 45th International Congress and Exposition of Noise Control Engineering (INTER-NOISE 2016) in Hamburg (Germany) 21-24 August 2016

Licentiate theses submitted by CHARMEC researchers during Stage 8



The 24th International Congress of Theoretical and Applied Mechanics (ICTAM 2016) in Montreal (Canada) 21-26 August 2016

The 12th International Workshop on Railway Noise (IWRN12) in Terrigal (Australia) 12-16 September 2016

The 19th Nordic Seminar on Railway Technology in Luleå (Sweden) 14-15 September 2016

The 29th Nordic Seminar on Computational Mechanics (NSCM-29) in Gothenburg (Sweden) 26-28 October 2016

The 18th International Wheelset Congress (IWC18) in Chengdu (China) 7-11 November 2016

The 8th International Conference on Low Cycle Fatigue (LCF8) in Dresden (Germany) 27-29 June 2017

The 25th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2017) in Rockhampton (Australia) 14-18 August 2017

The 11th International Heavy Haul Association Conference (IHHA 2017) in Cape Town (RSA) 2-6 September 2017

The 38th Risø International Symposium on Materials Science and Engineering in Risø/Roskilde (Denmark) 4-8 September 2017

The XIV International Conference on Computational Plasticity (COMPLAS 2017) in Barcelona (Spain) 5-7 September 2017

The 30th Nordic Seminar on Computational Mechanics (NSCM-30) in Kgs Lyngby (Denmark) 25-27 October 2017

The 97th Annual Meeting of the Transportation Research Board (TRB) in Washington DC (USA) 7-11 January 2018

The 36th International Conference & Exposition on Structural Dynamics / International Modal Analysis Conference (IMAC XXXVI) in Orlando FL (USA) 12-15 February 2018

The 7th Transport Research Arena (TRA 2018) in Vienna (Austria) 16-19 April 2018

The 20th Nordic Seminar on Railway Technology in Gothenburg (Sweden) 12-13 June 2018

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

PARTNERS IN INDUSTRY

The status report that follows applies as of October 2018. 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 a new slab track oriented PhD project at CHARMEC which runs since 2016.

Bombardier Transportation GmbH (2000)
As a leading provider of mobility solutions, Bombardier Transportation is a global manufacturer of vehicles and equipment for railway operations, as well as being a maintenance and service provider for rolling stock. The company's range of solutions includes very high-speed trains, intercity fleets, regional & commuter multiple units, metros, passenger coaches, locomotives, trams, propulsion systems, turn-key transit systems and rail control solutions. A worldwide presence and network is provided by over 39 000 employees, of whom 1800 are in Sweden.

The Mechanical Product Unit within the Rolling Stock Equipment division of Bombardier Transportation provides the direct support link to CHARMEC. A key focus is given to CHARMEC's activities surrounding 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 include wheelset component material technology, as well as braking system friction pair behaviours and their performance.

Faiveley Transport Nordic AB (1997)
The Wabtec Corporation is a leading supplier of value-added, technology-based products and services for freight rail, passenger transit and select industrial markets worldwide 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 is around 18 000, of whom 180 are based in Landskrona (Sweden).

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 35 locations throughout Sweden. 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.

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 maintenance providers.

SJ AB (2006)
SJ is a limited liability company owned by the Swedish state and is tasked with operating profitable passenger rail services, both independently and on behalf of national and regional traffic authorities. SJ operates 1 200 daily departures from 284 stations – from Narvik in the North to Copenhagen in the South, and from Stockholm in the East to Oslo

in the West, with almost 130 000 passengers per day in total. SJ's own rail services are primarily long-distance, comprising high-speed and night-train services as well as regional rail services. Tendered services mainly comprise shorter rail journeys for commuting to work or school within one county or region. One such example is SJ's subsidiary, SJ Götalandståg, which is tasked with operating commuter and regional trains in Western Sweden.

SJ is part of the solution for meeting Sweden's climate targets and all our trains in Sweden carry the Good Environmental Choice (Bra Miljöval) label. The SJ group has around 4 500 employees, of which on-train staff and train drivers are the largest groups. SJ expects CHARMEC research projects to create an increased understanding of, and a better platform for, improving technical solutions and maintenance services for the rolling stock, focusing on fulfilling customer needs, safety and sustainability.

SNC-Lavalin Rail & Transit AB (1995 and 1992)
Founded in 1911, SNC-Lavalin 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, SNC-Lavalin's employees are proud to build what matters. Our teams provide comprehensive end-to-end project solutions – including capital investment, consulting, design, engineering, construction management, sustaining capital, and operations and maintenance – to clients across oil and gas, mining and metallurgy, infrastructure, clean power, nuclear and EDPM (engineering design and project management). On July 3, 2017, SNC-Lavalin acquired Atkins, one of the world's most respected design, engineering and project management consultancies, which has been integrated into our sectors.

SNC-Lavalin maintains exceptionally high standards for health and safety, ethics and compliance and environmental protection, and is committed to delivering quality projects on budget and on schedule to the complete satisfaction of its clients.

In Sweden the company is based in Stockholm, Göteborg, Malmö, Helsingborg, Västerås, and employs 400 people. The purpose of our involvement with CHARMEC is to market the brand, develop networks, build knowledge, facilitate recruitment, develop existing services, and get inspiration for new ventures.

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 230 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 close to 25 000 wheelsets are connected to the pool. 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 7 050 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. 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 11 600 employees worldwide. For the financial year 1 April 2017 – 31 March 2018, the sales of the voestalpine Group (including all four divisions) amounted to MEUR 12 900. The Metal Engineering Division integrates all steel activities of the Group in the business units Rail Technology, Turnout Systems, Welding Consumables, Wire Technology, Tubulars and Steel. voestalpine Schienen GmbH 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. The voestalpine vae Group is a turnout system supplier including switching and locking mechanisms and a provider of advanced monitoring/ diagnostics solutions for the rail infrastructure as well as for the rolling stock. The main Austrian factory is located in Zeltweg.

RESULTS AND EFFECTS IN INDUSTRY

In October 2018, Trafikverket and our partners in the Industrial Interests Group for Stage 8 and Stage 9 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.

Bombardier Transportation

Through the previous CHARMEC Stages, the wheelset research projects dealing with 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. When earlier CHARMEC projects have been concluded 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. Bombardier Transportation 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.

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 in a certain wheel type. This analysis is critical if Green Cargo is to be able to develop appropriate remedies to overcome this problem. 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 two 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 our products, technical meetings with customers, and have represented Lucchini Sweden on the CEN and ERWA committees.

