STAGE 7

TRIENNIAL REPORT
1 July 2012–30 June 2015

REVIEW
1 July 1995–30 June 2012

PLANS
1 July 2015–30 June 2018

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 7 (1 July 2012 – 30 June 2015) 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 128–130 display an overview of all 117 projects that have been (or are being) carried out within CHARMEC. Some results from the period 1 July 2015 – 31 May 2016 have been added.

The report has been compiled by a number of contributors with Professor Roger Lundén, Docent Elena Kabo 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 June 2016
ANDERS EKBERG
Director of CHARMEC

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

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

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REFLECTIONS FROM THE DIRECTOR

In many countries – including Sweden – railway operations are at an all-time high and many railways are struggling with demanding issues regarding reliability and costs. As operations reach the capacity limit, the margin for faults diminishes and the cost for maintenance and mitigating measures soars. These are known facts, and actions such as the planning for new lines are taken in many countries. This will also facilitate the shift of transports from road to rail as is strongly advocated by, e g, the EU.

In this situation the role of railway research, and in particular research in railway mechanics, is more important than ever before. To allow for operation and maintenance of existing lines within reasonable economical and operational limits, there will be required a higher precision in deciding the most efficient actions. Similarly, it is necessary to base the design of new lines and trains on solid research results to keep the investments within acceptable limits and to ensure the robustness of the new systems. Here railway mechanics research plays a fundamental role since it affects the majority of costs for both infrastructure and running gear.

On the following pages, we provide an overview of our research and how it relates to the overall aims of a more robust and (cost) efficient railway. We endeavor to understand and predict loading, deformation, vibration, noise, and deterioration of railway components and systems. This knowledge can then be translated into engineering solutions where our research results are being implemented. This strive towards implementation is always present, but perhaps most clear in the European projects presented on pages 86–96. These projects also highlight the close co-operation between railway mechanics and other disciplines, such as economy and logistics, which is present in all our projects.

Finally, it must be noticed that the research accounted for in the following is the result of hard and dedicated work of individual professionals: the qualified staff of our industrial partners, our dedicated doctoral students and senior researchers, and the knowledgeable colleagues from all over the world with whom we co-operate. Thanks to all of them, we know that the challenges currently facing the railway systems will be met.

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

EXECUTIVE SUMMARY

The Competence Centre CHAlmers Railway MEChanics, abbreviated 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 (since 2005 part of the Department of Applied 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 twelve partners during Stage 7 (including Lucchini) have been involved since 1995, and another four have been involved for twelve years or more. Two members served on the CHARMEC Board from 1995, one of them up to June 2014 and one until the end of Stage 7. Another key factor is the core group of committed CHARMEC researchers at Chalmers University of Technology who have served the Centre for a long time, and are still actively involved. Some of them have worked for CHARMEC since the start in 1995, or even from the start of the railway-related activities in 1987.

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 have contributed to this study. In a report from VINNOVA 2013 the impact of CHARMEC's research is quantified, see page 116.

The annual budget for the three years of Stage 7 (1 July 2012 – 30 June 2015) has been MSEK 24.2 (about MEUR 2.7), see page 124. Three parties have provided funding: Chalmers University of Technology, Trafikverket, and an Industrial Interests Group comprising 12 partners. In total, 29 ordinary research projects, five EU projects and three development projects were carried out within the six programme areas during Stage 7,

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

At Chalmers, 41 people (project leaders, academic supervisors, doctoral students and senior researchers) from four departments out of a total of 17 at Chalmers, see page 131, have been involved. They published 104 scientific papers in international journals and conference proceedings during Stage 7 (including those in print). Seven Licentiate degrees and eleven PhD degrees were conferred during Stage 7. A total of 52 Licentiate degrees and 41 PhD degrees in railway mechanics have been awarded up to June 2015 at Chalmers, see page 110. More than 100 partners (industries, universities, institutes, public agencies, consultancies) from 18 countries have been involved in our European projects during Stage 7.

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. 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. Activities will continue during Stage 8.

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 *			

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

The approximate exchange rate (May 2016) is 1 MSEK = 0.11 MEUR

* After Board Meeting on 8 February 2016

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 total 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. In addition to the six previous members, a new member, Adtranz Sweden (now Bombardier Transportation Sweden), 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 / Stockholm Urban Transit Administration) and voestalpine Bahnsysteme GmbH & CoKG (Austrian rail and switch manufacturer) joined as new industrial partners. All three had become involved during Stage 3. 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) replaced SJ Machine Division.

The Principal Agreement for CHARMEC's Stage 5 (1 July 2006 – 30 June 2009) followed VINNOVA's Principal Agreement for the Centre's Stage 4. However, Banverket was directly included in the agreement and also assigned part of the administrative role that was previously filled by VINNOVA. Otherwise, the rights and obligations of the three parties (Chalmers University of Technology, Banverket and the Industrial Interests Group) were the same as in the Principal Agreement for Stage 4. 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. For a brief outline of CHARMEC's Stage 8 (1 July 2015 – 30 June 2018), see page 127. 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 7 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 – an international consultancy with Swedish headquarters in Stockholm/Solna

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

SLL Trafikförvaltningen – responsible for the regional traffic in the Greater Stockholm area

SJ – passenger train operator, headquartered in Stockholm

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

voestalpine Bahnsysteme – an Austrian manufacturer of rails and switches with headquarters in Leoben and Vienna (and Zeltweg), respectively

ÅF Infrastructure – the infrastructure branch of the *ÅF* consultancy with headquarters in Stockholm

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

Karin Markides, President of Chalmers University of Technology 2006–2015, 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 7 (decision dated 2014-10-02):

Annika Renfors (chair)	Trafikverket
Rikard Bolmsvik	Abetong
Jakob Wingren	Bombardier Transportation
Jan Sterner	Faiveley Transport
Martin Modéer	Green Cargo
Martin Schilke	Interfleet Technology
Erik Kihlberg	Lucchini Sweden
Per Gelang	SweMaint
Susanne Rymell	SJ
Robert Lagnebäck	SLL Trafikförvaltningen
Björn Drakenberg	voestalpine Metal Engineering
Thomas Axelsson	ÅF Infrastructure
Sebastian Stichel	Royal Institute of Technology (KTH)
Hans Andersson	Chalmers
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 succeeded by Ingemar Frej of Trafikverket, see page 127. He also acted as chairman at the Board meeting on 3 June 2015.

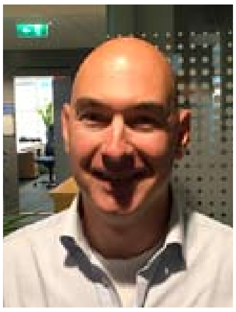
On 1 July 2013, Håkan Anderson of voestalpine Bahnsysteme (now voestalpine Metal Engineering) was succeeded by Björn Drakenberg. Martin Modéer of Green Cargo succeeded Marcin Tubylewicz on 5 November 2013. Thomas Axelsson of ÅF Infrastructure joined the Board of CHARMEC on 25 March 2014. Martin Schilke of Interfleet Technology succeeded Hugo von Bahr on 2 October 2014. The decisions on these changes by President Karin Markides of Chalmers University are dated 2013-04-04, 2013-11-05, 2014-03-25 and 2014-10-14, respectively. Roger Lundén, now Professor in Railway Mechanics at the Chalmers Department of Applied Mechanics, 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 Karin Markides dated 2012-08-29).

BOARD MEMBERS

The Board of CHARMEC at its meeting on 8 May 2016 in Solna

From the left: ***Jakob Wingren*** of Bombardier Transportation Sweden (Stages 7+8); ***Sebastian Stichel*** of KTH Railway Group (Stages 7+8); ***Uday Kumar*** of JVTC Luleå University of Technology (invited); ***Tilo Reuter*** of SweMaint (Stage 8); ***Roger Lundén*** of Chalmers Applied Mechanics (Director of CHARMEC 1997-2012); ***Susanne Rymell*** of SJ (Stages 6+7+8); ***Per Lövsund*** of Chalmers (Stages 6+7+8); ***Rikard Bolmsvik*** of Abetong (Stages 5+6+7+8); ***Anders Ekberg*** of Chalmers Applied Mechanics (Director of CHARMEC); ***Erik Kihlberg*** of Lucchini Sweden (Stages 6+7+8); ***Ingemar Frej*** of Trafikverket (Chairperson, Stage 8); ***Björn Drakenberg*** of voestalpine Metal Engineering (Stages 7+8)

Hans Andersson of SP Technical Research Institute of Sweden and Chalmers (Stages 1+2+3+4+5+6+7)

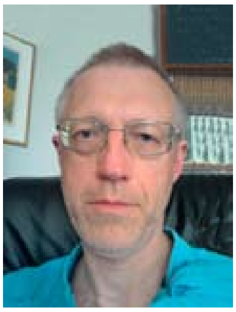


Thomas Axelsson of ÅF Infrastructure (Stage 7)

Per Gelang of SweMaint (Stages 6+7)

Annika Renfors of Trafikverket (Chairperson, Stages 6+7)

Hugo von Bahr of Interfleet Technology (Stages 1+2+3+4+5+6+7)



Jan Sterner of Faiveley Transport (Stage 7)

Martin Modéer of Green Cargo (Stage 7)

Fredrik Blennow of Faiveley Transport (Stage 8)

Robert Lagnebäck of SL (Stages 7+8)

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

QUALITY ASSESSMENT AND KNOWLEDGE TRANSFER

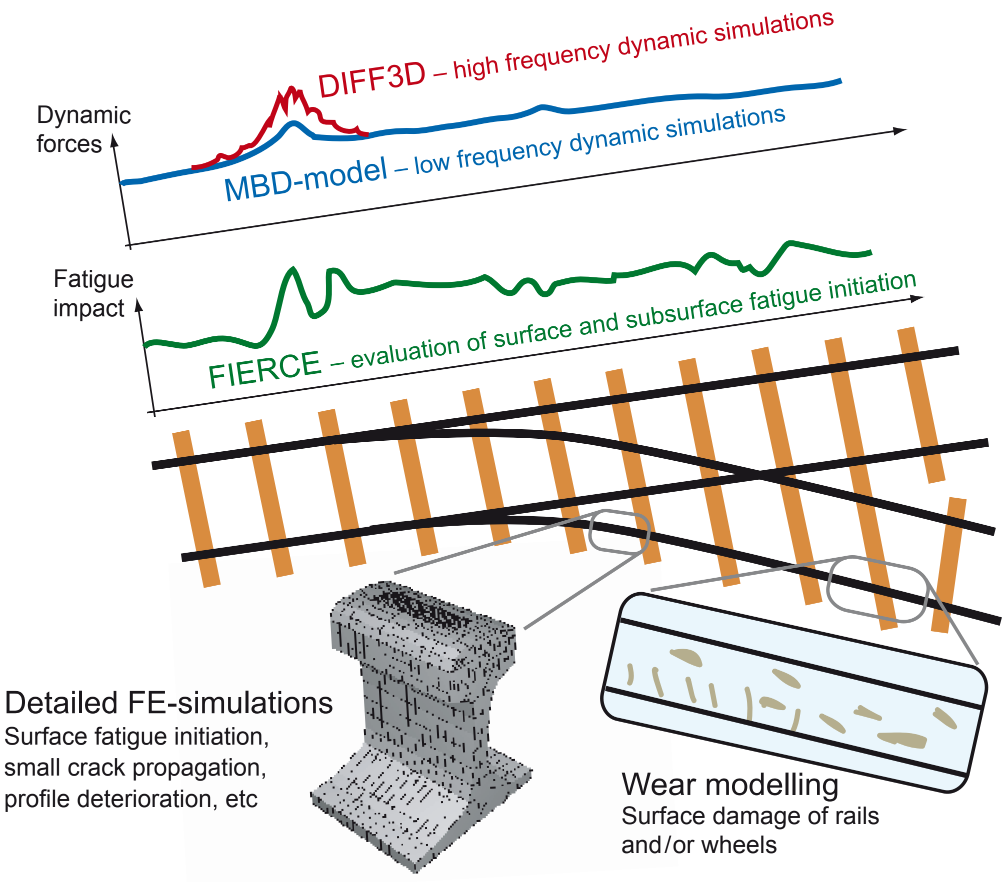
In our opinion, an assessment of the quality and quantity of the results and effects achieved by a Competence Centre like CHARMEC should take the following points into consideration:

- 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 (see page 110)
- 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 7, 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.
For DIFF3D and FIERCE, see projects TS4 and MU9 on pages 16 and 43

PROGRAMME AREAS CHARMEC STAGE 7

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

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. 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 7

Research at the Centre during Stage 7 (1 July 2012 – 30 June 2015) has been carried out as planned. The Board of CHARMEC met as follows:

13 September	2012	6 February	2014
29 November	2012	7 May	2014
21 February	2013	9 September	2014
25 April	2013	26 November	2014
5 September	2013	16 February	2015
25 November	2013	3 June	2015

Detailed minutes were recorded at all meetings. Early decisions were made concerning the content and funding of projects carried over from Stage 6 and of new projects started during Stage 7. 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. In 2013, VINNOVA (Sweden's Innovation Agency) published a report on the long-term industrial impacts of the Swedish Competence Centres concluding that CHARMEC has strongly contributed to an economic impact for society and industry, see page 116.

The NUTEK/VINNOVA ten-year funding of CHARMEC, totalling kSEK 52 300, ended on 30 June 2005. Additional contributions from Banverket/Trafikverket and Chalmers University of Technology, replaced the VINNOVA funding during the last year (1 July 2005 – 30 June 2006) of CHARMEC's Stage 4 and during Stages 5, 6 and 7. During Stages 5 and 6 VINNOVA contributed funding for projects TS11, VB10, MU18 and EU10, see the Triennial Report for Stage 6. During Stage 7 VINNOVA has provided funding to projects EU13 and SP26. VR (The Swedish Research Council) contributed a three-year funding of project MU25 during Stages 5 and 6. Family Ekman's Research Donation funded project SD6 during Stages 5 and 6 and project SD9 during Stages 6 and 7. During Stage 7, UIC (International Union of Railways) has provided financial support for project SP27. There is also a bilateral agreement with Lucchini Sweden, see page 97.

Chalmers has profiled its research activities into eight so-called Areas of Advance (in Swedish: Styrkeområden). During Stage 7, CHARMEC has received financial support from the two areas Energy and Materials. During Stages 6 and 7, CHARMEC researchers have received funding from the area Transport, including for the post-doc project VB12, which is reported as in-kind contributions. During Stages 6 and 7, project MU26 was financed by the joint Department of Mathematical Sciences at Chalmers University of Technology and the University of Gothenburg and also by the Swedish Energy Agency. Also this funding is reported as in-kind contributions.

Through interviews and Road Shows* with the CHARMEC partners during 2011 and 2012, research needs were identified. These needs have influenced the Board's decisions regarding the start of new projects during Stage 7. Keywords that summarize the views expressed by Banverket/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

As during Stages 5 and 6, Road Shows (see below) were carried out during Stage 7 with special visits to or meetings with Trafikverket and the companies. An outcome of this work is a project catalogue, first developed during Stage 6 and updated during Stage 7, with 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 Stage 7. 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.

The staff attached to the Centre during Stage 7, both at Chalmers (22 project leaders/principal advisers/senior researchers and 22 PhD students), at Trafikverket, and in the Industrial Interests Group, have been actively involved. Generally CHARMEC projects have reference groups. Most of these groups consist of members from Trafikverket and the Industrial Interest 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.

Seven licentiate theses and eleven PhD dissertations in railway mechanics were presented by CHARMEC's doctoral candidates during Stage 7, see page 110. In addition, 65 articles were published (or accepted for publication) in international scientific journals with a referee system, 42 papers were published in the proceedings of international conferences with a referee system, 18 EU reports were delivered, 11 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. Three of our eleven new PhDs during Stage 7 continue their work as post-docs at the University and CHARMEC. The remaining eight are employed by the industry where four now work full-time within the railway mechanics field.

As during Stages 1–6, 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. During Stage 7 the presentations from the industry were:

Rikard Bolmsvik (at Chalmers)	Abetong	13 Sept 2012
Anders Åbacken (in Västerås)	Bombardier	29 Nov 2012
Sebastian Stichel (at Chalmers)	KTH	21 Febr 2013
Johan Oscarsson (in Solna)	Interfleet	25 April 2013
Jan Sterner (at Chalmers)	Faiveley	5 Sept 2013
Martin Modéer (at Chalmers)	Green Cargo	6 Febr 2014
Susanne Rymell (in Stockholm)	SJ	7 May 2014
Björn Drakenberg (at Chalmers)	voestalpine	9 Sept 2014
Anders Frid, Tony Johansson and Thomas Axelsson (in Gothenburg)	ÅF	26 Nov 2014
Tilo Reuter (at Chalmers)	SweMaint	16 Febr 2015
Erik Kihlberg (in Surahammar)	Lucchini	3 June 2015

At the seminar on 3 June 2015 Hans Andersson gave a presentation "Reflections after 20 years in the Board of CHARMEC".

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 7 comprised more than 100 organizations in 18 countries; see under projects EU12, EU13, EU14, EU15 and EU16. We also co-operate with railway bodies in Australia, Canada, India, Japan and the USA.