SJ

CHARMEC has provided support and expertise to SJ in several projects. Recent examples are the reviewing, evaluation and mapping of critical dimensional parameters of existing old wheelsets still in use. In addition, the braking performance of old wheels with brake block systems has been compared with the performance of wheels with a newer design. SJ has also benefitted from research results related to particle emissions provided by CHARMEC. The centre is highly appreciated and 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. During Stages 7 and 8, SJ increased its participation in CHARMEC projects and reference groups.

SNC-Lavalin Rail & Transit

CHARMEC has given SNC-Lavalin an outstanding research environment. We have gained a better understanding of wheel–rail contact forces, material properties, crack initiation, crack propagation, fatigue failure, maintenance, brake systems etc, all of which have benefitted the company's clients. SNC-Lavalin has employed a PhD from CHARMEC, and we see a potential for recruiting more PhDs from CHARMEC. SNC-Lavalin appreciates the valuable contact network that CHARMEC brings.

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 leads to substantial cost savings.

The Principal Agreement for Stage 9 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 2020 Programme Shift2Rail.

voestalpine Metal Engineering

Understanding the mechanisms of crack initiation and crack growth in rails caused by repeated wheel–rail contact loading is vital for voestalpine Schienen. During Stages 5, 6, 7 and 8, 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 detail in Stage 9. For voestalpine VAE, 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.

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. Picture courtesy of SJ

SPECIAL EVENTS AND ACHIEVEMENTS (Stage 8)

Board meetings relocated

Six of the twelve meetings of the CHARMEC Board during Stage 8 were combined with visits to organizations outside Chalmers: to Interfleet Technology AB (now SNC-Lavalin Rail & Transit AB) in Stockholm/Bromma on 25 November 2015; to Trafikverket in Stockholm/Solna on 12 May 2016; to Abetong AB in Vislanda and Alvesta on 23 November 2016; to SweMaint AB in Gothenburg on 9 May 2017; to SJ AB in Stockholm/Hagalund on 29 November 2017, and to Faiveley Transport Nordic AB in Landskrona on 22 May 2018. The seminars held at the Board meetings can also be followed via internet (Skype).

Leaving members

With due acknowledgement from CHARMEC, Board members Jakob Wingren of Bombardier Transportation (2012–2017), Robert Lagnebäck of SLL Trafikförvaltningen (2012–2016), Martin Schilke of SNC-Lavalin (2014–2016), Bengt Fors of Green Cargo (2015–2018) and Fredrik Holmberg of Bombardier Transportation (2017–2018) left the Board during Stage 8.

Project catalogue

At the start of CHARMEC's Stage 9 (1 July 2018–30 June 2021), a 30-page catalogue with 47 possible new research projects was compiled and discussed with the centre's partners. Among the items are rail welding, switch dynamics, contact cracks, damage growth and materials at high temperatures.

New departmental structure at Chalmers

As of 1 May 2017 the following reorganization affecting CHARMEC is in force: Former Department of Applied Mechanics now belongs to the new Department of Mechanics and Maritime Sciences (in short M2) except for the Division of Material and Computational Mechanics, which is now part of the new Department of Industrial and Materials Science (in short IMS).This latter department also includes the activities in the former Department of Materials and Manufacturing Technology. Former Department of Civil and Environmental Engineering is now part of the new Department of Architecture and Civil Engineering (in short ACE). In total the number of departments at Chalmers has shrunk from 18 to 13. The management and administration of CHARMEC falls under M2 from 1 May 2017.

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.

VINNOVA

VINNOVA (Sweden´s Innovation Agency) had a central role (after NUTEK) at the start of CHARMEC. During Stage 8 this agency financed project SP26, see page 59.

Family Ekman's Research Donation

During Stages 5, 6, 7 and 8, funds from this donation to Chalmers University have financed CHARMEC's projects SD6 and SD9. Overall, a total of about MSEK 20 from the donation has contributed to several research projects at the university during the years 2004–2017. In September 2016, the family representative Mr Ronny Ekman attended Milan Mousavi's doctoral examination in project SD9. In a meeting with Chalmers University at ETH (Swiss Federal Institute of Technology) in Zurich (Switzerland) on 3 May 2018, Ronny Ekman took part. Professor Emeritus Bengt Åkesson has been responsible for the use of the donation at Chalmers.

Areas of Advance

Chalmers University has profiled its research activities around eleven 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 been financially supported from them.

High-speed tracks in Sweden

Trafikverket is now planning sections of high-speed rail lines in Sweden. To establish demands on such lines with a so-called fixed track, or slab track, CHARMEC has started the new projects TS19 and VB13, see pages 22 and 29, which are financially supported by Trafikverket. Also the term ballastless track is in use here.

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 researchers participate in grading committees of PhD theses and act as discussion leaders at licentiate seminars at KTH, and, in the same way, KTH researchers serve at Chalmers. Collaboration also takes place between research groups at KTH and Chalmers, for example in project EU18. KTH is represented in the reference groups of projects TS20, MU22, MU31 and MU33.

JVTC at LTU

Collaboration with Luleå JVTC (the Railway Research Centre at Luleå University of Technology in northern Sweden) takes place in project TS15 and others. Professor Uday Kumar, who is Director of JVTC, is invited to CHARMEC Board meetings and, in the same way, CHARMEC’s Anders Ekberg is invited to JVTC Board meetings.

Denmark, Finland and Norway

Several meetings between CHARMEC and research establishments, government agencies and private companies in our Nordic neighbour countries took place also during Stage 8. For instance, Søren Lambertsen and Laszlo Tolnai from DSB (Danish Railways) met with our Roger Lundén and Tore Vernersson at Chalmers on 27 October 2016 to discuss maintenance of axles and wheels. Further, Roger Lundén visited the maintenance depot of DSB in Århus on 13 March 2017. Johan Ahlström in projects MU28, MU29 and MU30 co-operates with researchers at DTU (Technical University of Denmark). He and his research groups regularly attend the annual Risø International Symposium on Materials Science and Engineering.

RTRI

During Stage 8, CHARMEC has continued its co-operation in our MU and SD projects with the Railway Technical Research Institute (RTRI) in Tokyo (Japan). Among the involved researchers at RTRI (and our co-authors of scientific articles) are Drs Kazuyuki Handa, Katsuyoshi Igeuchi, Motohide Matsui and Toru Miyauchi.