An indication of the high scientific standards achieved in the activities of the University and the Industry at CHARMEC is the high level of acceptance of articles for journals and contributions to conferences. Around 475 such articles and contributions have been published internationally so far. A total of 52 Licentiate degrees and 41 PhD degrees in railway mechanics have been awarded at Chalmers up to June 2015, see page 110.

A graduate course on contact mechanics with wheel/rail applications and a graduate course on thermal stresses with a railway focus were held during Stage 7, see page 120.

It is obvious, in retrospect, that without the framework and support of the NUTEK/VINNOVA Competence Centre concept, and later by Banverket/Trafikverket, the relatively small university-industry collaboration in railway mechanics, which already existed at Chalmers before 1 July 1995, would never have expanded, intramurally and extramurally, nationally and internationally, as it has during the past 20 years of CHARMEC's Stages 1 to 7.

*A team of senior researchers from CHARMEC visited (or held meeting with) each one of Trafikverket and the eleven partner companies, staged a "Road Show" presenting CHARMEC, and interviewed a group of specially summoned company employees. For Trafikverket it was organized as a meeting on Shift2Rail held during a CHARMEC Board meeting. Our Johan Ahlström (JA), Anders Ekberg (AE), Elena Kabo (EK), Roger Lundén (RL), Jens Nielsen (JN), Björn Pålsson (BP), Peter Torstensson (PT) and Tore Vernersson (TV) took part. The visits/meetings were as follows from April to November 2014:

Abetong	Växjö	28 April	AE+JN
Lucchini	Surahammar	20 May	RL+TV
Faiveley	Landskrona	22 May	RL+TV
Interfleet	Solna	22 May	AE
voestalpine VAE	Gothenburg	2 June	RL+JN+BP
voestalpine Schienen	Gothenburg	2 June	JA+AE
SJ	Stockholm	25 August	JA+EK
Bombardier	Västerås	26 August	JA+AE
Green Cargo	Solna	27 August	AE+TV
ÅF Infrastructure	Helsingborg	5 October	AE+RL
SweMaint	Gothenburg	9 October	RL+TV
SL	Stockholm	22 October	AE+PT
Trafikverket	Gothenburg	26 November	AE+RL

PROJECTS AND RESULTS

The publications listed under the projects have not previously been registered in CHARMEC's Biennial and Triennial Reports 1 July 1995 – 30 June 2012 (Stages 1, 2, 3, 4, 5 and 6), 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 7, 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 and EU13, and the ongoing project EU14 belong 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 new European projects EU15 and EU16 belong to the Horizon 2020 Programme. It should be noted that external access to EU documents supplied by us and others is often limited.

The departments where the 117 listed CHARMEC projects (TS1 – SP27) 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 January 2005 when 17 large departments replaced the previous schools and departments. Solid Mechanics, Structural Mechanics and Machine and Vehicle Systems, for instance, are now part of a larger Department of Applied Mechanics. Engineering Metals (later followed by Materials Science and Engineering) is included in the larger Department of Materials and Manufacturing Technology. Applied Acoustics belongs to the new Department of Civil and Environmental Engineering. See page 131.

As for the project budgets presented for Stage 8, these include the sums allocated by the Board up until the meeting on 12 May 2016. The abbreviation Lic Eng stands for the intermediate academic degree *Licentiate of Engineering*, see page 110.

Interaction of train and track – Samverkan tåg/spår (TS) – Wechselwirkung von Zug und Gleis – Interaction entre le train et la voie

TS1. CALCULATION MODELS OF TRACK STRUCTURES

Beräkningsmodeller för spårkonstruktioner
Berechnungsmodelle für Gleiskonstruktionen
Modélisation des structures de voies ferrées

The TS1 project was completed with Johan Oscarsson's successful defence in public of his doctoral dissertation in April 2001, when he also left Chalmers to take up employment with first TrainTech Engineering (then Interfleet Technology, now SNC-Lavalin) and later Stockholm Public Transport Authority (Storstockholms Lokaltrafik, SL) in Stockholm. Professor Thomas Abrahamsson and Docent (now Professor) Jens Nielsen supervised Johan Oscarsson's research. The title of his dissertation is "Dynamic train/track interaction – linear and nonlinear track models with property scatter". The faculty-appointed external examiner of the dissertation was Dr (now Professor) Søren R K Nielsen from the Department of Structural Engineering at Aalborg University in Denmark.

CHARMEC's simulation model of train–track interaction, developed earlier and implemented in our computer program DIFF, was expanded in order better to reproduce the dynamics of railpads, ballast and subgrade. Measured non-linearities were considered. Stochastic realizations of track models were handled using a perturbation technique. Based on measurements on the Svealand Line in spring 2000, it was found that the scatter in railpad stiffness makes the largest contribution to the variance in the wheel–rail contact force. See also CHARMEC's Triennial Reports for Stages 2 and 3. Johan Oscarsson is now President of Tunnelbanan Teknik in Stockholm. He served on the Board of CHARMEC from November 2007 to August 2011.

PhD student Johan Oscarsson (doctorate earned in April 2001) of project TS1. Photo taken in 2000 in the Chalmers Solid Mechanics laboratory. For photos of Thomas Abrahamsson and Jens Nielsen, see page 16

TS2. RAILHEAD CORRUGATION FORMATION

Räffelbildning på rälhuvud
Riffelbildung auf dem Schienenkopf
Formation de l`usure ondulatoire sur le champignon du rail

The TS2 project was completed with Annika Igeland's (now Annika Lundberg) successful defence in public of her doctoral dissertation in January 1997, which was when she also left Chalmers. Tore Dahlberg (then Associate Professor at Chalmers Solid Mechanics) was her supervisor. The faculty-appointed external examiner of the dissertation was Dr (now Professor) David J Thompson from the Institute of Sound and Vibration Research (ISVR) in Southampton, UK. The title of the dissertation is "Dynamic train/track interaction – simulation of railhead corrugation growth under a moving bogie using mathematical models combined with full-scale measurements".

An important feature of the TS2 project was the studied interaction, via the track structure, between the two wheelsets in a bogie. Through numerical simulations, new reflection and resonance phenomena were discovered for the track under a running train. These phenomena manifest themselves with peaks in the spectral density function of the wheel–rail contact force. See also CHARMEC's Biennial and Triennial Reports for Stages 1 and 2.

PhD student Annika Igeland of project TS2 and Dr (now Professor) David J Thompson of ISVR at the defence in public of her doctoral dissertation in January 1997. For a photo of Tore Dahlberg, see page 85 in CHARMEC's Triennal Report for Stage 6

TS3. SLEEPER AND RAILPAD DYNAMICS

Sliprarnas och mellanläggens dynamik
Dynamik der Schwellen und Zwischenlagen
Dynamique des traverses et des semelles de rail

The TS3 project was completed with Åsa Fenander's (now Åsa Sällström) successful defence in public of her doctoral dissertation in May 1997 and her continued work for CHARMEC up until September of the same year, when she left Chalmers. Tore Dahlberg (then Associate Professor at Chalmers Solid Mechanics) was her supervisor. The faculty-appointed external examiner of the dissertation was Professor George A Lesieutre from the Department of Aerospace Engineering at Pennsylvania State University, USA. The title of the dissertation is "Modelling stiffness and damping by use of fractional calculus with application to railpads".

A central feature of the TS3 project was the use of fractional time derivatives for better modelling of the constitutive behaviour of the railpads with their frequency-dependent stiffness and damping. Experimental results from the TNO laboratory in the Netherlands and CHARMEC's Goose Hill measurements in 1993 on the West Coast Line in Sweden were exploited. The application of modal synthesis in mathematical simulations when modelling damping using fractional derivatives was explored. See also CHARMEC's Biennial and Triennial Reports for Stages 1 and 2.

PhD student Åsa Fenander (doctorate earned in May 1997) of project TS3 inspecting an instrumented wheelset in the Chalmers Solid Mechanics laboratory. For a photo of Tore Dahlberg, see page 85 in CHARMEC's Triennal Report for Stage 6

TS4. LATERAL TRACK DYNAMICS

Lateraldynamik och korrugering
Lateraldynamik der Gleiskonstruktionen
Dynamique latérale des voies ferrées

The TS4 project was completed with Clas Andersson's successful defence in public of his doctoral dissertation in June 2003. He continued his work at CHARMEC in the TS7 project up to December 2003, when he left Chalmers. Professor Thomas Abrahamsson and Docent (now Professor) Jens Nielsen supervised Clas Andersson's research. The title of his dissertation is "Modelling and simulation of train/track interaction including wear prediction". The faculty-appointed external examiner of the dissertation was Professor Mats Berg of the KTH Railway Group in Stockholm.

The planar DIFF calculation model developed by CHARMEC was extended to serve as a tool for the analysis of three-dimensional train–track interaction (vertical, lateral and longitudinal) in the frequency range up to approximately 1500 Hz. Both tangent and curved track can be investigated using the new computer program DIFF3D.

Professor Thomas Abrahamsson (left) and Dr Clas Andersson (doctorate earned in June 2003) of project TS4. Photo taken in 2003

The experimental basis of the track model was developed in full-scale measurements in co-operation with Banverket (now Trafikverket) at Grundbro on a stretch of tangent track on the Svealand Line in spring 2002. See also CHARMEC's Triennial Reports for Stages 2 and 3.

TS5. OUT-OF-ROUND WHEELS – CAUSES AND CONSEQUENCES

Orunda hjul – orsaker och konsekvenser
Unrunde Räder – Ursachen und Konsequenzen
Faux-ronds des roues – causes et conséquences

The TS5 project was completed with Anders Johansson's successful defence in public of his doctoral dissertation in September 2005. Docent (now Professor) Jens Nielsen and Professor Roger Lundén were his supervisors. The faculty-appointed external examiner of the dissertation was Dr (now Professor) Simon Iwnicki from the Department of Engineering and Technology at Manchester Metropolitan University, UK. The title of the dissertation is "Out-of-round railway wheels – causes and consequences: an investigation including field tests, out-of-roundness measurements and numerical simulations".

Wheel tread irregularities occurring in different types of train traffic in Sweden (high-speed, passenger, freight, commuter, subway) were assessed in project TS5. High roughness (corrugation) levels, with wavelengths between 30 mm and 80 mm, were found on tread-braked freight wheels and tread-braked powered X2 high-speed train wheels. The polygonalization of C20 subway wheels in Stockholm was quantified. A calibrated numerical tool for qualitative and quantitative prediction of wheel out-of- roundness and rail corrugation growth was developed. See also CHARMEC's Triennial Reports for Stages 2, 3 and 4.

From the left: PhD student Elias Kassa (doctorate earned in October 2007) of project TS7, PhD student Anders Johansson (doctorate earned in September 2005) of project TS5, and their supervisor Docent (now Professor) Jens Nielsen. Photo taken at the SweMaint maintenance shop in Gothenburg in 2003

TS6. IDENTIFICATION OF DYNAMIC FORCES IN TRAINS

Identifiering av dynamiska krafter i tåg
Identifizierung von dynamischen Kräften in Zügen
Identification des forces dynamiques dans les trains

The TS6 project was completed with Lars Nordström's successful defence in public of his doctoral dissertation in November 2005, when he also left Chalmers. Professor Thomas Abrahamsson and Dr Peter Möller, Senior Lecturer, were his supervisors. The faculty-appointed external examiner of the dissertation was Professor Anders Klarbring from the Department of Mechanical Engineering at Linköping Institute of Technology in Sweden. The title of the dissertation is "Input estimation in structural dynamics".

The general aim of project TS6 was to study, on a broad scale, possible methods for the calculation of forces acting at locations inaccessible for direct measurements. Starting from a basis of measured accelerations and other responses in appropriate positions and directions onboard a running wagon, attempts should be made to determine the exciting contact forces on the wagon wheels.

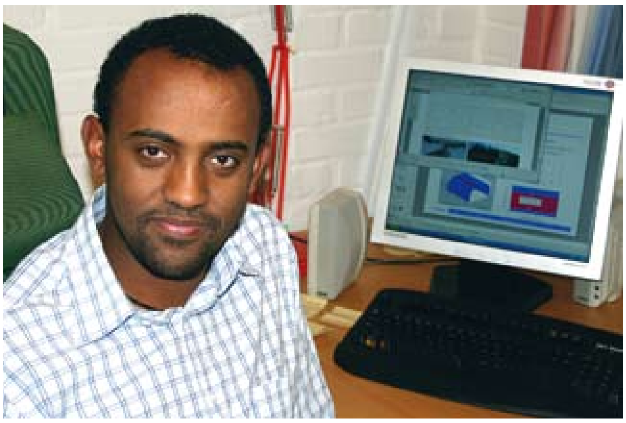
The sensitivity of indirect input estimation (i e, load identification) to the noise that will contaminate measurement data has been examined. Measured data from a full-scale wheelset mounted and excited in the laboratory of Chalmers Applied Mechanics (see photo) were used. See also CHARMEC's Triennial Reports for Stages 2, 3 and 4.

From the left: PhD student Lars Nordström (doctorate earned in November 2005) of project TS6, PhD student Johanna Lilja (licentiate gained in November 2006) of project TS9, and their supervisors Professor Thomas Abrahamsson and Dr Peter Möller. Photo taken in 2003 at the wheelset test rig in the laboratory of Chalmers Solid Mechanics

TS7. DYNAMICS OF TRACK SWITCHES

Spårväxlars dynamik
Dynamik von Eisenbahnweichen
Dynamique des aiguillages de voies ferrées

The TS7 project was completed with Elias Kassa's successful defence in public of his doctoral dissertation in October 2007, when he also left Chalmers. Professor Jens Nielsen was the supervisor of his research work. The faculty-appointed external examiner of the dissertation was Dr Robert D Fröhling from Transnet in the Republic of South Africa. The title of the dissertation is "Dynamic train–turnout interaction – mathematical modelling, numerical simulation and field testing". For a photo of Jens Nielsen, see page 16.



PhD student Elias Kassa (doctorate earned in October 2007) in project TS7. Photo taken in 2006

The aim of the TS7 project was to obtain a basic understanding of how railway switches (turnouts) could be developed to achieve lower maintenance costs, fewer traffic disruptions and longer inspection intervals. Multibody system (MBS) models of dynamic interaction between the running train and a standard turnout design (UIC60-760-1:15) have been established. Variations in rail profile, track stiffness and track inertia along the turnout, and contact between the back of the wheel flange and the check rail, were considered. There has been close co-operation with the CHARMEC partner voestalpine VAE in Austria. See also CHARMEC's Triennial Reports for Stages 3, 4 and 5. Elias Kassa is now Professor in Railway Engineering at NTNU in Trondheim, Norway.

TS8. INTEGRATED TRACK DYNAMICS

Integrerad spårdynamik
Integrierte Gleisdynamik
Dynamique intégrée de la voie

Project leader	Professor Jens Nielsen, Applied Mechanics/ Division of Dynamics
Doctoral candidate	None (only senior researcher in this project)
Period	2003-10-01 – 2018-06-30
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 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 (*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 train–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. The 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 11th International Workshop on Railway Noise (IWRN11) in Uddevalla, Sweden, on 2013-09-09–13 and also acted as editor of the reviewed proceedings. He evaluated abstracts for the symposia on Vehicle System Dynamics in Qingdao (China) in August 2013 and in Graz (Austria) in August 2015.

The project work also includes planning, preparation, support and follow-up of research proposals. Examples of these activities are the launched project TS17, the project proposal 'Railway track structure – a holistic optimisation of design and maintenance for improved performance' submitted to VINNOVA (Transport- och miljöinnovationer 2013) which led to our project SP26, a project proposal on the optimization of track design to minimize track noise while considering LCC, safety and ground vibration (prepared for Schweizerische Bundesbahnen, SBB), and the planning of the EU project proposal TRANQUIL.

Measurements of the geometry of wheel flats were performed together with Magnus Melin at the SweMaint workshop in Sävedalen on 2013-02-25 using an improved measurement set-up from Lloyd's Register ODS.

Jens Nielsen gave his annual lecture on 'Introduction to train–track dynamics' at NBIU (Nordisk Banteknisk Ingenjörsutbildning) in Tällberg in September 2012–2015. He has contributed to a new IHHA Best Practice Handbook with chapters on rail corrugation and tread defect initiated out-of-round wheels.

Astrid Pieringer, Wolfgang Kropp and Jens Nielsen: The influence of contact modelling on simulated wheel/rail interaction due to wheel flats, *Wear*, vol 314, nos 1–2, 2014, pp 273–281 (revised article from conference *CM2012*. Also listed under projects VB10 and VB12)

Anders Ekberg, Elena Kabo and Jens Nielsen: Allowable wheel loads, crack sizes and inspection intervals to prevent rail breaks, *Proceedings International Heavy Haul Association Conference (IHHA 2015)*, Perth (Australia) June 2015, pp 30–38 (also listed under project MU22)

Peter Torstensson and Jens Nielsen: Rail corrugation growth on curves – measurements, modelling and mitigation. In Jens Nielsen et al (eds) *Noise and Vibration Mitigation for Rail Transportation Systems, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 126, 2015, pp 659–666 (revised article from workshop *IWRN11*. Also listed under project TS16)

Ejder Eken and Robert Friberg: Modelling of dynamic track forces generated by tram vehicles, Master thesis, *Chalmers Applied Mechanics*, Gothenburg 2013, 130 pp. Authors received Swedtrain's price as best railway related Master thesis work in Sweden during 2015

TS9. TRACK DYNAMICS AND SLEEPERS

Spårdynamik och slipras
Gleisdynamik und Schwellen
Dynamique de voie et les traverses

Project TS9 focused on the design loads for a concrete sleeper installed in a track carrying different types of traffic. Important issues here are the true statistical spread of the loads on the individual sleeper from rails and ballast, the influence of ballast settlements, and the optimal shape of a sleeper. A probabilistic design method for sleepers was developed.