Professor Roger Lundén visited RTRI on 9 November 2015 in combination with his attending the symposium STECH 2015 in Chiba (Japan), where he was a member of the International Scientific Committee. STECH stands for “Speed-Up and Sustainable Technology for Railway and Maglev Systems”. In parallel, and at the same location, the fair Mass-Trans Innovation was held.

Switch manufacturer Mi-Ne from Hakata/Kyushu (Japan) demonstrated repair of a rail with a squat (see our project MU31 on page 38) at the fair in Chiba

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 headings specified by the Board in each case are Background and aims, Reference group, Work performed, Results achieved, Published material, Future plans, Check against initial schedule, Follow-up of budget, and Miscellaneous. All of these two-page reports are edited, compiled into a document (about 50 pages) and submitted to the CHARMEC Board before their next meeting when they are studied and discussed. All semi-annual reports have been written in English since 30 June 2003. Bengt Åkesson continues to be responsible for editing of the reports together with Birgitta Johanson.

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 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 promoted. Doctoral students should be encouraged by the PRG to make study visits and 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. Some projects have a joint PRG.

At a meeting in 2008, the Board decided that all doctoral projects should have a PRG, that notes should be taken at all meetings, that these notes should be sent to CHARMEC's Director and 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 been continuously updated since 2001.

Doctoral examinations

Our 45 doctoral examinations in railway mechanics are listed on page 62. As seen, four of these took place during Stage 8 and eleven during Stage 7. Dimitrios Nikas in project MU28 defended his doctoral dissertation on 18 October 2018. Ali Esmaeili and Dimosthenis Floros in projects MU32 and MU33 defended their doctoral dissertations on 10 and 18 January 2019, respectively.

Implementation of research results

Starting in 2013, results from each of CHARMEC's concluded research projects that are ready for industrial implementation are compiled in special documents distributed to the Board members.

Assistant Professors

During Stage 8, Dr Astrid Pieringer, Dr Peter Torstensson and Dr Björn Pålsson (now Senior Lecturer) have continued to be engaged as Assistant Professor (Swedish: forskarassistent) at CHARMEC. They have been active in projects VB12, TS16 and TS18, respectively.

Appointment of Associate Professor

As of 13 March 2017, President Stefan Bengtsson of Chalmers University appointed our Johan Ahlström (projects MU28 etc) Associate Professor in Materials Technology. His qualitive and quantitive merits had been assessed by Professor Herbert Danninger of Technische Universität Wien (Austria), Professor Reinhard Pippan of Erich Schmidt Institute of the Austrian Academy of Sciences (also Montanuniversität Leoben) and Professor Ali Fatemi of University of Toledo (OH, USA). Johan Ahlström's inauguration lecture on 10 March 2017 had the title "Railway wheel and rail steels – properties and damage mechanisms".

Appointment of Docent

After an expert review of his academic achievements, our Tore Vernersson (projects SD4, SD7, SD8, SD10 etc) was awarded the degree of Docent (highest academic qualification in Sweden) on 20 September 2016. The reviewing experts were Professor Moyra McDill of Carleton University in Ottawa (Canada) and Professor Lars-Erik Lindgren of Luleå University of Technology in Luleå (Sweden). The title of Tore Vernersson's docent lecture on 20 September 2016 was "Friction brakes – development and challenges from a railway perspective".

Present from CHARMEC at the inauguration ceremony on 28 September 2018 for new professors at Chalmers University were (from below and the left): Magnus Ekh (MU34 etc), Elena Kabo (TS20 and MU31 etc), Jens Nielsen (TS8 and EU16 etc), Thomas Abrahamsson (TS14), Bengt Åkesson, Tore Vernersson (SD10 etc), Anders Ekberg (Director and EU14 etc), Roger Lundén (SD10 etc), Jim Brouzoulis (MU20), Björn Pålsson (TS18 and EU14 etc), Peter Torstensson (TS16 and EU16 etc) and Mikael Fermér (doctoral dissertation in 1993 on railway braking supervised by Roger Lundén)

Appointment of Research Professors

From 1 September 2017 and 1 January 2018, respectively, our Elena Kabo (projects MU31 etc) and Jens Nielsen (projects TS8 etc) have been employed at Chalmers and CHARMEC as so-called Research Professors (they were earlier hired by us from the companies Qamcom Research and Technology AB and ÅF AB, respectively). A Research Professor follows a new Specialist Track which has been established at Chalmers University in parallel to the standard Faculty Track. Elena Kabo held her inauguration lecture "On track towards sustainable tracks" on 24 August 2017, and Jens Nielsen held his corresponding lecture "Integrated analysis of dynamic vehicle-track interaction and degradation of railway tracks" on 19 October 2017.

Skiing in Hauser Kaibling before the 27th workshop in January 2017. From the left: Johan Ahlström, Rudi Wiltschi, David Künstner, Roger Lundén, Anders Ekberg, Magnus Ekh, Stephan Scheriau, Knut Andreas Meyer and Rostyslav Skrypnyk

Guest researchers

Doctoral student Matthias Germonpré from Katholieke Universiteit Leuven in Belgium spent March–May 2017 at CHARMEC studying vibrational excitation caused by stiffness variations along the track as part of project EU16. Master's student Guilhem Dumont from Ecole Polytéchnique Universitaire de Lille in France stayed May–July 2017 investigating frictional welding of rails in project EU15 WRIST.

Björn Paulsson

Former employee of Trafikverket in Borlänge and co-worker at UIC in Paris, Dr hc Björn Paulsson, was engaged by CHARMEC during Stage 8 starting in September 2016. His main contributions have been to project SP28, see page 61, and to our EU projects. Björn Paulsson was the first chairman 1995–2008 of the Board of CHARMEC.

Exchange with voestalpine

As previously, meetings between CHARMEC researchers and their Austrian colleagues at rail manufacturer voestalpine Schienen GmbH in Leoben and switch manufacturer voestalpine VAE GmbH in Zeltweg were held twice a year during Stage 8. Experts were invited to these two-day workshops from the Austrian Academy of Science (Erich Schmid Institute of Materials Science) and from the Materials Centre Leoben, which are both linked to the University of Leoben, and from the Competence Centre Virtuelles Fahrzeug (ViF) in Graz.

The meetings during Stage 8 were held on 18–19 January 2016 in Leoben and Zeltweg, 7–8 June 2016 in Gothenburg, 16–17 January 2017 in Leoben and Zeltweg, 13–14 June 2017 in Gothenburg, and 15–16 January 2018 in Leoben and Zeltweg. The 30th workshop was held on 4–5 June 2018 in Gothenburg including a celebration party at New Älvsborg Fortress in the mouth of Göta River.

In December 2017, Uwe Ossberger of voestalpine VAE visited CHARMEC to learn about the company's use of our in-house software DIFF (developed in the TS projects) for simulation of dynamic interaction between vehicle and track.

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 also has assisted Lucchini Sweden on the CEN and ERWA committees, see further page 72. The collaboration also involves the mother company Lucchini RS in Lombardy, Italy.

Brake test rig in Surahammar

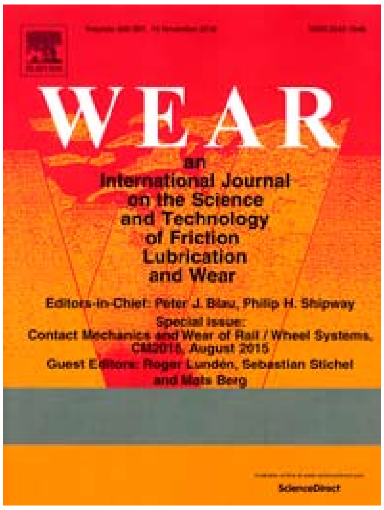
This Swedish rig, see page 58, has been decommissioned during Stage 8. In addition to the test rigs at RTRI in Japan, new nearby facilities are now being sought for by CHARMEC.

SPECIAL EVENTS … (cont'd)

CM2015 and CM2018

The International Conference on Contact Mechanics and Wear of Rail/Wheel Systems, held every third year, is central to CHARMEC's activities. As mentioned in the Triennial Report for Stage 7, selected peer-reviewed papers from the 10th conference CM2015 in Colorado Springs (USA) would be published in a Special Issue of the scientific periodical Wear with our Anders Ekberg and Roger Lundén being Guest Editors together with Stuart Grassie, Mats Berg and Sebastian Stichel. This issue appeared in November 2016, see photo. CHARMEC had 12 participants in CM2015 and among the 48 articles in Wear, 10 have authors from our centre. The 11th CM conference was held at Delft University of Technology in The Netherlands on 24–27 September 2018 with 13 researchers from CHARMEC attending.

Our Roger Lundén served on the International Committee of the CM conferences during the years 2001–2015, being its chairman 2003–2006. Anders Ekberg has the same membership from 2015 and he is now chairman of the committee (from September 2018).



Front cover of Special Issue of Wear featuring 48 articles from CM2015

IWRN 12

The 12th International Workshop on Railway Noise (IWRN 12) was arranged in Terrigal (Australia) on 12–15 September 2016 with CHARMEC's Jens Nielsen, Astrid Pieringer and Peter Torstensson taking part. Jens Nielsen is a member of the international committee of the IWRN workshops. As described in the previous Triennial Report, the IWRN 11 was organized by CHARMEC in Uddevalla (Sweden). The IWRN 13 will be held in Gent (Belgium) on 16–20 September 2019.

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). The assistance includes clarification of the reasons behind the damage and measures to deal with the issue with a minimum of disturbance to operations. CHARMEC also assists LKAB and its subsidiary MTAB in improving braking performance on their 120-tonne wagons and 360-tonne locomotives, see page 43.

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 which researchers from CHARMEC take part. The latest one, IHHA11 on 2–6 September 2017 in Cape Town (RSA), was attended by our Elena Kabo, Roger Lundén and Jens Nielsen. It was followed-up by a NHH mini-conference in Kiruna on 27 October 2017. The next IHHA STS Conference will be held in Narvik (Norway) on 10–14 June 2019. Here STS stands for Specialist Technical Session.

ERWA and IWC

Five wheelset manufacturers (groups) from eight European countries, including Lucchini Sweden, belong to the European Railway Wheels Association (ERWA). This association was launched in Rome (Italy) in 2001 and since 2004 has been known as the UNIFE Railway Wheels Committee with 11 member companies from 9 different countries. UNIFE (Union des Industries Ferroviaires Européennes) is the Union of European Railway Industries. During the first part of Stage 8, Roger Lundén continued to serve on ERWA's technical committee and took part in meetings, most of which were held at UNIFE in Brussels (Belgium).

ERWA has assumed overall responsibility for the International Wheelset Congresses (IWC) which were started in 1963 and are held every third year. Roger Lundén and Tore Vernersson took part in the 18th IWC in Chengdu (China) on 7–11 November 2016. The 19th IWC will be held in Venice (Italy) on 16–20 June 2019. Our Elena Kabo serves on its technical committee.

Up-grading of tracks for freight transports

This work started in project EU14 and was there presented in Deliverable 1.1.4, see the Triennial Report for Stage 7. Our activities have continued during Stage 8.

Editorial Boards of JRRT and FFEMS

Since 2005, Roger Lundén has been a member of the Editorial Board of the IMechE Journal of Rail and Rapid Transit (JRRT). Many research results in railway mechanics from Chalmers/CHARMEC have been published in this periodical (more than 60 articles up to autumn 2018). IMechE stands for Institution of Mechanical Engineers with premises on Birdcage Walk in Westminster, London (UK). A Special Issue of JRRT containing selected peer-reviewed contributions from the conference IHHA11, see above, with Roger Lundén being one of five Guest Editors will soon be published.

During the years 2004–2016, Roger Lundén has been a member of the Editorial Board of the international scientific journal Fatigue & Fracture of Engineering Materials & Structures (FFEMS). Several results of CHARMEC's research have been published in this journal.

Editorial Board of IJRT

Since 2013, Jens Nielsen is a member of the Editorial Board of the International Journal of Rail Transportation (IJRT).

Contact mechanics course

A renewed graduate course on contact mechanics was given at Chalmers during Stage 8 by Professor Roger Lundén and Professor Magnus Ekh, with five of CHARMEC's doctoral students attending. The two parts of the course are "Engineering contact mechanics" (Lundén) and "Computational contact mechanics" (Ekh).

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 8, the 31st, 32nd and 33rd NBIU took place with Jens Nielsen taking part for the 19th, 20th and 21th time.

Professional training for railway projects

At Campus Varberg, some 90 km south of Gothenburg, a two-year training programme has been provided since 2010 for students aiming at a professional career as a planning engineer in the railway sector. The programme was initiated by Banverket (now Trafikverket), it falls under the Swedish National Agency for Higher Vocational Education, and is organized by Folkuniversitetet. Roger Lundén served on an advisory board until 2016.