An instrumented sleeper with load-measuring cells (see photo) over its bottom surface was designed and manufactured, and in-field measurements were performed on the Iron Ore Line in northern Sweden (at Harrträsk close to Gällivare) and on the Southern Main Line (at Torpsbruk and Liatorp close to Alvesta).

Professors Thomas Abrahamsson and Jens Nielsen were supervisors and Mr Sadegh Rahrovani (doctorate earned in March 2016) assisted in the project TS9. See also CHARMEC's Triennial Report for Stage 4 with information on Johanna Lilja's licentiate thesis entitled "Preliminaries for probabilistic railway sleeper design". Johanna Lilja left Chalmers in March 2010 to take up a position with the consultancy FS Dynamics in Gothenburg. Her work at CHARMEC was being continued as part of the new project TS14.

PhD student Johanna Lilja (licentiate gained in November 2006) and her supervisor Professor Thomas Abrahamsson in project TS9. On the table lies one of the 32 three-point load-measuring cells (i e, adding up to a total 96 sensors) which were placed on the bottom surface of the test sleeper. Photo taken in 2006 For a photo of Jens Nielsen, see page 16

TS10. TRACK RESPONSE WHEN USING UNDER SLEEPER PADS (USP)

Spår med slipras på underlägg
Gleise mit Schwellen auf Zwischenlagen
Voies ferrées avec traverses sur semelles

The TS10 project was concluded in June 2012 with two reports on the field studies in Kiesen and Malmö, see CHARMEC's Triennial Report for Stage 6. Under Sleeper Pads (USP) are primarily installed to reduce structure-borne vibrations, maintain track quality index and allow for a prospective reduced depth of the ballast layer. The use of USP could therefore be an interesting alternative to the blasting of bedrock to allow for an increased ballast depth. The objective of project TS10 was to increase the understanding of the influence of USP on the dynamic response of the assembled track structure and its individual components. Several planning and reporting meetings were held with the manufacturing company Getzner Werkstoffe GmbH (Austria) and their Swedish agency Christian Berner AB, and with Schweizerische Bundesbahnen (SBB Infrastruktur).

Results from field measurements at Kiesen (close to Bern in Switzerland) tally with the results of our numerical parameter study. It appears that track settlement is slowed down when USP are used, implying that track quality is being maintained more effectively. Field measurements have also been performed in the Malmö City Tunnel in Sweden, at one of the transition zones between slab track and ballasted track using Infranord's recording cars STRIX and IMV100.

Under Sleeper Pads (courtesy Getzner Werkstoffe GmbH)

TS11. RAIL CORRUGATION GROWTH ON CURVES

Korrugeringstillväxt på räls i kurvor
Zunahme der Riffelbildung auf der Schienenoberfläche in Kurven
Accroissement de l'usure ondulatoire sur les rails dans les courbes

For a photo of Peter Torstensson, see page 29

The TS11 project was concluded with Peter Torstensson's successful defence in public of his doctoral dissertation in November 2012. Professor Jens Nielsen and Dr Anders Frid of Bombardier Transportation were supervisors. The faculty-appointed external examiner of the dissertation was Dr Stuart Grassie of Stuart Grassie Engineering Ltd, UK. The title of the dissertation is "Rail corrugation growth on curves". Peter Torstensson continues his research at Chalmers Applied Mechanics, see project TS16.

Short-pitch rail corrugation often develops on the low (inner) rail on small radius curves and causes increased noise and vibration levels on railway networks worldwide. In the absence of a generally applicable treatment, track owners are forced to run expensive rail grinding programs on a regular basis to manage these problems. In project TS11, CHARMEC's in-house simulation software DIFF3D has been employed and further developed to model the dynamic interaction between train and track on curves. The model allows for studies of the influence of the level of traction as well as wheel–rail friction, rail cant, curve radius, and non-symmetric rail profiles. The dynamic properties of both vehicle and track are being considered. The distribution of stick and slip over the contact patch between wheel and rail is calculated and used in a wear model for prediction of rail corrugation growth.

In-field measurements have been used to validate both the growth rate of the corrugation and its variation along the curve. Numerical simulations in DIFF3D show that the excitation of the first symmetric and the first antisymmetric bending eigenmodes of the leading wheelset in a bogie seems to be strongly related to the corrugation wavelengths observed in the field. Numerical predictions show that corrugation on the low rail develops for a wheel–rail friction coefficient of 0.6, but not for a friction coefficient of 0.3. This has been verified by field measurements using low rail friction management. Due to the phase difference between the calculated wear and the actual rail irregularity, the corrugation formation is predicted to translate along the rail (not been verified by field measurements).

Measurements of rail corrugation on a curve with a radius of 120 m between Alvik and Stora Mossen on SL's network in Stockholm have been performed, see photo. These included train speed, rail acceleration, train pass-by noise, friction coefficient, rail profile, and track receptance. Within a rail grinding interval of one year, severe short-pitch corrugation was found to have built up on the low (inner) rail of the SL curve, with maximum peak-to-peak magnitudes of about 0.15 mm. Low rail friction management was found to be an effective measure to reduce corrugation growth.

Corrugation of low rail on a curve of SL track at Stora Mossen in Stockholm For a photo of Jens Nielsen and Anders Frid, see page 103

Collaboration between projects TS11 and MU20 has taken place. A computer model representing the conditions in the wear test rig of voestalpine in Leoben (Austria) has been established to calibrate a wear model for the voestalpine 350HT rails used by SL. The project was partially financed by VINNOVA. See also CHARMEC's Triennial Report for Stage 6.

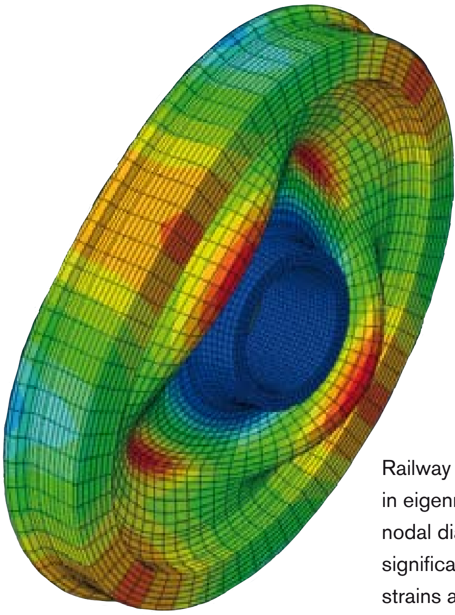
Peter Torstensson and Martin Schilke: Rail corrugation growth on small radius curves – measurements and validation of a numerical prediction model, *Wear*, vol 303, nos 1-2, 2013, pp 381-396 (revised article from conference *CM2012*. Also listed under project MU24)

Peter Torstensson, Astrid Pieringer and Jens Nielsen: Simulation of rail roughness growth on small radius curves using a non-Hertzian and non-steady wheel/rail interaction model, *Wear*, vol 314, nos 1-2, 2014, pp 241-253 (revised article from conference *CM2012*. Also listed under project VB10)

TS12. IDENTIFICATION OF WHEEL-RAIL CONTACT FORCES

Identifiering av kontaktkrafter mellan hjul och räl
Identifizierung von Kontaktkräften zwischen Rad und Schiene
Identification des forces de contact entre roue et rail

The TS12 project was concluded with Hamed Ronasi's successful defence in public of his doctoral dissertation on 29 March 2012. Docent (now Professor) Fredrik Larsson, Dr (now Docent) Håkan Johansson, Dr Peter Möller, Professor Jens Nielsen and Professor Kenneth Runesson were supervisors. The faculty-appointed external examiner of the dissertation was Professor Tadeusz Uhl from the Faculty of Mechanical Engineering and Robotics at the AGH University of Science and Technology in Kraków, Poland. The title of the dissertation is "Inverse identification of dynamic wheel–rail contact forces". After the dissertation Hamed Ronasi left Chalmers for a position with L B Foster / Kelsan Technologies in Vancouver (Canada). He is now employed by Müller HRM Engineering in Gothenburg.



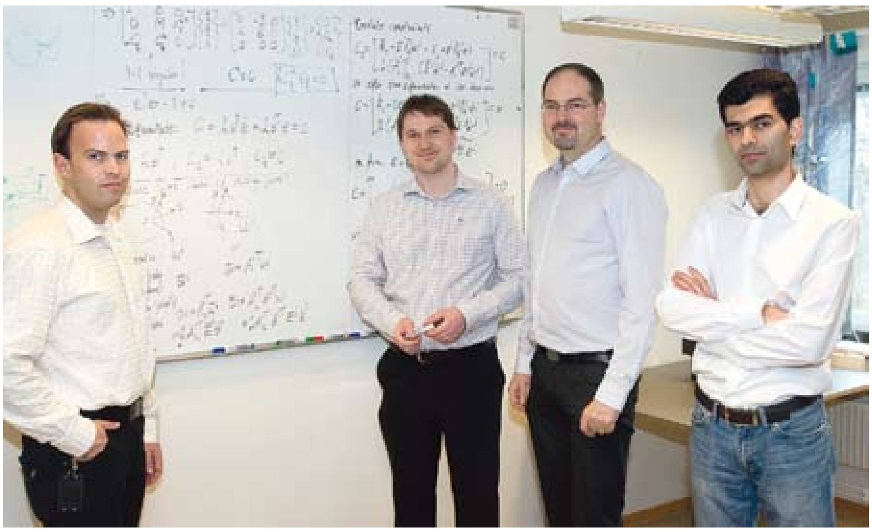
Railway wheel vibrating in eigenmode with two nodal diameters causing significant contributions to strains at gauge positions

The work to develop methods for more accurate evaluation of the contact forces between wheel and rail began in project TS6 and was further pursued in project TS12. As these forces cannot be measured directly on a rolling wheel, one studied approach has been to register the strain or acceleration at various positions and directions on a wheel or axle and then estimate the forces based on the measured data. However, existing schemes have so far typically involved either a simplified wheel model (neglecting inertia) or, in the case of more advanced models, implied strong restrictions in terms of the choice of spatial and temporal discretization of the underlying equations relating to the motion of the wheel.

In the current project, the vertical contact force is determined through the solution of an inverse problem. A mathematical minimization problem is considered in which the sought time history of the contact force is such that the discrepancy between the predicted (based on finite element analysis) and the measured response (strains) is minimized. A particular feature of this formulation is that the discretization of the pertinent state equations in space-time, the sampling instances of the measurements, and the parameterization of the sought contact force are all independent of each other. See also CHARMEC's Triennial Reports for Stages 5 and 6.

Hamed Ronasi and Jens Nielsen: Inverse identification of wheel–rail contact forces based on observation of wheel disc strains – an evaluation of three numerical algorithms, *Vehicle System Dynamics*, vol 51, no 1, 2013, pp 74-90

Hamed Ronasi, Håkan Johansson and Fredrik Larsson: Identification of wheel–rail contact forces, an inverse scheme and finite element model of the wheel, *IMechE Journal of Rail and Rapid Transit*, vol 228, no F4, 2013, pp 343-354



PhD student Hamed Ronasi (right; doctorate earned in March 2012) in project TS12 and his supervisors Docent (now Professor) Fredrik Larsson (left), Dr (now Docent) Håkan Johansson (second from the left) and Professor Jens Nielsen. Photo taken in 2009. For photos of Dr Peter Möller and Professor Kenneth Runesson, see pages 17 and 39

TS13. OPTIMIZATION OF TRACK SWITCHES

Optimering av spårväxlar
Optimierung von Eisenbahnweichen
Optimisation des aiguillages de voies ferrées

Project leaders	Professor Jens Nielsen and Professor Thomas Abrahamsson, Applied Mechanics/ Division of Dynamics
Doctoral candidate	Mr Björn Pålsson (from 2008-09-01; Lic Eng April 2011; PhD February 2014)
Period	2008-09-01 – 2014-02-28
Chalmers budget (excluding university basic resources)	Stage 5: ksek 650 Stage 6: ksek 2 550 Stage 7: ksek 894
Industrial interests in-kind budget	Stage 5: ksek 0 + 0 + 200 Stage 6: ksek 50 + 200 + 200 Stage 7: ksek 50 + 100 + 100 (*SL + Trafikverket + voestalpine*)

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

For photos of Jens Nielsen, Thomas Abrahamsson and Björn Pålsson, see pages 16 and 29

Switches & Crossings (s&c, turnouts, points) are composed of a switch panel and a crossing panel connected by a closure panel, see sketch on page 26. Only in Sweden there are over 12 000 turnouts in its some 17 000 km of track, and s&c account for a considerable part of reported track faults. In project ts13, numerical methods have been developed for the optimal design of s&c aiming at a reduction of dynamic wheel–rail contact forces and subsequent s&c component degradation. Examples of design variables used in the optimization are rail profile, stiffness of resilient layers (such as rail pads and under sleeper pads), and prescribed track gauge variation in the switch panel. The methods used take into account the stochastic distribution (scatter) of load parameters such as worn wheel profiles and varying train speed, axle load and wheel–rail friction.

For the switch panel, separate optimizations were performed for prescribed gauge widening and switch rail geometry. It was shown that the optimized geometry is beneficial for a large set of worn wheel profiles. It was also found that there are many of these wheel profiles that make the full transition from stock rail to switch rail at a smaller switch rail thickness than does the nominal s1002 profile. This means that the s1002 wheel profile is not the worst-case scenario with respect to switch rail vertical loading. This fact should be accounted for in an optimization of switch rail profile geometry.

In the final stage of project ts13, the work focused on crossing geometry optimization. The optimization was performed to minimize wheel–rail contact stresses and the vertical wheel acceleration as a set of representative wheel profiles passes over the crossing. The created crossing design was parameterized in two areas: the cross-sections of wing rail and crossing nose and the vertical positions of wing rail and crossing nose rail cross-sections as functions of the crossing's longitudinal co-ordinate. It was found that small variations in the longitudinal level of the wing rail could be used to distribute the wing rail to crossing nose transitions more evenly within the transition zone.

The ts13 project was completed with Björn Pålsson's successful defence in public of his doctoral dissertation (see below) on 28 February 2014. The faculty-appointed external examiner was Professor Stefano Bruni from Politecnico di Milano in Italy. The reference group for project ts13 had members from Trafikverket, sl Technology and vae. Project ts13 was continuously presented and discussed during biannual workshops with participants from University of Leoben (Austria), vae, voestalpine Schienen and charmec, see page 118. Björn Pålsson has now taken up a position of Assistant Professor (Swedish: forskarassistent) at Chalmers Applied Mechanics/Division of Dynamics.

Björn Pålsson: On the optimization of railway switches, *Proceedings 17th Nordic Seminar on Railway Technology*, Tammsvik (Sweden) October 2012, 1+27 pp (Summary and PowerPoint presentation)

Björn Pålsson: Optimisation of railway crossing geometry considering a set of representative wheel profiles, *Proceedings 23rd International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2013)*, Qingdao (China) August 2013, 10 pp

Björn Pålsson: Design optimisation of switch rails in railway turnouts, *Vehicle System Dynamics,* vol 51, no 10, 2013, pp 1619–1639

Björn Pålsson: Optimisation of railway switches and crossings, Doctoral Dissertation, *Chalmers Applied Mechanics*, Gothenburg February 2014, 160 pp (Summary and six appended papers)

Björn Pålsson: Optimisation of railway crossing geometry considering a set of representative wheel profiles, *Vehicle System Dynamics*, vol 53, no 2, 2015, pp 274–301 (revised article from symposium *IAVSD 2013*)

Björn Pålsson and Jens Nielsen: Dynamic vehicle track interaction in switches and crossings and the influence of rail pad stiffness – field measurements and validation of a simulation model, *Vehicle System Dynamics*, vol 53, no 6, 2015, pp 734–755

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 leaders	Professor Thomas Abrahamsson and Professor Jens Nielsen, Applied Mechanics/ Division of Dynamics
Doctoral candidate	Mr Sadegh Rahrovani (from 2011-03-01; Lic Eng February 2014; PhD March 2016)
Period	2011-03-01–2016-03-31
Chalmers budget (excluding university basic resources)	Stage 6: KSEK 1800 Stage 7: KSEK 2775 Stage 8: KSEK 670
Industrial interests in-kind budget	Stage 6: KSEK 200 Stage 7: KSEK 360 Stage 8: KSEK 100 (*Abetong*)

This project aimed at the optimal properties of a railway track, with the design parameters for optimization being related to the railway sleeper and those track components which interface the sleeper. The results obtained in the previous project TS9 have been incorporated. Since track properties vary significantly in space and time, a stochastic approach was taken and the optimization targets the sleeper reliability. As an optimization will rely on fast simulations, dual level modelling is used. At the first stage, a detailed model based on first principles is used. At the second stage, a substantially simplified reduced-order model was established, with input-output relations that mimic those of the detailed model. This surrogate model is being used for optimization and the detailed model for error control. Much of the project work has been devoted to developing methods that can speed up the computations for optimization.