Svenska Mekanikdagar

This two-day conference (in English: Swedish Mechanics Days) is held every other year and normally circulates between Swedish universities and institutes of technology. During Stage 8, Uppsala University hosted the conference on 12–13 June 2017. Several of CHARMEC's researchers have presented their results at the conferences but these minor papers are not included in the reference lists of the CHARMEC projects in the foregoing.

Nordic Rail Fair

CHARMEC took part in the 11th Nordic Rail Fair at the Elmia Exhibition Centre in Jönköping (Sweden) on 6–8 October 2015. We shared a stand with KTH Railway Group and Luleå Railway Research Centre (JVTC). Our research projects were displayed and printed material was distributed to visitors. In contrast, CHARMEC did not have a stand at the 12th Fair on 10–12 October 2017 following a decision by our Board on 23 November 2016. However, a group of our doctoral candidates together with Professor Roger Lundén visited the fair. The next Nordic Rail Fair will take place on 8–10 October 2019.

CHARMEC's Jens Nielsen serving at the 11th Nordic Rail Fair

Nordic seminars on railway technology

The Railway Research Centre (JVTC) at Luleå University of Technology in northern Sweden organized the 19th Nordic Seminar on Railway Technology in Luleå on 14–15 September 2016 with about 90 participants. The 20th seminar was arranged by CHARMEC in Gothenburg on 12–13 June 2018 under the theme "Research and innovations for a sustainable railway (Forskning och innovationer för en hållbar järnväg)". About 115 people took part, see page 37. Introductory speeches at the seminar were delivered by

President and CEO Stefan Bengtsson of Chalmers and Director General Lena Erixon of Trafikverket (the Swedish Transport Administration). Contributions to the seminars from CHARMEC's researchers are listed under the project descriptions in the foregoing.

Swedtrain

Swedtrain is the Swedish Association of Railway Industries. Our students Ejder Eken and Robert Friberg received the 2015 Swedtrain Award for Best Master's Thesis. Their work had the title "Modelling of dynamic track forces generated by tram vehicles" and had been supervised by Dr Anders Frid of ÅF and Professor Jens Nielsen of CHARMEC. Further, our students Arthur Aglat and Jannik Theyssen received the corresponding Swedtrain award in 2017 for their work "Design of a test rig for railway curve squealing noise" which had been supervised by Dr Astrid Pieringer and Professor Wolfgang Kropp of CHARMEC. Swedtrain is one of the organizations that arrange the annual Järnvägsdagen (The railway day) in Sweden where researchers from CHARMEC take part.

Jannik Theyssen (left) och Arthur Aglat surrounded by Swedtrain's Pia Lagerlöf and KTH's Stefan Östlund at the award ceremony in Stockholm on 17 May 2018

VTI

Staff from CHARMEC also take part in the annual meetings arranged by VTI, the Swedish National Road and Transport Research Institute located in Linköping. Since 1 December, 2017 Dr Peter Torstensson from CHARMEC is an employee of VTI at its office in Gothenburg.

Göteborgs Spårvägar

During Stage 8 renewed contacts were taken between Göteborgs Spårvägar (Gothenburg Trams) and CHARMEC to consider a possible co-operation. For instance, their Florencio Garcia and Joakim Jörgensen met with our Anders Ekberg, Astrid Pieringer, Peter Torstensson and Ivan Zenzerovich on 27 August 2015 to discuss abatement of squeal noise, see projects VB11 and VB13 on pages 26 and 29.

DB Systemtechnik

DB Systemtechnik GmbH is the engineering office of Deutsche Bahn AG. A co-operation with them has been established through our Dr Astrid Pieringer who works in a project at their Department of Acoustics, Vibrations, Aerodynamics and HVAC in Munich during the period May 2018–June 2019. This is part of the Marie Skłodowska-Curie Individual Fellowship obtained by her.

The overall objective of the project at DB Systemtechnik is to advance the development towards condition-based maintenance of railway tracks by developing a new methodology for Acoustic MONitoring of TRACK quality (AMONTRACK). Numerical methods from our projects VB10 and VB12 will be combined with experimental results registered by their Schallmesswagen (SMW), which records its own rolling noise and vertical axle box acceleration. Detection and assessment of localized track faults such as squats, deteriorated joints and hanging sleepers are aimed at. Also acoustically relevant track properties will be evaluated.

Track to the future

This British project engages researchers from the country´s universities in Birmingham, Huddersfield, Nottingham and Southampton. Our Anders Ekberg is a member of the project's international scientific committee which met at Dillington House in Somerset on 9 October 2015, 26 July 2017 and 19–20 July 2018.

SweMaint

CHARMEC's industrial partner SweMaint AB hosts a wheelset pool for freight wagons. Our Anders Ekberg delivered a lecture for the customers of the pool in Gothenburg on 9 February 2017 with the title "Wheel damage and breakdown" where in particular winter problems were discussed. Anders Ekberg has also supported the company in an investigation of a damaged axle.

Indian Railways

The co-operation with India's RDSO (Research Design & Standards Organisation, Ministry of Railways) on the design of concrete monobloc sleepers in our project SP27 (financed by UIC) was successfully finalized during Stage 8. Further, Professor Nalinaksh S Vyas from the Department of Mechanical Engineering at Indian Institute of Technology Kanpur (Uttar Pradesh) visited CHARMEC on 9 October 2015 and 19 September 2016 to discuss possible co-operation. He is chairman of the Technology Mission for Indian Railways (TMIR) and reported, among other matters, that a railway Delhi-Calcutta-Chennai-Mumbai-Delhi is under construction within their project Dedicated Freight Corridor Corporation of India Limited (DFCCIL).

Korean Railways

From Korean Railroad Research Institute in Seoul (South Korea), Dr Hyun-Kyu visited CHARMEC on 16 May 2016 to discuss high-speed lines on sleeper track and ballast-less track. Both types exist in South Korea and a possible co-operation with us when renovating the first type was elaborated on.

UTMIS

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 the seminars arranged by UTMIS.

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 EU18 in 2016–2019 during Stage 8. Lately these projects have belonged to the Horizon 2020 Framework Programme and have fallen under the Shift2Rail joint technology initiative, see below.

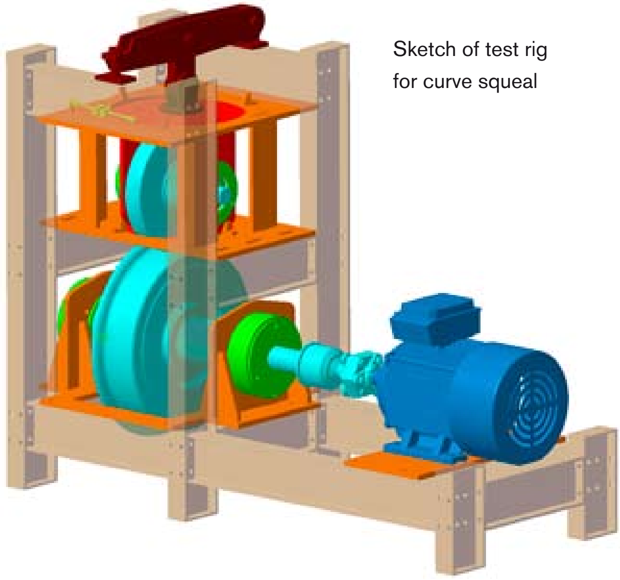
Shift2Rail

Shift2Rail

Shift2Rail is an initiative within the EU Horizon 2020 programme with "focused research and innovation in the rail area for 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 71 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". Projects are In2Track (September 2016 –February 2019) and Fr8Rail (September 2016–August 2019) with continuations through the projects In2Track-2 (starting November 2018) and Fr8Rail-2 (starting May 2018).

Test rig for curve squeal

This rig is being built by the Division of Applied Acoustics at Chalmers for use in project VB13, see page 29. It was designed by Master's students Arthur Aglat and Jannik Theyssen.



Sketch of test rig for curve squeal

CHARMEC´s FactFlashes

Under this heading, CHARMEC researchers are publishing (mostly in Swedish) short items accounting for some of our achievements, aimed at a wide audience (see www.charmec.chalmers.se/FactFlash/).

Associated projects AP

The new project AP5 "Deformations of piled slab track on soft soils", financed by Trafikverket, is being run since 2016 at the Chalmers Department of Architecture and Civil Engineering. As mentioned in the previous Triennial Report, our Gaël Le Gigan on 3 December 2015 successfully defended his doctoral dissertation in project AP4 "Improved performance of brake discs".

CHARMEC Publications 1995-2015

A 123-page document listing 960 unique publications written by CHARMEC's researchers during the centre's first 20 years has been compiled by Bengt Åkesson and Roger Lundén. The document is available at "http://www.chalmers.se/charmec". A list covering research in railway mechanics at Chalmers before the start in 1995 of CHARMEC is given in the publication.

Bengt Åkesson, Tore Dahlberg and Roger Lundén: Railway mechanics research 1987-1995 at Chalmers University in Gothenburg – dynamic train/track interaction and railway wheelsets, Research Report F185, *Chalmers Solid Mechanics*, Gothenburg 1996, 42 pp

FINANCIAL REPORT

This is a presentation of the cash and in-kind investments for Stage 8, 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 8 dated 1 October 2015.

Report per party

Budgeted cash and in-kind investments per party according to the Principal Agreement for Stage 8 are presented in Table 1. Included are also cash contributions from Chalmers, Trafikverket, UIC and VINNOVA that were not included in the Principal Agreement for Stage 8. Cash contributions from the EU are also included although they are not a formal part of CHARMEC's budget. In the new EU 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 25 November 2015, 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: 2015-11-15, 2016-03-01, 2016-09-01, 2017-03-01, 2017-09-01 and 2018-03-01. This proposal was accepted by all partners.

In April 2011, Trafikverket approved a project proposal from Luleå Technical University (LTU) providing three years of funding for two parallel doctoral projects on track switches, one at LTU and one at Chalmers/CHARMEC. The project at CHARMEC is TS15 "Improved availability and reduced life cycle cost of track switches" with a total budget (for five years; the last two years were approved in May 2015) of kSEK 4 775. In 2016, an additional amount of kSEK 411 was approved. Of the total amount kSEK 5 186, kSEK 725 are assigned to Stage 6, kSEK 2 704 to Stage 7 and kSEK 1 757 to Stage 8. The full amount has been invoiced. 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 a total budget kSEK 2 000, of which kSEK 1 760

Table 1. Cash and in-kind contributions (kSEK) per party during Stage 8

Party	Cash		In-kind		Total	
	Budget	Paid	Budget	Performed	Budget	Paid/Performed
Chalmers	14 853	14 853	4 450	4 450	19 303	19 303
Abetong	1 554	1 554	714	437	2 268	1 991
Bombardier	1 800	1 800	1 200	1 247	3 000	3 047
Faiveley	1 050	1 050	600	569	1 650	1 619
Green Cargo	660	660	330	0	990	660
Lucchini	1 485	1 485	900	910	2 385	2 395
SJ	660	660	–	–	660	660
SNC-Lavalin	195	195	150	66	345	261
SweMaint	162	162	162	30	324	192
Trafikverket	20 970	20 970	–	–	20 970	20 970
voestalpine	2 316	2 316	2 460	2 709	4 776	5 025
EU	12 331	12 331	–	–	12 331	12 331
EU Shift2Rail	3 885	3 885	–	–	3 885	3 885
UIC	176	176	–	–	176	176
VINNOVA	566	566	–	–	566	566
From Stage 7	4 235	4 235	–	–	4 235	4 235
Total	66 898	66 898	10 966	10 418	77 864	77 316

Note 1 The funding from EU does not formally belong to CHARMEC's budget

Note 2 For "EU Shift2Rail", kSEK 3 555 are the EU contribution to EU17 and kSEK 330 are the funding for EU18 are assigned to Stage 8 and kSEK 240 to Stage 9. At the end of Stage 8, kSEK 1 760 had been invoiced. 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 a total budget kSEK 2 000, of which kSEK 833 are assigned to Stage 8 and kSEK 1 167 to Stage 9. At the end of Stage 8, kSEK 833 had been invoiced. In December 2016, Trafikverket agreed to contribute kSEK 120, and was invoiced this amount, to the project SP28 "Prevention and mitigation of derailments". This project has also received funds from UIC, see Table 1.

In 2015, the EU approved a project proposal from Chalmers/CHARMEC and our European partners providing kEUR 217 to the EU project "Capacity4Rail". An additional kEUR 157 was approved in 2017. In 2015, the EU approved a project proposal from Chalmers/CHARMEC and our European partners providing kEUR 417 to the EU project "WRIST". In 2015, the EU approved a project proposal from Chalmers/CHARMEC and our European partners providing kEUR 502 to the EU16 project "In2Rail". An additional kEUR 129 was approved in 2016 and 2017. The EU funding does not formally belong to CHARMEC's budget.