Fast and efficient simulation methods to treat large-scale finite element models with local non-linearity, such as railway tracks with partially hanging sleepers, have been studied. A new ordinary differential equation (ODE) solver based on an efficient and accurate linear ODE solver was proposed and its accuracy and efficiency to treat a moderate-size non-linear track model have been proved. Geometric and structural properties of the developed integrator have been examined and an extremely accurate energy preservation has been demonstrated. Although calculation speed was the target of the solver design, the solver has also been found to have very good preservation properties as a result of its backbone linear exponential solver. The work was done in co-operation with Dr Klas Modin (previously involved in vehicle system simulation) at the Department of Mathematics.

A bachelor thesis (see below) was supervised by Sadegh Rahrovani and Dr Rikard Bolmsvik focusing on construction, monitoring and maintenance procedures to obtain a suitable ballast condition for railway sleepers. Comparison of tamping and stone-blowing procedures and the benefits and disadvantages of each are discussed. Sadegh Rahrovani presented his licentiate thesis (see below) at a seminar on 27 February 2014 with Dr Clas Andersson (see project TS4) of GKN Aerospace introducing the discussion.

PhD student Sadegh Rahrovani (right) and his supervisor Professor Thomas Abrahamsson from project TS14. Photo taken in 2012. For a photo of Professor Jens Nielsen, see page 25

TS14. (cont'd)

An in-field study in collaboration with Trafikverket and Abetong to determine the track properties of the ballast stiffness along the length of a sleeper has been planned. Since in-field experiments are expensive and time-consuming, an identifiability study and preplanning of test experiments (based on simulation data) has been performed. The aim is to identify unknown track parameters, first using synthetic data and later using field test data. The identified parameter statistics will act as the basis of track optimization. The modelling and computational issues that typically arise in spatially-varying parameter estimation problems, such as in spatial variation of the boundary stiffness along the length of each individual railway sleeper, were investigated in depth. This work was done in collaboration with the Institute for Risk and Uncertainty at the University of Liverpool (UK) during Sadegh Rahrovani's stay there.

A thin-film sensing technique, provided by Sensor Products Inc, for measuring the sleeper-ballast pressure was tried in a field test at Räppe (close to Växjö) with further calibration tests in laboratory. The results were evaluated with focus on calibration accuracy, sampling and filtering, and maximum load range for the sensor. The technique was found to work well and a thin-film pressure sensor device has been bought but still awaits use in field tests.

The work on efficient reliability analysis started in project TS9 was expanded engaging a subset simulation technique that is deemed to be efficient for the evaluation of the reliability for systems with stochastic properties. The reference group for the project had members from Abetong, Dr Plica Ingenieure in Munich (Germany) and Trafikverket.

Many essential ingredients are now in place to conduct a reliability based optimization. The remaining major obstacle for probabilistic sleeper design is the lack of field data. The use of the thin-film pressure sensor in a series of in-situ tests and test data processing after these needs to be done before an actual sleeper optimization can be made.

Sadegh Rahrovani successfully defended his doctoral dissertation (see below) in public on 18 March 2016. The faculty-appointed external examiner of the dissertation was Professor Erik Johnson from the Department of Civil and Environmental Engineering, University of Southern California, USA.

Sadegh Rahrovani, Majid Khorsand Vakilzadeh and Thomas Abrahamsson: A metric for modal truncation in model reduction problems, Part 1: Performance and error analysis, *Proceedings 31st International Modal Analysis Conference (IMAC XXXI)*, Garden Grove CA (USA) February 2013, vol 7, 2014, pp 781–788

Sadegh Rahrovani, Majid Khorsand Vakilzadeh and Thomas Abrahamsson: A metric for modal truncation in model reduction problems, Part 2: Extension to systems with high-dimensional input space, *ibidem*, pp 789–796

Sadegh Rahrovani, Majid Khorsand Vakilzadeh and Thomas Abrahamsson: On Gramian-based techniques for minimal realization of large-scale mechanical systems, *ibidem*, pp 797–805

Sadegh Rahrovani and Thomas Abrahamsson: A new parameter perturbation method suitable for reliability analysis of large dynamic systems, *Proceedings 11th International Conference on Structural Safety & Reliability (ICOSSAR 2013)*, New York NY (USA) June 2013, pp 5343–5349

Alexander Andersson, Hanna Berglund, Johan Blomberg and Oscar Yman: The influence of stiffness variations in railway tracks. A study on design, construction, monitoring and maintenance procedures to obtain suitable support conditions for railway sleepers, BSc Thesis 2013:02, ISSN 1654-4676, *Chalmers Applied Mechanics*, Gothenburg 2013, 90 pp

Sadegh Rahrovani, Thomas Abrahamsson and Klas Modin: An efficient exponential integrator for large nonlinear stiff systems, Part 1: Theorectical investigation, *Proceedings 32nd International Modal Analysis Conference (IMAC XXXII)*, Orlando FL (USA) February 2014, vol 2, 2014, pp 259–268

Sadegh Rahrovani, Thomas Abrahamsson and Klas Modin: An efficient exponential integrator for large nonlinear stiff systems, Part 2: Symplecticity and global error analysis, *ibidem*, pp 269–280

Sadegh Rahrovani: An integration-reduction scheme for simulation of large systems with local nonlinearity and uncertainty – application to moving load problems in railway mechanics, Licentiate Thesis, *Chalmers Applied Mechanics*, Gothenburg February 2014, 71 pp (Summary and four appended papers)

Sadegh Rahrovani, Majid Khorsand Vakilzadeh and Thomas Abrahamsson: Modal dominancy analysis based on modal contribution to frequency response function H2-norm, *Mechanical Systems and Signal Processing*, vol 48, nos 1–2, 2014, pp 218–231

Sadegh Rahrovani, Thomas Abrahamsson and Klas Modin: Integration of Hamiltonian systems with a structure preserving algorithm, *Proceedings 26th International Conference on Noise and Vibration Engineering (ISMA 2014) including 5th International Conference on Uncertainty in Structural Dynamics (USD 2014)*, Leuven (Belgium) September 2014, pp 2915–2929

Sadegh Rahrovani, Thomas Abrahamsson and Klas Modin: Stability limitations in simulation of dynamical systems with multiple time-scales, *Proceedings 33rd International Modal Analysis Conference (IMAC XXXIII)*, Orlando FL (USA) February 2015, vol 1, 2016, pp 93–105

Sadegh Rahrovani, Sin-Kui Au and Thomas Abrahamsson: Bayesian treatment of spatially varying parameter estimation problems via canonical BUS, *Proceedings 34th International Modal Analysis Conference (IMAC XXXIV)*, Orlando FL (USA) February 2016 (in printing)

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)

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

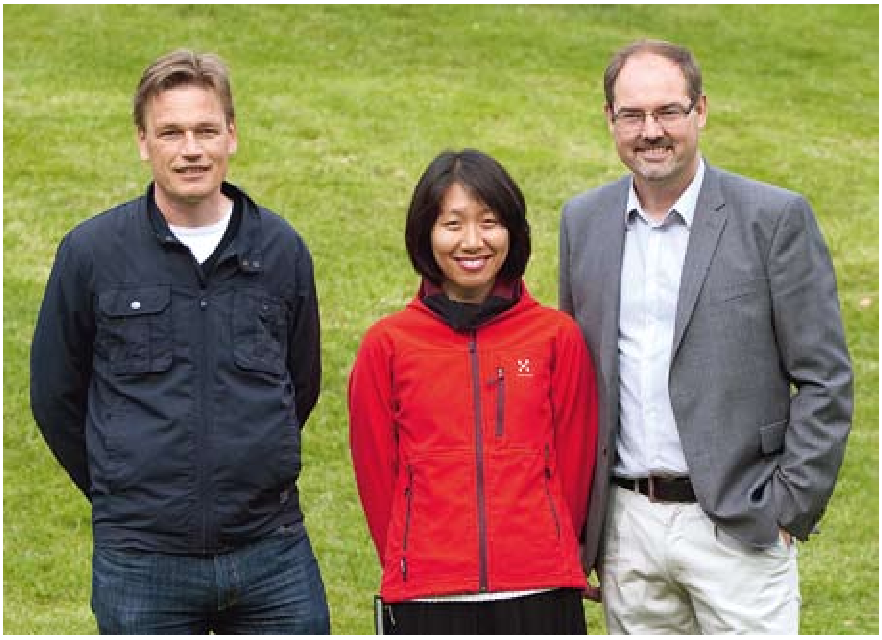
Project leaders	Professor Jens Nielsen, Applied Mechanics/ Division of Dynamics, and Professor Magnus Ekh, Applied Mechanics/ Division of Material and Computational Mechanics
Doctoral candidate	Ms Xin Li (from 2012-01-09; Lic Eng November 2014)
Period	2011-07-01 – 2017-01-31
Chalmers budget (excluding university basic resources)	Stage 6: KSEK 725 Stage 7: KSEK 2704 Stage 8: KSEK 1671
Industrial interests in-kind budget	Stage 6: KSEK – Stage 7: KSEK 200 + 200 + 200 Stage 8: KSEK 200 + 0 + 200 (*Abetong + Trafikverket + voestalpine)*

The project is 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, will be 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, will be used to predict wheel–rail contact forces and track geometry degradation. A stochastic distribution of load parameters such as amount of wear of wheel profiles and variations in train speed, axle load, and wheel–rail friction will be considered. The methodology developed in INNOTRACK (see project EU10) and project TS13 will be applied.

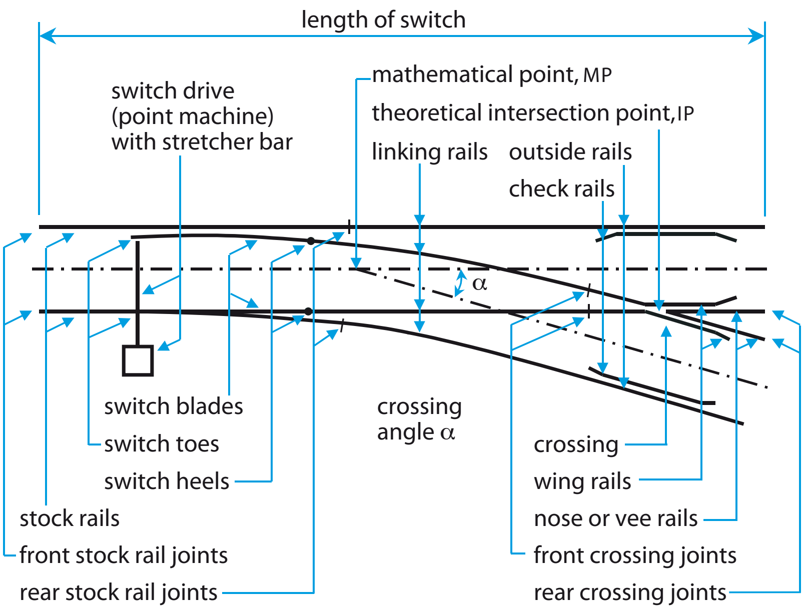
An iterative methodology for simulation of vehicle–track dynamics and prediction of track settlement in S&C has been developed. The FE model of a track switch developed in project SP17 is being used for calculation of track stiffness, track irregularities and sleeper–ballast contact pressure along the track switch (turnout). The FE model is also applied to tune a track model with space-dependent properties that is used in the calculation of vehicle dynamics and dynamic wheel–rail contact forces. Track settlement has been calculated according to a calibrated empirical model found in the literature, which describes settlement as a function of sleeper–ballast contact pressure. Calculated sleeper–ballast contact pressures show that the rail and sleeper arrangement at the crossing, together with the flexibility of the rail pads and base plate pads of a modern Swedish track switch, provide a good load distribution and attenuation of the impact load generated on the crossing nose.

Modelling of track substructure (ballast and subgrade) under cyclic loading has been performed based on a Cycle Densification Model (CDM). The model has been integrated



PhD student Xin Li and her supervisors Professor Jens Nielsen (right) and Professor Magnus Ekh from project TS15. Photo taken in 2012

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"

as a subroutine in the ABAQUS software and is used for prediction of track settlement in S&C. This model with different parameter sets for ballast and sub-ballast has been verified against results from the test track facility in the laboratory of CEDEX in Spain and leads to settlements in the right order of magnitude. The influence of boundary conditions, mesh size and applied impact load on calculated track settlements has been studied. It is concluded that a minimum of two adjacent sleepers on either side of the investigated sleeper need to be accounted for in the settlement model. In the studied load range, a linear relation between the magnitude of the impact load and the predicted settlement after 100 000 load cycles has been observed. The modelling framework can be used to predict differential track settlement accounting for heterogeneity of track components and loading conditions. Xin Li presented her licentiate thesis (see below) at a seminar on 25 November 2014 with Dr Eric Berggren of EBER Dynamics introducing the discussion.

A methodology for simulation of high-frequency dynamic vehicle–track interaction in a railway crossing has been developed. It includes a consistent approach for solving the vertical non-Hertzian (potentially multiple) wheel–rail contact problem based on Green's functions, calculated from FE models of wheelset and track, and the use of an implementation of Kalker's variational method CONTACT. The track model is based on a linear, time-invariant and non-periodic FE model of a railway turnout accounting for variations in rail cross-sections and sleeper lengths, and including base plates and resilient elements. In each time-step of the simulation, the three-dimensional surface geometry of crossing and wheel is described by four-noded linear elements.

The research plan for project TS15 is dated 2011-06-13. The reference group for project TS15 and a parallel project at LTU has members from Abetong, VAE, Vossloh Nordic and Trafikverket. Project TS15 has continuously been presented and discussed during biannual workshops with participants from University of Leoben (Austria), VAE, voestalpine Schienen and CHARMEC, see page 118.

Xin Li, Jens Nielsen and Björn Pålsson: Numerical prediction of track settlement in railway turnouts, *Proceedings 23rd International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2013)*, Qingdao (China) August 2013, 10 pp

Xin Li, Jens Nielsen and Björn Pålsson: Numerical prediction of track settlement in railway turnouts, *Vehicle System Dynamics*, vol 52, supplement 1, 2014, pp 421–439 (revised article from symposium *IAVSD 2013*)

Xin Li, Jens Nielsen and Björn Pålsson: Simulation of track settlement in railway turnouts, *Proceedings 18th Nordic Seminar on Railway Technology*, Bergen (Norway) October 2014, 1+21 pp (Summary and Power Point presentation)

Xin Li: Simulation of track settlement in railway turnouts – an iterative approach, Licentiate Thesis, *Chalmers Applied Mechanics*, Gothenburg November 2014, 72 pp (Summary and two appended papers)

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* (accepted for publication)

Xin Li, Peter Torstensson and Jens Nielsen: Vertical dynamic vehicle–track interaction in a railway crossing predicted by moving Green's functions, *Proceedings 24th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2015)*, Graz (Austria) August 2015, 9 pp (also listed under project TS16)

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), Applied Mechanics/ Division of Dynamics
Doctoral candidate	None (only senior researcher in this project)
Period	2013-01-01 – 2017-05-31
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 900 Stage 8: KSEK 1 900
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 29

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 able to simulate braking noise will be developed. Besides providing a deeper understanding of this complex phenomenon, the ultimate goal is to apply the model in the search for a design solution to the problem.

A computational framework for efficient time-domain simulation of dynamic multibody systems labelled RAVEN (RAil VEhicle Noise) has been developed and validated against the model DIFF by Jens Nielsen (see project TS8) for the case of dynamic vehicle–track interaction. To account for three-dimensional non-Hertzian and non-steady wheel–rail contact, Astrid Pieringer's implementation of Kalker's variational method (see project VB12) is applied. RAVEN has been modified and is used also in project MU31 to investigate stresses and resulting forces in the wheel–rail contact induced by rail surface irregularities. In collaboration with project TS15, RAVEN has been extended to enable simulations of vertical dynamic vehicle–track interaction in a crossing.

During May 2014 Peter Torstensson visited Polytechnic University of Valencia (Spain) to collaborate with Professor Luis Baeza. A model for complex linear stability analysis of railway tread brakes was developed. Inertial effects due to wheel rotation as well as damping provided by tangential wheel–rail contact forces were accounted for. The brake–wheel contact was modelled by use of kinematic constraint equations. For verification purposes, this model has been applied to mimic the conditions in Lucchini's test rig in Surahammar. It is able to capture the dominant unstable eigenmodes of the wheel-brake system.

During the period March–July 2015, the PhD student Juan Giner Navarro of the Polytechnic University of Valencia visited CHARMEC. Together with co-workers, he has developed a rail model based on a mathematical description applying Eulerian co-ordinates. During the stay, a collaborative work with projects TS16 and VB12 focusing on railway curve squeal was performed.