Chalmers/CHARMEC participates in the EU Shift2Rail programme as a Linked Third Party to Trafikverket. In 2016, Trafikverket and 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 October 2013, VINNOVA approved a project proposal from CHARMEC providing funding for the SP26 project "Holistic optimization of tracks". The total budget of the project is kSEK 3 877, of which kSEK 3 331 are VINNOVA funds and the remaining amount is in-kind contributions from Abetong, Trafikverket and EBER Dynamics. CHARMEC's share of the VINNOVA funds, after contract amendments 2016 and 2018, is kSEK 1 730 of which kSEK 1 164 are assigned to Stage 7 and the remaining amount, kSEK 566, to Stage 8.

In August 2017, it was agreed that UIC would contribute kEUR 18 to the SP28 project "Prevention and mitigation of derailments" and the full amount has been invoiced. Also Trafikverket has contributed to SP28, see above.

Chalmers University supports CHARMEC financially. For Stage 8, the agreed amount was kSEK 125 from Area of Advance "Materials Science", kSEK 125 from Area of Advance "Energy", kSEK 3 240 centrally from the Department of Mechanics and Maritime Sciences and kSEK 2 673 from its Division of Dynamics. The Division of Computational Mechanics contributed kSEK 2 673 and the Division of Engineering Materials contributed kSEK 1 605. Here both divisions are from May 2017 part of the Department of Industrial and Materials Science. The Division of Technical Acoustics in the Department Architecture and Civil Engineering contributed kSEK 535. Chalmers also agreed to contribute kSEK 1 600 during Stage 8 to the SD9 project "Multiobjective optimization of bogie system and vibration control" from a donation, see page 68. The Department of Mechanics and Maritime Sciences contributed kSEK 500 to project TS18. Finally, Chalmers supports EU projects, which during Stage 8 has meant a contribution of kSEK 403 + 242 + 563 +554 + 15 = kSEK 1 777 to the projects EU14, EU15, EU16, EU17 and EU18.

Table 2. Budgeted and used cash and in-kind contributions (kSEK) during Stage 8, with the Industrial Interests Group (including Trafikverket) 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	9 876	9 784	1 510	1 096	500	500	11 886	11 380
VB	2 733	2 887	230	306	400	400	3 363	3 593
MU	15 838	15 408	2 540	3 546	1 650	1 650	20 028	20 604
SD	5 595	6 046	680	836	600	600	6 875	7 482
EU	13 972	13 589	0	0	0	0	13 972	13 589
EU Shift2Rail	9 546	9 873	0	0	0	0	9 546	9 873
SP	862	1 744	0	184	0	0	862	1 928
Management	2 900	3 081	0	0	1 300	1 300	4 200	4 381
Total	61 322	62 412	4 960	5 968	4 450	4 450	70 732	72 830

Note 1 Budget under "Cash" is as of 23 November 2018. These amounts have been transferred to the projects
Note 2 In-kind contributions from Chalmers include support from Areas of Advance "Energy" and "Transport"
Note 3 The balance in cash to be transferred to CHARMEC's Stage 9 by 30 June 2018 is kSEK 66 898 – 61 322 = kSEK 5 576

FINANCIAL … (cont'd)

The following amounts in cash, totalling KSEK 30 852, due for CHARMEC's Stage 8 have been received as per agreements:

6 × KSEK 259	Abetong
6 × KSEK 300	Bombardier Transportation Sweden
6 × KSEK 175	Faiveley Transport Nordic
6 × KSEK 110	Green Cargo
6 × KSEK 247.5	Lucchini Sweden
6 × KSEK 110	SJ
6 × KSEK 32.5	SNC-Lavalin
6 × KSEK 27	SweMaint
6 × KSEK 2 750 + 4 470 = KSEK 20 970	Trafikverket
6 × KSEK 212	voestalpine Schienen
6 × KSEK 174	voestalpine VAE

From EU, KSEK 2 816 + 3 332 + 3 878 = KSEK 10 026 in cash have been received for the projects EU14, EU15 and EU16 for Stage 8. For EU14, additionally KSEK 125 (assuming EUR 1 = SEK 10) will be received and for EU16 additionally KSEK 2 180 are expected (assuming EUR 1 = SEK 10) for Stage 8. These sums are included in the amounts in Table 1.

From Trafikverket, KSEK 3 555 + 330 = KSEK 3 885 in cash have been received for the Shift2Rail projects EU17 and EU18 for Stage 8. Here the amount KSEK 3 555 for EU17 originates from EU. Additionally, KSEK 4 452 has been received from Trafikverket for project EU17, but the same amount has been refunded to the basic funding from Trafikverket (not shown in Table 1 since these amounts cancel each other).

From VINNOVA, KSEK 566 in cash have been received for project SP28 for Stage 8. From UIC, KSEK 96 (KEUR 10) has been received and an additional KSEK 80 (KEUR 8; assuming EUR 1 = SEK 10) are due for project SP28. However, the full amount KSEK 176 is included in Table 1.

In total, KSEK 125 + 125 + 3 240 + 2 673 + 2 673 + 1 605 + 535 + 1 600 + 500 + 1 777 = KSEK 14 853 have been received from Chalmers for Stage 8. 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 8, 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 (KSEK 1 450) originate from the Area of Advance "Transport" (KSEK 1 300) and the Area of Advance "Energy" (KSEK 150) at Chalmers and have not been shown separately.

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.

MANAGEMENT AND ADMINISTRATION

Director	Professor Anders Ekberg (from 2012-10-01)
Period	1995-07-01 – 2018-06-30 (2021-06-30)
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 3 000
Industrial interests in-kind budget and results, see pages 14–61	—

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 the Shift2Rail Programme during Stage 8, 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.

CHARMEC STAGE 9

The Principal Agreement for CHARMEC's Stage 9 (1 July 2018 – 30 June 2021) largely follows VINNOVA's Principal Agreement for the Centre's Stage 4. As with Stages 5, 6, 7 and 8, Trafikverket (earlier Banverket) has been included in the agreement for Stage 9 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 and 8.

The programme areas in Stage 9 are the same as those during Stage 8, 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 is one of the Joint Undertaking (JU) members of Shift2Rail, which has a total budget of MEUR 920. Trafikverket will carry out most of its research activities in co-operation with research environments, among them CHARMEC. This means that Trafikverket's financing will be combined with that of Shift2Rail, implying that CHARMEC's total budget will increase. This larger involvement in EU projects has created new possibilities and challenges for CHARMEC and its partners. As an example, we entered Stage 8 as Scientific and Technical co-ordinator of one of the Shift2Rail projects (see EU17 In2Track on page 56).