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

Peter Torstensson, Astrid Pieringer and Luis Baeza: Towards a model for prediction of railway tread brake noise, *Proceedings International Conference on Noise and Vibration Engineering (ISMA2014)*, Leuven (Belgium) September 2014, pp 3543–3556 (also listed under project VB12)

Robin Andersson, Peter Torstensson, Elena Kabo and Fredrik Larsson: The influence of rail surface irregularities on contact forces and local stresses, *Vehicle System Dynamics*, vol 53, no 1, 2015, pp 68–87 (also listed under project MU31)

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, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August–September 2015, 9 pp (also listed under project MU31)

Xin Li, Peter Torstensson and Jens Nielsen: Vertical dynamic vehicle–track interaction in a railway crossing predicted by moving Green's functions, *Proceedings 24th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2015)*, Graz (Austria) August 2015, 9 pp (also listed under project TS15)

Astrid Pieringer, Peter Torstensson and Juan Giner Navarro: Curve squeal of rail vehicles – linear stability analysis and non-linear time-domain simulation, *Proceedings Third International Conference on Railway Technology (Railways 2016)*, Cagliari (Sardinia, Italy) April 2016, 16 pp (also listed under project VB12)

Peter Torstensson and Jens Nielsen: Rail corrugation growth on curves – measurements, modelling and mitigation. In Jens Nielsen et al (editors): *Noise and Vibration Mitigation for Rail Transportation Systems, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 126, 2015, pp 659–666 (revised article from workshop *IWRN11*. Also listed under project TS8)

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	Professor Jens Nielsen, Applied Mechanics/ Division of Dynamics, and Professor Magnus Ekh, Applied Mechanics / Division of Material and Computational Mechanics
Assistant supervisor	Dr Jim Brouzoulis, Assistant Professor (Swedish: forskarassistent), Applied Mechanics
Doctoral candidate	Mr Rostyslav Skrypnyk, MSc (from 2015-05-26)
Period	2015-05-27 – 2015-06-30 (– 2019-12-31)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 150 Stage 8: kSEK 3000
Industrial interests in-kind budget	Stage 7: kSEK 15 + 50 + 100 Stage 8: 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 (project EU10), for prediction of rail profile degradation in track switches by integrating several cross-disciplinary numerical models and tools, will be applied and extended. Robustness and computational efficiency of the methodology will be improved by formulating meta-models using, for example, Response Surface Modelling. The models will be calibrated and validated versus damaged rail profiles measured in the field. A better understanding of required production tolerances and maintenance action limits for rail profile degradation will be established.

Work on re-establishing models and simulation environment from projects EU10 and SP21 has been initiated. A literature survey of meta-modelling techniques and response surface modelling has started. Simulation of wheel–rail contact conditions, accounting for non-linear material properties, local contact geometry and plasticity, will be made more numerically efficient by replacing the finite element models from project EU10 with calibrated meta-models. Rostyslav Skrypnyk participated in NSM-28, see below. The research plan for project TS17 is dated 2015-06-04.

Rostyslav Skrypnyk, Jim Brouzoulis, Magnus Ekh and Jens Nielsen: Simulation of material degradation in track switches, *Proceedings 28th Nordic Seminar on Computational Mechanics (NSCM-28)*, Tallinn (Estonia) October 2015, pp 157–159

PhD student Rostyslav Skrypnyk in front of his supervisors Professor Jens Nielsen right, Professor Magnus Ekh (middle) and Dr Jim Brouzoulis from project TS17

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, Assistant Professor (Swedish: forskarassistent), Applied Mechanics/ Division of Dynamics
Doctoral candidate	None (only senior researcher in this project)
Period	2014-03-01 – 2015-06-30 (– 2018-06-30)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 1 000 Stage 8: kSEK 3 000
Industrial interests in-kind budget	Stage 7: kSEK 15 + 50 + 100 Stage 8: kSEK – *(SL + Trafikverket + ÅF)*

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 will be 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. In the strive to make the methods computationally efficient, identification of the most influential parameters with regard to degradation is also of interest. The uncertainty in deterioration rates due to uncertainties in input parameters will be considered.

A framework for simulation of interaction between vehicles and rail curves of different radii has been established using the commercial multibody simulation code SIMPACK. The framework allows for the automated evaluation of load collectives, which consist of many simulation runs with different vehicle parameter settings, and includes the Manchester Benchmark vehicles, wear estimates using Archard's law, RCF estimates using the $T\gamma$ model and variance estimates where the repeatability in predicted damage for load collectives of different sizes can be assessed.

The studies explore the influence of scatter in wheel profile geometry. The investigations have also covered correlations between rail damage and combined wheel and rail profile properties such as equivalent conicity and radial steering index.

It has been found that the sample size required to obtain repeatable results for randomly generated load collectives varies greatly with curve radius, vehicle and damage criterion. It has been shown that a non-linear damage criterion such as the $T\gamma$ model for RCF damage requires a larger load collective to reach the same variance as a wear estimate using a constant wear coefficient. This is due to the thresholds in the damage criterion resulting in non-linearities. The research plan for project TS18 is dated 2014-01-15.

Björn Pålsson: Optimisation of railway crossing geometry considering a representative set of wheel profiles, *Proceedings 18th Nordic Seminar on Railway Technology*, Bergen (Norway) October 2014, 1+28 pp (Summary and PowerPoint presentation)

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 (IAVSD 2015)*, Graz (Austria) August 2015, 10 pp

Dr Peter Torstensson (left) and Dr Björn Pålsson in projects TS16 and TS18. Both are now Assistant Professors

VB1. STRUCTURAL VIBRATIONS FROM RAILWAY TRAFFIC

Byggnadsvibrationer från järnvägstrafik
Gebäudeschwingungen durch Eisenbahnverkehr
Vibrations de bâtiments causées par le traffic ferroviaire

Project VB1 was completed with Johan Jonsson's successful defence in public of his doctoral dissertation in June 2000. Professor Sven Ohlsson and Professor Thomas Abrahamsson supervised the research. The faculty-appointed external examiner of the dissertation was Dr Christian Madshus from the Norwegian Geotechnical Institute (NGI) in Oslo, Norway. The title of the dissertation is "On ground and structural vibrations related to railway traffic".

An important conclusion from the project was that only low-frequency vibrations are effectively transmitted from a passing train through the ground into a nearby building foundation. Two- and three-dimensional analytical and numerical models were developed and applied. Extensive multi-channel field measurements (in three directions, both at ground surface level and at a depth of 6 m below the ground surface) were performed beside the railway at Alvhem north of Gothenburg, where clay is found to a depth of approximately 40 m. Structural vibrations were measured at the same place on a specially designed concrete slab (0.12 m × 9.00 m × 10.00 m) constructed later on a gravel bed with steel frames of different resonance frequencies mounted on it. By use of compressed air in preplaced hoses under the slab, this could later be lifted from the ground for a separate measurement of its dynamic properties including the steel frames.

For a photo of Johan Jonsson, see page 32. See also CHARMEC's Biennial and Triennial Reports for Stages 1 and 2.

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

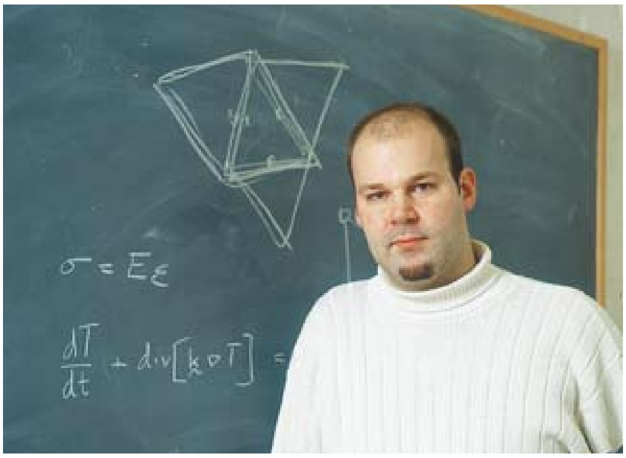
VB2. NOISE FROM TREAD BRAKED RAILWAY VEHICLES

Buller från blockbromsade järnvägsfordon
Rollgeräusche von Zügen mit Klotzbremsen
Bruit émis par les trains freinés par sabot

Freight trains run to a large extent at night, and have also proved noisier than passenger trains. The reason for the latter is that freight trains are nearly always tread-braked while passenger trains are disc-braked. Thermal interaction between the wheel and the brake blocks causes a corrugated tread on the wheel. For the running train this results in oscillating contact forces that excite vibrations in the wheel and rail, with noise radiation as a consequence.

Extensive braking experiments were performed on the test rig (inertia dynamometer) at Surahammar, see page 76, and mathematical modelling and numerical simulations were carried out. Brake blocks of cast iron, sintered material and composite material were investigated. Surface temperatures were measured with an IR camera and the tread waiviness (after cooling) with a mechanical displacement probe. See CHARMEC's Biennial and Triennial Reports for Stages 1, 2 and 3, and also project SD4 below.

Project VB2 was led by Professor Roger Lundén assisted by Dr Peter Möller. The doctoral candidate Martin Petersson gained his licentiate in the project in October 1999 but then left Chalmers for employment elsewhere. The title of his licentiate thesis is "Noise-related roughness of railway wheels – testing of thermomechanical interaction between brake block and wheel tread".



PhD student Martin Petersson (licentiate gained in October 1999) of project VB2. Photo taken in 2000. For photos of Roger Lundén and Peter Möller, see pages 31 and 17

Tore Vernersson was also involved in VB2 and gained his licentiate in that project but later transferred to projects VB3, VB4, EU1, EU8 and SD4. He earned his doctorate in June 2006 in project SD4, see page 78.

VB3. TEST RIG FOR RAILWAY NOISE

Provrigg för järnvägsbuller
Prüfstand für Eisenbahnlärm
Banc pour d´essai pour le bruit ferroviaire

The Railway Noise Test Rig (RNTR) has been designed and constructed as planned, and the VB3 project was completed on 30 June 2000. A 25 m stretch of full-scale track with UIC60 rails was used. A further development of the rig has taken place in the VB4 project. The RNTR was built outdoors on the Adtranz Wheelset (now Lucchini Sweden) factory site in Surahammar. A special feature of RNTR is that wheelset and track, which are not in mechanical contact, can be excited both together and separately (three different tests with the same excitation). The level and directivity of sound from a wheelset (or a bogie) and the track can thereby be established both in total and separately. Microphone sweeps are performed over a quarter of a spherical surface. The track can be statically preloaded. In 2015 the test rig was scrapped. See also CHARMEC's Biennial and Triennial Reports for Stages 1, 2 and 3.

VB4. VIBRATIONS AND EXTERNAL NOISE FROM TRAIN AND TRACK

Vibrationer och externbuller från tåg och spår
Schwingungen und externe Geräusche von Zug und Gleis
Vibrations et bruit extérieur émis par le train et la voie

With higher speeds and axle loads, railway traffic is an increasing source of noise pollution in the community. A predominant part of the noise-generating vibrations stems from the contact between wheel and rail because of irregularities on the running surfaces. The VB4 project has used and developed the RNTR, see VB3. It can demonstrate how the vibration and noise properties of various track and onboard components can be predicted for the running train.

Project VB4 was led by Professor Roger Lundén assisted by Dr Anders Frid of Bombardier Transportation Sweden and Docent (now Professor) Jens Nielsen. The doctoral candidate Carl Fredrik Hartung left Chalmers after obtaining his licentiate in November 2002. The VB4 project was then partially discontinued. The title of the licentiate thesis is "A full-scale test rig for railway rolling noise".

Visualization of the noise emitted from a wheel prototype as measured in the RNTR at frequency 875 Hz in project VB4. Red indicates a high level of sound pressure and blue indicates a low level. A reflecting ground surface is used in this experiment. Photo taken in 2002

Tore Vernersson contributed early in the project and resumed work with the RNTR during Stage 5 with funds remaining from Stage 4. See CHARMEC's Triennial Reports for Stages 2 and 3 and also the new projects VB10 and VB11 on noise emission.

From the left: PhD student Tore Vernersson (doctorate earned in June 2006), the supervisor Professor Roger Lundén, and PhD student Carl Fredrik Hartung (licentiate gained in November 2002). Photo taken in 2000. For a photo of Dr Anders Frid and Professor Jens Nielsen, see page103

VB5. WAVE PROPAGATION UNDER HIGH-SPEED TRAINS

Vågutbredning under höghastighetståg
Wellenausbreitung unter Hochgeschwindigkeitszügen
Propagation d´ondes sous des trains à grande vitesse

Project VB5 was completed with Torbjörn Ekevid's successful defence in public of his doctoral dissertation in December 2002 and his continued work in the project until March 2004. Professor Nils-Erik Wiberg from the Department of Structural Mechanics was his supervisor. The faculty-appointed external examiner of the dissertation was Professor Roger Owen from the Department of Civil Engineering at the University of Wales in Swansea, UK. The title of the dissertation is "Computational solid wave propagation – numerical techniques and industrial applications". The project was partially financed by the Swedish Foundation for Strategic Research (SSF) through its National Graduate School in Scientific Computation (NGSSC).

At places in Sweden where ground conditions are poor with deep layers of soft clay, high vibration levels have been observed on the embankment and surrounding ground when high-speed trains passed. A shock, similar to that experienced when an aircraft breaks the sound barrier, occurs when the increasing speed of the train exceeds the Rayleigh wave speed on the ground. On certain stretches of track in Sweden, the maximum permissible train speed has had to be reduced. By means of numerical simulations and parallel in-field measurements at Ledsgård on the West Coast Line south of Gothenburg, the VB5 project has provided an understanding of which factors affect the vibration levels. Parametric studies have clarified the roles of the speed of the train and the properties of the clay. One measure to reduce the ground vibrations is the installation of lime-cement columns, see project VB9 which was partly a continuation of VB5. See also CHARMEC's Triennial Reports for Stages 2, 3 and 4.

From the left: Dr Torbjörn Ekevid (doctorate earned in December 2002) and his supervisor Professor Nils-Erik Wiberg in project VB5. Photo taken in 2003

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

VB6. INTERACTION OF TRAIN, SOIL AND BUILDINGS

Interaktion mellan tåg, mark och byggnader
Wechselwirkung von Zug, Boden und Gebäuden
Interaction entre train, sol et bâtiments

The VB6 project was intended as a continuation of VB1 with a greater orientation towards constructive measures for the reduction of vibrations in buildings beside the track. The project was terminated (prematurely) in December 2001 when Johan Jonsson left Chalmers for employment elsewhere. Project VB8 partially replaced VB6.

Dr Johan Jonsson of the VB1 and VB6 projects (doctorate earned in June 2000). Photo taken in 2003

VB7. VIBRATION TRANSMISSION IN RAILWAY VEHICLES

Vibrationsöverföring i järnvägsfordon
Schwingungsübertragung in Eisenbahnfahrzeugen
Transmission de vibrations dans les véhicules ferroviaires

Project VB7 was completed with Per Sjövall's successful defence in public of his doctoral dissertation in November 2007. Professor Thomas Abrahamsson, Applied Mechanics, and Professor Tomas McKelvey, Signals and Systems, supervised the research. The faculty-appointed external examiner of the dissertation was Professor Daniel J Rixen from the Faculty of Mechanical, Maritime and Materials Engineering at Delft University of Technology in the Netherlands. The title of the dissertation is "Identification and synthesis of components for vibration transfer and path analysis".

Structure-borne vibrations and sound (SBV&S) are generated by the contact between wheel and rail and transmitted via the bogie structure into the car body. The aim of the VB7 project was to develop and investigate system identification methods and models to allow for analysis, prediction and reduction of SBV&S through a bogie. The focus has been on semi-physical modelling of the bogie suspension system (air cushions, dampers, etc).

A small-scale physical experiment was designed and used in the laboratory of Chalmers Applied Mechanics. A method based on Kalman filter theory was developed, whereby problems of sensor placement and prediction of responses inaccessible for direct measurement are simultaneously approached. See also CHARMEC's Triennial Report for Stage 4.

PhD student Per Sjövall (centre; doctorate earned in November 2007) and his supervisors Professor Thomas Abrahamsson (left) and Professor Tomas McKelvey in the VB7 project inspecting a bogie at Gothenburg railway station. Photo taken in 2006

VB8. GROUND VIBRATIONS FROM RAILWAYS

Markvibrationer från järnväg
Bodenschwingungen von Eisenbahnen
Vibrations de sol causées par le chemin de fer

Project VB8 was completed with Anders Karlström's successful defence in public of his doctoral dissertation in October 2006. Professor Anders Boström and Professor Thomas Abrahamsson from Chalmers Applied Mechanics were his supervisors. The faculty-appointed external examiner of the dissertation was Professor Andrei V Metrikine from the Faculty of Civil Engineering and Geosciences at Delft University of Technology in the Netherlands. The title of the dissertation is "On the modelling of train induced ground vibrations with analytical methods".

Refined models of the ground vibrations caused by train passages were established using simple analytical descriptions of sleepers and rails on a viscoelastic embankment resting on a layered viscoelastic ground.