President of Chalmers University of Technology, Stefan Bengtsson, signed the contracts for Stage 9 on 27 August 2018. Funding (kSEK) for Stage 9 (as of 23 November 2018) is shown in the adjoining table. He also appointed the following Board members for CHARMEC's Stage 9 (decision dated 16 August 2018):

Ingemar Frej	Trafikverket (chair)
Rikard Bolmsvik	Abetong
Roger Deuce	Bombardier Transportation
Fredrik Blennow	Faiveley Transport
Markus Gardbring	Green Cargo
Erik Kihlberg	Lucchini Sweden
Susanne Rymell	SJ
Sven-Ivar Karlsson	SNC-Lavalin
Tilo Reuter	SweMaint
Björn Drakenberg	voestalpine Metal Engineering
Sebastian Stichel	KTH Railway Group
Per Lövsund	Chalmers Mechanics and Maritime Sciences

For photos of the new Board, see page 9.

On 16 August 2018, Stefan Bengtsson also appointed Anders Ekberg as Director of CHARMEC for Stage 9.

	Cash	In-kind	Total
Industrial Interests Group	9 732	5 766	15 498
Trafikverket	16 500	–	16 500
Chalmers	12 867	1 200	14 067
Chalmers (AoA Transport)	–	2 000	2 000
Trafikverket (projects)	1 407	–	1 407
Trafikverket (Shift2Rail)	8 014	–	8 014
EU (Shift2Rail)	14 288	–	14 288
InfraSweden2030	100	–	100
From Stage 8	5 576	–	5 576
Total	68 484	8 966	77 450

CONCLUDING REMARKS

Stage 8 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. I believe that CHARMEC provides first rate research, is a knowledgeable dialogue partner, an important information hub, and an expert network builder. Stage 8 has also shown that Railway Mechanics more than ever is key to the development of sustainable land transport both in Sweden and internationally. CHARMEC looks forward to Stage 9 with confidence. Our motto of "academic excellence combined with industrial relevance" will continue.

Gothenburg in January 2019

ANDERS EKBERG

CHARMEC RESEARCH 1995 – 2018 (Status as of January 2019)

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
Prof Jens Nielsen / Prof Elena Kabo / Dr Peter Torstensson
Ms Xin Li [1]

TS16 Time-domain model of railway braking noise [3]
Dr Peter Torstensson

TS17 Optimization of materials in track switches
Prof Jens Nielsen / Prof Magnus Ekh / Dr Björn Pålsson
Mr Rostyslav Skrypnyk [1]

TS18 Numerical simulations of train-track deterioration
Dr Björn Pålsson

TS19 Design criteria for slab track structures
Prof Jens Nielsen / Dr Rikard Bolmsvik / Prof Anders Ekberg
Mr Emil Aggestam [1]

TS20 Wheel tread damage – identification and effects
Prof Elena Kabo / Prof Anders Ekberg / Prof Jens Nielsen / Doc Tore Vernersson
Mr Michele Maglio

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 [3]
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

Departments involved at Chalmers:
Architecture and Civil Engineering
Industrial and Materials Science
Mechanics and Maritime Sciences

The abbreviation ***Doc*** is used for ***Docent*** which is the highest academic qualification in Sweden (above the doctor's level)

Upper name(s):
Project leader(s) and supervisor(s)

Lower name(s):
Doctoral candidate(s) or coworker(s)

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**
Prof Johan Ahlström / Prof Christer Persson
Ms Casey Jessop [1]

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**
Prof Magnus Ekh / Prof Johan Ahlström / Doc Tore Vernersson
Mr Ali Esmaeili [2]

MU33 **Numerical simulation of rolling contact fatigue crack growth in rails**
Prof Fredrik Larsson / Prof Anders Ekberg
Mr Dimosthenis Floros [2]

MU34 **Influence of anisotropy on deterioration of rail materials**
Prof Magnus Ekh / Prof Johan Ahlström
Mr Knut Andreas Meyer [1]

Notes:

1. Licentiate (*teknologie licentiat*)
2. PhD (*teknologie doktor*)
3. This project has been finished
4. Later at Linköping Institute of Technology
5. Rolling Contact Fatigue

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 for modern trains**
  Doc Tore Vernersson / Prof Roger Lundén
  Mr Mandeep Singh Walia [1]

- **EU16** – **In2Rail** [3]
  Prof Anders Ekberg and co-workers
- **EU17** – **In2Track**
  Prof Anders Ekberg and co-workers
- **EU18** – **Fr8Rail**
  Prof Anders Ekberg / Tore Vernersson

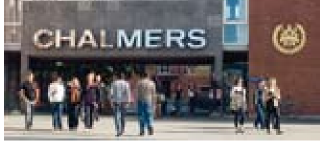
EU Parallel EU projects
Programme area 5

- **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
- **EU12** – **RIVAS** [3]
  Prof Jens Nielsen and co-workers
- **EU13** – **D-RAIL** [3]
  Doc Anders Ekberg and co-workers
- **EU14** – **Capacity4Rail** [3]
  Prof Anders Ekberg and co-workers
- **EU15** – **WRIST**
  Prof Lennart Josefson / Dr Jim Brouzoulis

SP Parallel special projects
Programme area 6

- **SP7** – **Lateral track stability**
- **SP8** – **Design of insulated joints**
- **SP9** – **Sleeper design for 30 tonne axle load**
- **SP10** – **Noise reduction measures and EU project QCITY**
- **SP11** – **Vertical contact forces of high-speed trains**
- **SP12** – **New sleeper specifications**
- **SP13** – **Alarm limits for wheel damage**
- **SP14** – **Particle emissions and noise from railways**
- **SP15** – **Computer program for design of block brakes**
- **SP16** – **Dynamic properties of timber sleepers and concrete replacement sleepers**
- **SP17** – **Switch sleeper specifications**
- **SP18** – **Ground vibrations – influence of vehicle parameters**
- **SP19** – **Optimum track stiffness**
- **SP20** – **Classification of wheel damage forms**
- **SP21** – **Optimum material selection for track switches**
- **SP22** – **Implementing INNOTRACK results at Trafikverket**
- **SP23** – **Optimized prestressed concrete sleeper**
- **SP24** – **Derailment risks in switches**
- **SP26** – **Holistic optimization of tracks**
- **SP27** – **Optimized prestressed concrete sleeper – phase II**
- **SP28** – **Prevention and mitigation of derailments**

All projects SP1–SP27 are reported in the Triennial Report for Stage 7



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Eva Olsson Group
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