Calculated results for supersonic train speeds showed that trenches along the railway have a positive effect on the attenuation of ground vibrations on the outer side of the trench. See also CHARMEC's Triennial Report for Stage 4.

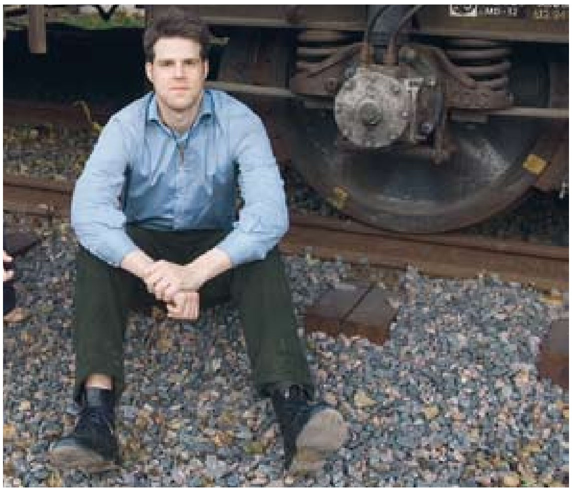
Dr Anders Karlström (left; doctorate earned in October 2006) and his supervisor Professor Anders Boström in project VB8. Photo taken in 2006. For a photo of Thomas Abrahamsson, see above

VB9. DYNAMICS OF RAILWAY SYSTEMS

Dynamik hos järnvägssystem
Dynamik von Eisenbahnsystemen
Dynamique des systèmes du chemin de fer

The VB9 project was completed with Håkan Lane's successful defence in public of his doctoral dissertation in May 2007, when he also left Chalmers. Professor Nils-Erik Wiberg from Chalmers Applied Mechanics and Dr (now Professor) Torbjörn Ekevid from Växjö University (now Linnæus University) were his supervisors. The faculty-appointed external examiner of the dissertation was Professor Göran Sandberg from the Division of Structural Mechanics in the Faculty of Engineering at Lund University (LTH) in Sweden. The title of the dissertation is "Computational railway dynamics – integrated track-train-subgrade modeling sand simulation".

The overall goal of project VB9 was to provide three-dimensional simulations of the entire railway system. Vehicle, track and underground were modelled as one compound system using the finite element (FE) method combined with rigid-body dynamics. Modern techniques for adaptive FE mesh generation were applied and parallel computing was employed in the numerical evaluations.



PhD student Håkan Lane (doctorate earned in May 2007) of project VB9. Photo taken in 2006

Wave propagation in rails, embankment and surrounding ground were studied, in particular for combinations of high train speed and soft clay in the underground. Knowledge and skills gained in the previous project VB5 were utilized. Practical vibration counter-measures in the form of installed lime-cement columns were studied numerically. See also CHARMEC's Triennial Reports for Stages 4 and 5.

From projects VB10 and VB11 (Gothenburg tram on line 8)

VB10. EXTERNAL NOISE GENERATION FROM TRAINS

Extern bullergenerering från tåg
Externe Geräuscherzeugung durch Züge
Bruit extérieur généré par les trains

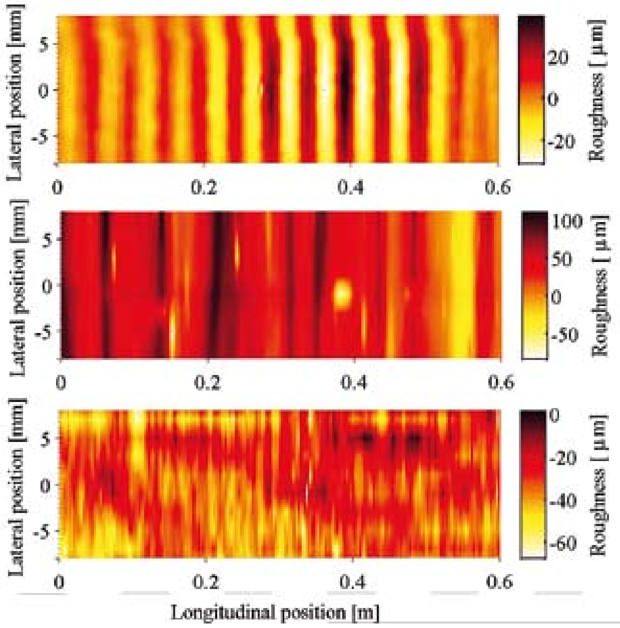
The project was partially financed by VINNOVA (through CHARMEC's budget)

For photos of Astrid Pieringer, Wolfgang Kropp and Anders Frid, see pages 36 and 103

The VB10 project was concluded with Astrid Pieringer's successful defence in public of her doctoral dissertation in May 2011. Professor Wolfang Kropp led the project assisted by Dr Anders Frid of Bombardier Transportation. The faculty-appointed external examiner of the dissertation was Dr (now Professor) Luis Baeza Gonzalez from Universidad Politécnica de Valencia in Spain. The title of the dissertation is "Time-domain modelling of high-frequency wheel/rail interaction". Astrid Pieringer continues her research at Chalmers Applied Acoustics, see project VB12. See also CHARMEC's Triennial Reports for Stages 5 and 6.

Traffic operators, infrastructure administrators, train manufacturers and society in general all have an interest in reducing external noise from railways. For moderate train speeds, the interaction between wheel and rail is the main source of noise emission. Rolling and impact noise are caused by the vertical interaction excited by roughness and discrete irregularities on the running surfaces of wheel and rail, whereas squeal noise, predominantly occurring on curves, is generated by the tangential interaction. Rolling noise and impact noise from wheel flats and rail joints are broadband phenomena involving a large range of frequencies in the audible domain. Contrary to that, squeal noise is generally a tonal sound that dominates all other types of noise when it occurs. The overall aim of project VB10 was to develop suitable models for wheel–rail interaction and the ensuing noise generation. Projects VB10 and TS11 have been run in close co-operation.

Vertical interaction models have been formulated in the time-domain allowing the inclusion of non-linearities in the wheel–rail contact zone. Linear models of wheel and track are represented by Green's functions, which leads to a computationally efficient formulation. In a refined contact model, based on an influence-function method for an elastic half-space, the real three-dimensional (3D) wheel and rail geometries have been considered, with the roughness along several parallel lines being included. The model was applied to evaluate the contact filter effect, which consists in the attenuation of high-frequency excitation at the wheel–rail contact. The application of the 3D contact model was found to be preferable when the degree of correlation between roughness profiles across the width of the contact surfaces is low, see figures.



Three examples of measured roughness profiles utilized in project VB10. From top to bottom: corrugated rail, wheel with cast-iron block brakes, and wheel with sinter block brakes

Frictional instabilities during curve negotiation have been investigated using a combined vertical and tangential interaction model. For both a constant friction law and a friction curve falling with the sliding velocity, stick/slip oscillations were observed which can be linked to noise-emitting vibration modes of the wheels. The imposed lateral creepage, the friction coefficient and the lateral contact position were found to be key parameters for the occurrence of stick/slip and squeal. In particular, the conditions prevailing at the leading inner wheel of the bogie during curving (i e, under-radial position and contact towards the field side of the tread) were found to promote squeal.

Astrid Pieringer, Wolfgang Kropp and Jens Nielsen: The influence of contact modelling on simulated wheel/rail interaction due to wheel flats, *Wear*, vol 314, nos 1-2, 2014, pp 273-281 (revised article from conference *CM2012*. Also listed as under projects TS8 and VB12)

Peter Torstensson, Astrid Pieringer and Jens Nielsen: Simulation of rail roughness growth on small radius curves using a non-Hertzian and non-steady wheel–rail interaction model, *Wear*, vol 314, nos 1-2, 2014, pp 241-253 (revised article from conference *CM2012*. Also listed under project TS11)

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), Civil and Environmental Engineering / Division of Applied Acoustics
Doctoral candidates	Mr Ragnar Vidarsson, MSc (2011-01-15 – 2011-06-30) Mr Ivan Zenzerovic (from 2012-06-01; Lic Eng December 2014)
Period	2011-01-01 – 2017-05-31
Chalmers budget (excluding university basic resources)	Stage 6: KSEK 490 Stage 7: KSEK 2775 Stage 8: KSEK 1900
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, see photo on page 34. 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 solutions to reduce the noise have to increase wheel damping and to apply friction modifiers. However, it is desirable to gain a fundamental understanding of the mechanisms and causes of the squeal in order to find, if possible, appropriate vehicle and track designs to avoid or abate the generation of squeal noise. It should then be possible to predict not only the likelihood of noise but also its amplitude.

Project VB11 is divided into four parts: (i) further extension of the time-domain model developed in project VB10, (ii) an experimental validation of the model, (iii) extensive study to identify the essential parameters (and their complex interaction) responsible for curve squeal, and (iv) investigation of the potential to reduce curve squeal by design changes to track and wheel.

Aiming for an engineering model for curve squeal, the time-domain model for curve squeal developed in project VB10 has been modified and extended. A computationally efficient tangential point-contact model was developed and implemented 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. The regularized friction curve and the contact stiffness in the point-contact model are defined in a stringent way in relation to Kalker's model. 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. The squeal model based on point-contact is typically 2-3 times faster than the original model from VB10. The step towards an engineering model was completed by imple-

From the left: Dr (now Assistant Professor) Astrid Pieringer, Professor Wolfgang Kropp and PhD student Ivan Zenzerovic (licentiate gained in December 2014) in projects VB10 and VB11. Photo taken in 2012

VB11. (cont'd)

menting 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, wheel/rail contact position) and friction were performed using the proposed engineering model for squeal. Friction and kinematic parameters had a significant influence on squeal occurrence and amplitudes. The influence 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.

Ivan Zenzerovic presented his licentiate thesis (see below) at a seminar on 2 December 2014 with Dr Asier Alonso of CEIT at University of Navarra in Spain introducing the discussion.

Research has continued towards a more detailed modelling of the wheel–rail contact including the contact angle. A small influence was noticed for small values of this angle typically occurring at the wheel tread–rail head contact. High values of the contact angle, which may occur for contact near the wheel flange, led to significantly different squeal predictions. The present engineering squeal model was improved by including effects of spin creepage in the regularized friction curve, where spin is considered as an environmental variable that alters the friction curve. Together with the previously implemented inclusion of the contact angle, this significantly extends the point-contact squeal model and enables the evaluation of realistic wheel–rail contact cases. Recently, the squeal model was further extended to two-point contact between wheel and rail.

The joint reference group for projects VB11, VB12 and TS16 has members from Bombardier (in Germany, Sweden and Switzerland), Faiveley, ÅF, Interfleet Technology / SNC-Lavalin and Trafikverket. The research plan for project VB11 is dated 2010-05-15. The work has been delayed by the resignation of the original doctoral candidate and the recruitment of his successor. Ivan Zenzerovic's PhD is planned to be finalized by the end of 2016.

Ivan Zenzerovic, Astrid Pieringer and Wolfgang Kropp: Towards an engineering model for curve squeal, *Proceedings 11th International Workshop on Railway Noise (IWRN11)*, Uddevalla (Sweden) September 2013, pp 495–502

Ivan Zenzerovic, Astrid Pieringer and Wolfgang Kropp: Influence of wheel modal damping on curve-squeal amplitude and frequency, *Proceedings 18th Nordic Seminar on Railway Technology*, Bergen (Norway) October 2014, 1+18 pp (Summary and PowerPoint presentation)

Ivan Zenzerovic: Engineering model for curve squeal formulated in the time domain, Licentiate Thesis, *Chalmers Applied Acoustics*, Gothenburg December 2014, 119 pp (monograph)

Ivan Zenzerovic, Astrid Pieringer and Wolfgang Kropp: Towards an engineering model for curve squeal, *Noise and Vibration Mitigation for Rail Transportation Systems, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 126, 2015, pp 433–440 (revised paper from workshop *IWRN11*)

Ivan Zenzerovic, Wolfgang Kropp and Astrid Pieringer: An engineering time-domain model for curve squeal: tangential point-contact model and Green's functions approach, *Journal of Sound and Vibration* , vol 376, 2016, pp 149–165

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 PhD 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 is 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, alternatively, a single non-linear Hertzian contact spring, were

VB12. (cont'd)

Project leader	Dr Astrid Pieringer, Assistant Professor (Swedish: forskarassistent), Civil and Environmental Engineering / Division of Applied Acoustics
Doctoral candidate	None (only senior researcher in this project)
Period	2012-01-01 – 2016-12-31
Chalmers budget (excluding university basic resources)	Stage 7: see below Stage 8: see below
Industrial interests in-kind budget	Stage 7: kSEK 100 + 15 + 25 + 50 Stage 8: kSEK 100 + 15 + 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 and partly by the Chalmers Area of Advance Transport, profile Sustainable Vehicle Technologies

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.

Recently, a comparison of two models for the prediction of curve squeal noise has been initiated: the model for linear complex stability analysis in the frequency domain developed by Peter Torstensson in project TS16 and the model for non-linear wheel–rail interaction in the time-domain from project VB10. The same sub-models have been implemented in both of the full models. They are a rail model based on a mathematical description applying Eulerian co-ordinates (developed by Juan Giner, University of Valencia) and a model of a rotating wheel (Luis Baeza, University of Valencia). The time and frequency domain models are compared for varying train speeds and this work is ongoing.

Astrid Pieringer has co-operated with Dr Peter Torstensson in project TS16 and Professor Luis Baeza on the development of a model for railway tread brake noise, see project TS16. For the joint reference group of projects VB11, VB12 and TS16, see project VB11. The research plan for project VB12 is dated 2012-05-05.

Astrid Pieringer and Wolfgang Kropp: A three-dimensional numerical model for impact forces due to wheel flats, *Proceedings 17th Nordic Seminar on Railway Technology*, Tammsvik (Sweden) October 2012, 1+29 pages (Summary and PowerPoint presentation)

Astrid Pieringer: On the modelling of wheel/rail noise, *Proceedings AIA-DAGA 2013 Conference on Acoustics (40th Italian Annual Conference on Acoustics / 39th German Annual Conference on Acoustics)*, Meran (Italy) March 2013, 4 pp

Astrid Pieringer, Luis Baeza and Wolfgang Kropp: Modelling of railway curve squeal including effects of wheel rotation, *Proceedings 11th International Workshop on Railway Noise (IWRN11)*, Uddevalla (Sweden) September 2013, pp 479–486

Astrid Pieringer, Wolfgang Kropp and Jens Nielsen: The influence of contact modelling on simulated wheel/rail interaction due to wheel flats, *Wear*, vol 314, nos 1–2, 2014, pp 273–281 (revised article from conference *CM2012*. Also listed under projects TS8 and VB10)

Astrid Pieringer: A numerical investigation of curve squeal in the case of constant wheel/rail friction, *Journal of Sound and Vibration*, vol 333, no 18, 2014, pp 4295–4313

Peter Torstensson, Astrid Pieringer and Luis Baeza: Towards a model for prediction of railway treadbrake noise, *Proceedings International Conference on Noise and Vibration Engineering (ISMA2014)*, Leuven (Belgium) September 2014, pp 3543–3556 (also listed under project TS16)

Astrid Pieringer, Luis Baeza and Wolfgang Kropp: Modelling of railway curve squeal including effects of wheel rotation, *Noise and Vibration Mitigation for Rail Transportation Systems, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 126, 2015, pp 417–424 (revised paper from workshop *IWRN11*)

Astrid Pieringer, Peter Torstensson and Juan Giner Navarro: Curve squeal of rail vehicles – linear stability analysis and non-linear time-domain simulation, *Proceedings 3rd International Conference on Railway Technology (Railways 2016)*, Cagliari (Sardinia, Italy) April 2016, 16 pp (also listed under project TS16)

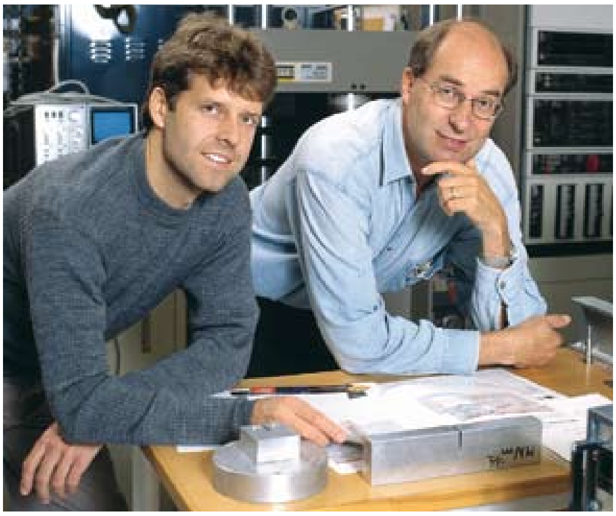
MU1. MECHANICAL PROPERTIES OF BALLAST

Ballastens mekaniska egenskaper
Mechanische Eigenschaften des Schotters
Propriétés mécaniques du ballast

The mechanical properties of ballast determine its ability to distribute the load carried down from the sleepers to the ground in such a way as to prevent detrimental deformations of the track. The MU1 project aimed to set up a constitutive model for the ballast mass, which in terms of continuum mechanics describes the relationship between stresses and deformations in a representative volume element (RVE) in an essentially arbitrary triaxial condition.

Constitutive models have been developed for both monotonic and repeated loading, making it possible to study the behaviour of the ballast mass when it is first rolled over and also when it is subject to long-term effects, such as subsidence and conditioned elasticity properties after being rolled over many times. Calibrations have been performed against laboratory experiments with ballast in triaxial cells.

Professor Kenneth Runesson led project MU1. After gaining his licentiate degree in January 1999, the doctoral candidate Lars Jacobsson left Chalmers for employment at SP Technical Research Institute of Sweden in Borås. His constitutive ballast model has been applied in the SP7 project reported below.



PhD student Lars Jacobsson (left; licentiate gained in January 1999) and his supervisor Professor Kenneth Runesson in project MU1. Photo taken in the laboratory of Chalmers Solid Mechanics in 2000

The title of the licentiate thesis is “A plasticity model for cohesionless material with emphasis on railway ballast”. Professor Kennet Axelsson of LTU (Luleå Technical University) Soil Mechanics and Foundation Engineering introduced the discussion at the licentiate seminar. See also CHARMEC’s Biennial and Triennial Reports for Stages 1, 2 and 3.

MU2. NEW MATERIALS IN WHEELS AND RAILS

Nya material i hjul och räler
Neue Werkstoffe in Rädern und Schienen
Nouveaux matériaux pour roues et rails

The MU2 project was completed with Johan Ahlström’s successful defence in public of his doctoral dissertation in March 2001. Professor Birger Karlsson of Chalmers Engineering Metals (now Materials and Manufacturing Technology) supervised the research. The title of the dissertation is “Thermal and mechanical behaviour of railway wheel steel”. The faculty-appointed external examiner of the dissertation was Professor Ian Hutchings from the Department of Materials Science and Metallurgy at the University of Cambridge, UK.

In co-operation with the wheelset manufacturer Lucchini Sweden (formerly Adtranz Wheelset) candidates for improved material quality were found based on extensive testing of specimens from different castings with different microalloying elements and different forging procedures and heat treatments up to the finished railway wheel. The fatigue behaviour and fracture toughness were studied. Models of phase transformations in a wheel during sliding contact with the rail were also investigated. See also CHARMEC’s Triennial Reports for Stages 2 and 3.

Johan Ahlström has been employed in his department at Chalmers since April 2001 (now Senior Lecturer in Materials and Manufacturing Technology) and involved in the CHARMEC projects MU13, MU15, MU16, MU23, MU24 and EU10. He was awarded the academic degree of Docent in March 2010, see page 110.

For a photo of Johan Ahlström and Birger Karlsson, see page 46.

MU3. MARTENSITE FORMATION AND DAMAGE AROUND RAILWAY WHEEL FLATS

Martensitbildning och skadeutveckling kring hjulplattor
Martensitbildung und Beschädigung an Flachstellen
Formation de martensite et dommage autour des plats de roue

The MU3 project was completed with Johan Jergéus' successful defence in public of his doctoral dissertation in January 1998, after which he left Chalmers. The title of his dissertation is "Railway wheel flats – martensite formation, residual stresses, and crack propagation". The faculty-appointed external examiner of the dissertation was Professor Lennart Karlsson from the Department of Computer Aided Design at Luleå Technical University, Sweden. Professor Roger Lundén together with Professor Bengt Åkesson from Chalmers Solid Mechanics (now Applied Mechanics) supervised the research in project MU3.

A numerical model for the prediction of martensite formation under and around a wheel flat was developed. The model was calibrated against the approximately 240 wheel flats that were created under controlled conditions in the field trials at Silinge (near Flen west of Stockholm) in September 1996. A constitutive model was developed for the calculation of stresses in a material undergoing phase transformations. Transformation plasticity and plastic hardening memory loss during phase transformations were studied. The models were implemented in a commercial finite element (FE) code. New and better guidelines were proposed for the turning of wheels with a flat. See also CHARMEC's Biennial and Triennial Reports for Stages 1, 2 and 3.

PhD student Johan Jergéus (doctorate earned in January 1998) in project MU3. Photo taken in 1997. For a photo of Professor Roger Lundén, see page 55

MU4. PREDICTION OF LIFETIME OF RAILWAY WHEELS

Prediktering av livslängd hos järnvägshjul
Vorhersage der Lebensdauer von Eisenbahnrädern
Prédiction de la durée de vie des roues ferroviaires

The MU4 project was completed with Anders Ekberg's successful defence in public of his doctoral dissertation in April 2000 and his finalizing work up to June 2000. The title of the dissertation is "Rolling contact fatigue of railway wheels – towards tread life prediction through numerical modelling considering material imperfections, probabilistic loading and operational data". The faculty-appointed external examiner of the dissertation was Professor Michael W Brown from the Department of Mechanical Engineering at the University of Sheffield, UK. Professor Roger Lundén of Chalmers Solid Mechanics (now Applied Mechanics) supervised Anders Ekberg's research.

An important outcome of the MU4 project was the computer program WLIFE (Wheel Life) for estimation of the fatigue life of the rim of forged wheels in operation. WLIFE is based on the results of numerical simulations and laboratory and field experiments. The Dang Van equivalent-stress criterion is applied in the calculation of fatigue damage of a material volume in a multiaxial stress field with rotating principal directions. Statistical simulations, through use of a neural network, supplement WLIFE and speed up the computer runs. It was found that rolling contact fatigue of railway wheels is mainly related to the combination of peak loads (overloads) and a local decrease (because of local defects) in the fatigue resistance. See also CHARMEC's Biennial and Triennial Reports for Stages 1, 2 and 3 and the following projects MU9, MU10, MU19, MU20, MU21, MU22, MU27, MU31, MU32, MU33 and MU34 with continued research in the same area.

Anders Ekberg has been employed as senior researcher at Chalmers Solid Mechanics (now Applied Mechanics) since April 2000, where he has worked in close co-operation with Dr (now Docent) Elena Kabo. In August 2005, Anders Ekberg was appointed Docent, see page 110.

For photos of Anders Ekberg and Roger Lundén, see pages 43 and 78.

MU5. MECHANICAL PROPERTIES OF CONCRETE SLEEPERS

Mekaniska egenskaper hos betongsliprar
Mechanische Eigenschaften von Betonschwellen
Propriétés mécaniques des traverses en béton

The MU5 project was completed with Rikard Gustavson's (now Rikard Bolmsvik) successful defence in public of his doctoral dissertation in November 2002. Professor Kent Gylltoft of Chalmers Structural Engineering / Concrete Structures (now Civil and Environmental Engineering) supervised the research. The title of the dissertation is "Structural behaviour of concrete railway sleepers". The faculty-appointed external examiner of the dissertation was Dr Jens Jacob Jensen from SINTEF Civil and Environmental Engineering in Trondheim, Norway.

Extensive laboratory experiments with small specimens were carried out to clarify the bonding (adhesion and friction) between strands (tendons) and concrete in a prestressed sleeper. The three-dimensional bonding model for the prestressed strands, as developed in project MU5, has been incorporated into the general computer program DIANA for concrete structures.

There was close collaboration in project MU5 with the sleeper manufacturer Abetong. See also CHARMEC's Triennial Reports for Stages 2, 3 and 4. From December 2002 and onwards, Rikard Bolmsvik has been employed by Abetong AB in Växjö, Sweden. He has since then been involved at CHARMEC in projects TS10, SP9, SP12, SP16, SP17, SP23, SP26 and SP27 and also serves on the Board of CHARMEC from July 2008, see pages 8 and 127.

PhD student Rikard Gustavson (left; doctorate earned in November 2002) and his supervisor Professor Kent Gylltoft in project MU5. Photo taken in the laboratory of Chalmers Concrete Structures in 2000. For a new photo of Rikard Gustavson (Bolmsvik), see page 9

Materials and maintenance – Material och underhåll (MU) – Werkstoff und Unterhalt – Matériaux et entretien

MU6. ROLLING CONTACT FATIGUE OF RAILS

Rullkontaktutmattning av järnvägsräl
Ermüdung von Schienen durch Rollkontakt
Fatigue des rails due au contact roulant

The MU6 project was completed with Jonas Ringsberg's successful defence in public of his doctoral dissertation in September 2000. The title of the dissertation is "Rolling contact fatigue of railway rails with emphasis on crack initiation". The faculty-appointed external examiner of the dissertation was Professor Roderick A Smith from the Department of Mechanical Engineering at the University of Sheffield, UK. Professor Lennart Josefson of Chalmers Solid Mechanics (now Applied Mechanics) supervised Jonas Ringsberg's research.

The rolling contact between railway wheels and rails often results in fatigue damage in the railhead. The MU6 project dealt with the cracks called head checks which, especially on curves, arise in a surface layer on the railhead. At high friction, gradually growing plastic deformation in shear occurs, so-called ratchetting. This phenomenon gradually leads to such an accumulation of damage that material fracture and cracks ensue. Work carried out in the MU6 project has made it possible to estimate the time that will elapse until head checks arise on a new or reground rail under a given traffic programme.

In April 2004, Jonas Ringsberg was appointed Docent, see page 110. He became a Senior Lecturer in the Department of Shipping and Marine Technology at Chalmers in November 2005 and a Professor in the same department in June 2009. See also CHARMEC's Triennial Reports for Stages 2, 3 and 4.

PhD student Jonas Ringsberg (left; doctorate earned in September 2000) and his supervisor Professor Lennart Josefson in project MU6. Photo taken in 2000

Materials and maintenance – Material och underhåll (MU) – Werkstoff und Unterhalt – Matériaux et entretien

MU7. LASER TREATMENT OF WHEELS AND RAILS

Laserbehandling av hjul och räl
Laserbehandlung von Rädern und Schienen
Traitement au laser des roues et des rails

The MU7 project was completed with Simon Niederhauser's successful defence in public of his doctoral dissertation in December 2005, when he also left Chalmers. The research was supervised by Professor Birger Karlsson from the Department of Materials and Manufacturing Technology. The title of the dissertation is "Laser cladded steel – microstructures and mechanical properties of relevance for railway applications". The faculty-appointed external examiner of the dissertation was Professor Andreas Mortensen from the Laboratory of Mechanical Metallurgy at Ecole Polytechnique Fédérale de Lausanne (EPFL) in Lausanne, Switzerland.

Project MU7 aimed to study opportunities for increasing the life and improving the functioning of railway wheels and rails onto which a surface layer (a coating) has been melted with the aid of laser technology and a powder flow. Such a process allows high-cost alloys to be cladded onto a cheaper substrate material, such as the railhead on curves. Tensile testing of rail materials with Co-Cr and Fe-Cr coatings demonstrated high yield strength and strong work hardening. See also CHARMEC's Triennial Reports for Stages 2, 3 and 4. The project was run in collaboration with the company Duroc Rail in Luleå, Sweden.

PhD students Simon Niederhauser (centre; doctorate earned in December 2005) in project MU7 and Niklas Köppen (left; licentiate gained in November 2006) in project MU16 together with Dr Peter Sotkovszki of Chalmers Materials Science and Engineering (now Materials and Manufacturing Technology). Photo taken in 2003

Materials and maintenance – Material och underhåll (MU) – Werkstoff und Unterhalt – Matériaux et entretien

MU8. BUTT-WELDING OF RAILS

Stumsvetsning av räl
Stumpfschweissen von Schienen
Soudure bout à bout de rails

The MU8 project was completed with Anders Skyttebol's successful defence in public of his doctoral dissertation in September 2004, when he also left Chalmers. The faculty-appointed external examiner of the dissertation was Professor Fredrick V Lawrence Jr from the Department of Civil and Environmental Engineering at the University of Illinois in Urbana-Champaign, USA. Professor Lennart Josefson together with Docent (now Professor) Jonas Ringsberg, both of Chalmers Applied Mechanics, supervised Anders Skyttebol's research. The title of the dissertation is "Continuous welded railway rails – residual stress analyses, fatigue assessments and experiments".

A detailed three-dimensional numerical simulation of the electrical, thermal and mechanical fields during flash butt-welding was performed in project MU8. Data for the thermal and electrical analyses were obtained both from the manufacturer of welding equipment and from Banverket's (now Trafikverket) shop at Sannahed. The constitutive model that was developed and verified by experiments, handles the recovery of hardening for a material that solidifies after being melted.

The redistribution of welding residual stresses and the growth of cracks in the rail weld was simulated. The time period for the growth of cracks from a size detectable by ultrasonics to a critical size was estimated. See also CHARMEC's Triennial Reports for Stages 3 and 4.

PhD student Anders Skyttebol (left; doctorate earned in September 2004) and his supervisor Professor Lennart Josefson in project MU8. Photo taken in 2003. For a more recent photo of Lennart Josefson, see page 48. For a photo of Jonas Ringsberg, see page 41

MU9. ROLLING CONTACT FATIGUE OF RAILWAY WHEELS

Rullkontaktutmattning av järnvägshjul
Ermüdung von Eisenbahnrädern durch Rollkontakt
Fatigue des roues ferroviaires due au contact roulant

Docent (now Professor) Anders Ekberg and Dr (now Docent) Elena Kabo (for photo, see below) led this senior research project, concluded in June 2006, with Professor Roger Lundén as their co-worker. The overall aim of project MU9 was to develop an "engineering" approach to rolling contact fatigue analysis while accounting for load magnitude, material quality, material anisotropy, material defects and manufacturing processes and also plastic deformations in operation. Several meetings were held with Bombardier Transportation, Deutsche Bahn, Duroc Rail, Lucchini Sweden, MTAB, Spoornet, Interfleet Technology and others for project discussions.

The computer program FIERCE (Fatigue Index Evaluator for Rolling Contact Environments) was developed and released as a stand-alone MATLAB code and has also been incorporated into commercial dynamic codes such as ADAMS/Rail and GENSYS. The FIERCE code evaluates the fatigue impact on the wheel rim based on the output from simulations of dynamic train–track interaction. Updated versions of FIERCE are being provided to Bombardier Transportation and other industrial partners. See also CHARMEC's Triennial Reports for Stages 3 and 4. The joint reference group for projects MU9 and MU10 included representatives from Bombardier Transportation Sweden and Interfleet Technology.

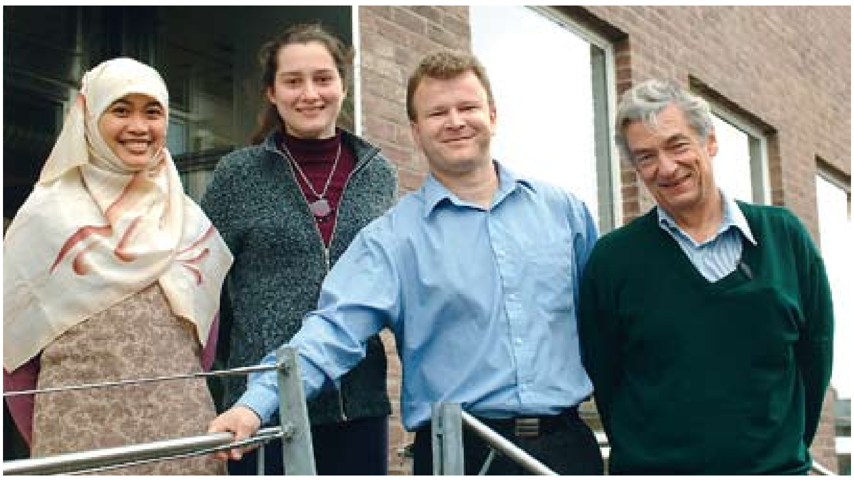
MU10. CRACK PROPAGATION IN RAILWAY WHEELS

Sprickfortplantning i järnvägshjul
Rissausbreitung in Eisenbahnrädern
Propagation de fissures dans les roues ferroviaires

The MU10 project was led by Professor Hans Andersson, Dr (now Docent) Elena Kabo and Docent (now Professor) Anders Ekberg. The doctoral candidate Eka Lansler left Chalmers after gaining her licentiate degree in January 2005 and a revised research plan was adopted. The title of Eka Lansler's thesis is "Subsurface rolling contact fatigue cracks in railway wheels – elastoplastic deformations and mechanisms of propagation". The discussion at the licentiate seminar was introduced by Professor Ulf Stigh from the University of Skövde, Sweden.

The aim of project MU10 was to establish suitable crack growth and fracture models for railway wheels. In particular, cracks initiated below the tread surface were studied, bearing in mind that such cracks grow in a multiaxial and essentially compressive stress field with rotating principal directions and that both elastic and elastoplastic material behaviour should be considered. It was found that the influence on crack propagation by operationally induced residual stresses and by plastic deformations during a load passage (a wheel revolution) is small.

In the continuation of the project, the influence of rail corrugation and wheel out-of-roundness on subsurface initiated rolling contact fatigue was studied. See also CHARMEC's Triennial Reports for Stages 3 and 4.



PhD student Eka Lansler (left; licentiate gained in January 2005) and her supervisors Professor Hans Andersson (right), Dr (now Docent) Elena Kabo and Docent (now Professor) Anders Ekberg in project MU10. Photo taken in 2003. For a new photo of Elena Kabo and Anders Ekberg, see page 70

MU11. EARLY CRACK GROWTH IN RAILS

Tidig spricktillväxt i räls
Frühstadium der Rissausbreitung in Schienen
Début de la propagation de fissures dans les rails

The aim of project MU11 was to develop numerical models for simulating and predicting the growth of surface cracks (head checks) once they have been initiated on the railhead. Professor Lennart Josefson, Dr (now Professor) Jonas Ringsberg and Professor Kenneth Runesson led the project. After gaining his licentiate degree in June 2005, the doctoral candidate Anders Bergkvist left Chalmers. The title of his thesis is "On the crack driving force in elastic-plastic fracture mechanics with application to rolling contact fatigue in rails". The discussion at the licentiate seminar was introduced by Dr (now Professor) Erland Johnson from the SP Technical Research Institute of Sweden.

A parameterized two-dimensional finite element model with a surface crack and a rolling contact load was established. Wear was included to account for a reduction in the effective crack growth rate due to crack mouth truncation. Short surface-breaking cracks were found to grow by shear. The highest crack growth rate along the railhead surface is in the direction of the largest reversed shear strain range. An in-depth study of the concept of "material forces" (from which the crack driving force can be computed) was pursued. Project MU17 can partially be seen as a continuation of project MU11. See also CHARMEC's Triennial Report for Stage 4.

PhD student Anders Bergkvist (left; licentiate gained in June 2005) and his supervisor Dr (now Professor) Jonas Ringsberg in project MU11. Photo taken in 2003. For photos of Professor Lennart Josefson and Professor Kenneth Runesson, see pages 48 and 49

MU12. CONTACT AND CRACK MECHANICS FOR RAILS

Kontakt- och sprickmekanik för räls
Kontakt- und Rissmechanik für Schienen
Mécanique de contact et de fissuration des rails

The MU12 project was completed with Per Heintz's successful defence in public of his doctoral dissertation in September 2006, when he also left Chalmers. Professor Peter Hansbo from Chalmers Applied Mechanics supervised the research. The title of the dissertation is "Finite element procedures for the numerical simulation of crack propagation and bilateral contact". The faculty-appointed external examiner of the dissertation was Professor Paul Steinman from the Department of Mechanical and Process Engineering at Technische Universität Kaiserslautern, Germany. The project was partially financed by the Chalmers Finite Element Center.

Numerical finite element (FE) techniques were developed to predict when and how a predefined crack in a rail will grow under given loading conditions. Lagrange multipliers (stabilized) were employed to enforce zero penetration and a balance of forces at the interface between wheel and rail. Adaptive FE calculations were carried out, applying so-called Eshelby mechanics (with material forces which are energy-conjugated to the propagation of defects in the material) as the starting point. The cracks studied can propagate through the individual finite elements.

Dr Per Heintz (left; doctorate earned in September 2006) and his supervisor Professor Peter Hansbo in project MU12. Photo taken in 2006

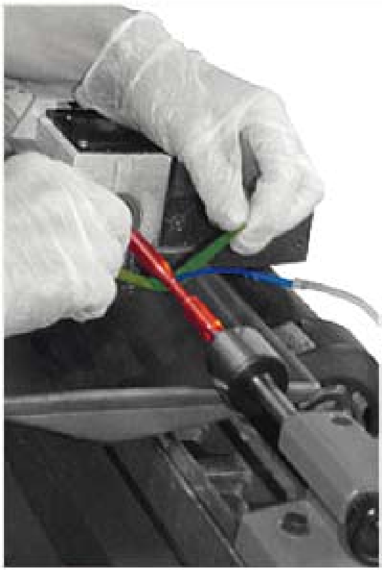
A set of Fortran module packages, written in Fortran 90/95, has been successfully compiled in both Windows and Linux operating systems. It is possible to import meshes and export results from and to the codes ABAQUS and LS-DYNA. See also CHARMEC's Triennial Reports for Stages 3 and 4.

MU13. WHEEL AND RAIL MATERIALS AT LOW TEMPERATURES

Hjul- och rälmaterial vid låga temperaturer
Werkstoffe für Räder und Schienen bei niedrigen Temperaturen
Matériaux des roues et rails aux basses températures

The researchers in this senior project, which concluded in June 2006, were Dr (now Docent) Johan Ahlström and Professor Birger Karlsson from Chalmers Materials and Manufacturing Technology (for photo, see page 46). The influence of operating temperatures down to −40°C on fatigue and fracture behaviour was studied. High loading rates in service at −40°C were simulated by slow rig testing at −60°C. The low-cycle fatigue behaviour at low temperatures was examined for the most promising of the wheel materials from the previous project MU2.

The joint reference group for projects MU13 and MU16 had members from Lucchini Sidermeccanica (Italy) and Bombardier Transportation Sweden. See also CHARMEC's Triennial Reports for Stages 3 and 4.



Preparation of a bar for fatigue testing in project MU13, starting with SiC grinding and finishing with diamond polishing. Rotating bar is shown in red and cooling water in blue

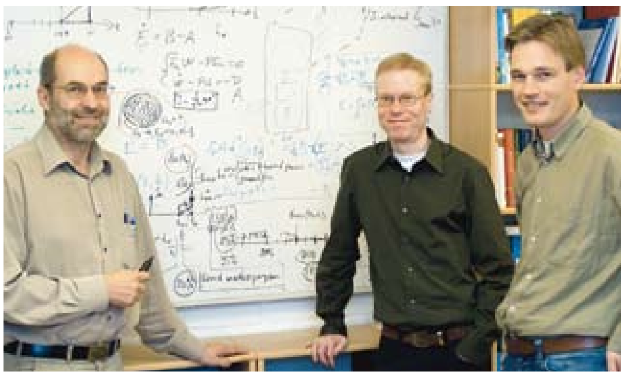
MU14. DAMAGE IN TRACK SWITCHES

Skador i spårväxlar
Schäden an Weichen
Détérioration des aiguillages

Docent (now Professor) Magnus Ekh and Professor Kenneth Runesson led project MU14. Its first part was concluded with Göran Johansson's successful defence in public of his doctoral dissertation in September 2006. The title of the dissertation is "On the modeling of large ratcheting strains and anisotropy in pearlitic steel". The faculty-appointed external examiner of the dissertation was Professor Bob Svendsen from the Faculty of Mechanical Engineering at the University of Dortmund, Germany. The project was then extended until June 2008 with Göran Johansson as part-time researcher.

The MU14 project aimed to provide a fundamental basis for the development of track switches (turnouts) which permit longer inspection intervals, have fewer faults at inspection, involve lower maintenance costs, and cause less disruption in rail traffic. One component under severe loading conditions is the crossing nose. Here mathematical modelling and simulation of large deformations and damage due to cyclic loading have been carried out.

MiniProf measurements of the dimensions of the crossing nose (made of manganese steel) have been made on a reference turnout UIC60-760-1:15 at Alingsås on the Western Main Line in Sweden. Parallel measurements have been performed in Stockholm (SL track) on a crossing nose made of the pearlitic rail steel 900A. The research was carried out in collaboration with the turnout manufacturer VAE in Austria and the Department of Materials and Manufacturing Technology at Chalmers. See also CHARMEC's Triennial Reports for Stages 3 and 4.



Dr Göran Johansson (centre; doctorate earned in September 2006) and his supervisors Docent (now Professor) Magnus Ekh (right) and Professor Kenneth Runesson in project MU14. Photo taken in 2006

MU15. MICROSTRUCTURAL DEVELOPMENT DURING LASER COATING

Mikrostrukturens utveckling under laserbeläggning
Entwicklung des Mikrogefüges bei Laserbeschichtung
Développement de la microstructure pendant le revêtement par laser

The researchers in this senior project which concluded in June 2006, were Professor Birger Karlsson and Dr (now Docent) Johan Ahlström from Chalmers Materials and Manufacturing Technology (for photo, see below). Project MU15 was carried out in collaboration with the company Duroc Rail in Luleå (Sweden) and aimed to find optimum microstructures and properties of the coating (Co-Cr using a laser-based method) and the underlying heat-affected zone (HAZ) for maximizing the lifespan of treated wheels and rails.

Some thirty specimens of the wheel material SURA B82 (corresponding to ER7) and five specimens of rail material UIC900A were hardened and ground followed by thermal exposure with the laser technique developed at Laserzentrum Leoben in Austria. A finite element model of the development of the temperature field during the laser treatment was established and numerical simulations were performed to enable extraction of more information from the tests.

The HAZ was found to develop with a thickness roughly the same as that of the clad itself. During the successive passes of the laser beam, the heating and cooling cycles resulted in austenitization and thereafter in the formation of either martensite or pearlite/bainite. The speed of the laser beam used during coating normally leads to martensite formation after the first pass. Subsequent passes result in tempering and considerable softening of the brittle martensite. Good control of geometry and passing speed is required to avoid untempered brittle martensite after a finished coating. Specific care must be taken at corners and at start and stop points of the running laser source. Compressive stresses built in during martensite formation were found to partly survive successive tempering steps. More astonishingly, such stresses were also preserved during later fatigue loading where they suppress cracking in the HAZ. See also CHARMEC's Triennial Reports for Stages 3 and 4.

Materials and maintenance – Material och underhåll (MU) – Werkstoff und Unterhalt – Matériaux et entretien

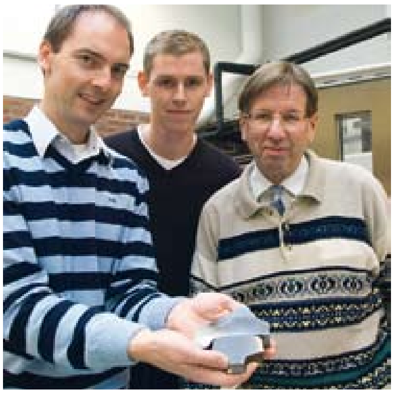
MU16. ALTERNATIVE MATERIALS FOR WHEELS AND RAILS

Alternativa material för hjul och räler
Alternative Werkstoffe für Räder und Schienen
Matériaux alternatifs pour roues et rails

Higher demands on service life together with higher nominal loadings argue for better wheel and rail materials. Cleaner steels, systematic ultrasonic testing of manufactured components and better control of brake systems in wagons should all decrease the likelihood of accidents in railway traffic. In practice, however, all components suffer now and then from unexpected high loadings, internal material defects and damage by foreign objects, such as gravel indents etc. This calls for more damage-tolerant base materials.

The doctoral candidate in project MU16, Niklas Köppen, left Chalmers after gaining his Licentiate of Engineering on 10 November 2006. The title of his licentiate thesis is "Deformation behaviour of near fully pearlitic railway steels during monotonic and cyclic loading". After Niklas Köppen's resignation, the project was run by the senior researchers and their Master's students. See also CHARMEC's Triennial Reports for Stages 3, 4 and 5.

During the first half of MU16, a batch of wheels with material specification UIC R8T from Lucchini Sidermeccanica in Italy was investigated with focus on low-cycle fatigue behaviour and monotonic deformation properties under different temperatures and strain rates. In the second half of MU16, three switch materials were studied with respect to monotonic and cyclic deformation properties: Mn13 (as-cast manganese steel), 51CrV4 (quenched and tempered steel), and Mn13 exposed to Explosion Deformation Hardening. Because of its higher sensitivity to defects under tensile stress, the Mn13EDH has a considerably shorter and more scattered fatigue life than the as-cast Mn13. In railway applications, however, the peak tensile stress levels are much lower than in our low-cycle fatigue tests and this explains why the material can still perform well in revenue service.



PhD student Niklas Köppen (centre; licentiate gained in November 2006) and his supervisors Dr (now Docent) Johan Ahlström (left) and Professor Birger Karlsson in project MU16. Photo taken in 2006

MU17. ELASTOPLASTIC CRACK PROPAGATION IN RAILS

Elastoplastisk sprickfortplantning i räls
Elastoplastische Rissausbreitung in Schienen
Propagation élastoplastique de fissures dans les rails

PhD student Johan Tillberg (middle; doctorate earned in December 2010) and his supervisors Professor Kenneth Runesson (left) and Docent (now Professor) Fredrik Larsson in project MU17. Photo taken in 2009. For a photo of Professor Lennart Josefson, see page 41

The MU17 project was completed with Johan Tillberg's successful defence in public of his doctoral dissertation in December 2010, when he also left Chalmers. Supervisors were Docent (now Professor) Fredrik Larsson, Professor Kenneth Runesson and Professor Lennart Josefson.The faculty-appointed external examiner of the dissertation was Professor Rolf Mahnken from the Faculty of Mechanical Engineering at the University of Paderborn in Germany. There has been close co-operation between projects MU17 and MU20. See also CHARMEC's Triennial Reports for Stages 5 and 6.

Project MU17 dealt with numerical simulation of crack propagation in rails in the context of rolling contact fatigue (RCF) and head check cracks, see photo. After reaching a depth of a few millimetre below the surface, these cracks may change their direction of propagation. In most cases, the cracks turn upwards into the rail surface. This leads to spalling, i e, small pieces of the surface material are detached. In some cases the cracks turn downwards into the rail, which can eventually cause complete rail failure.

An in-depth investigation has been conducted of models and methods in elastoplastic fracture mechanics in the presence of truly large plastic deformations. Such conditions are highly relevant for the early propagation of head checks in rails where several cracks interact in a complex fashion due to the rotating stress field during each single over-rolling of the wheels. The crack driving force (generalized J-integral) is defined here through "material forces" (also called "configurational forces"), which are vectorial measures of the energy release rate due to a (virtual) variation of the position of the crack tip. Several parametric studies of geometric and material properties that affect the interaction of surface cracks have been carried out for loading situations that mimic an over-rolling wheel. The peak value of the J-integral during an over-rolling was found to decrease with decreasing crack interspacing, a phenomenon called crack shielding.

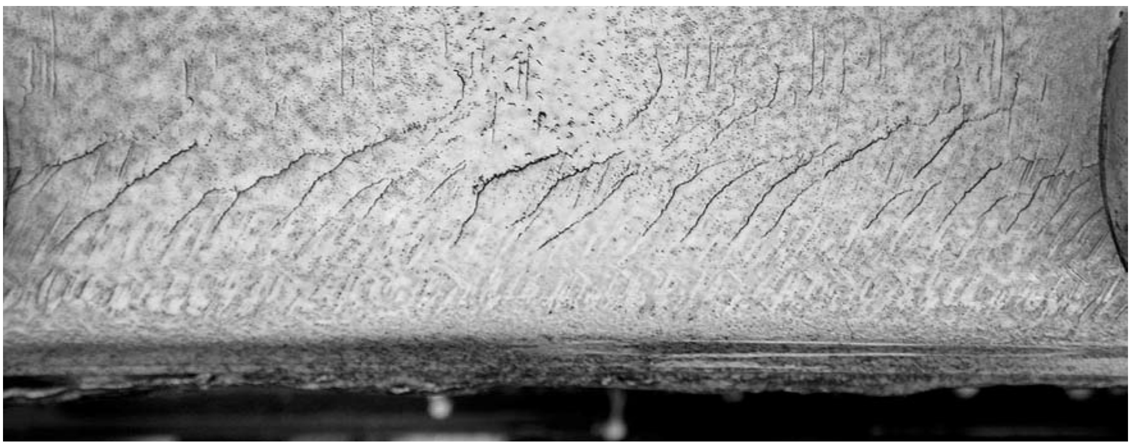


Photo of head checks on a railhead

MU18. WHEELS AND RAILS AT HIGH SPEEDS AND AXLE LOADS

Hjul och räler vid höga hastigheter och axellaster
Räder und Schienen bei hohen Geschwindigkeiten und Achslasten
Roues et rails à grande vitesse et à charge à l'essieu lourde

PhD student Johan Sandström (second from the right; doctorate earned in November 2011) in project MU18 together with his supervisors Docent (now Professor) Anders Ekberg (left), Professor Jacques de Maré (second from the left) and Professor Lennart Josefson. Photo taken in 2006

The MU18 project was completed with Johan Sandström's successful defence in public of his doctoral dissertation in November 2011. Supervisors were Docent (now Professor) Anders Ekberg and Professors Lennart Josefson, Kenneth Runesson and Jacques de Maré. The faculty-appointed external examiner of the dissertation was Professor Stefano Beretta from the Department of Mechanics at Politecnico di Milano in Italy. The title of the dissertation is "Wheels, rails and insulated joints – damage and failure probability at high speed and axle load". Johan Sandström now has a position at SP Technical Research Institute of Sweden in Gothenburg. The project was partially financed by VINNOVA. See also CHARMEC's Triennial Reports for Stages 5 and 6.

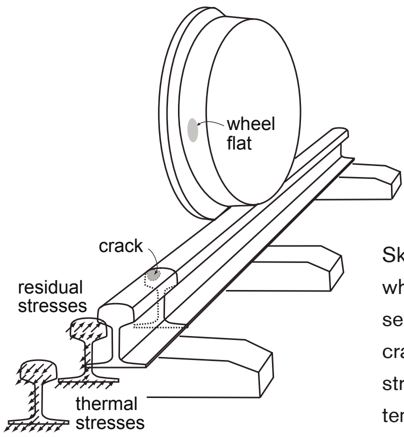
Increases in both maximum train speeds and maximum axle loads are being implemented in Sweden. This has raised a number of technical challenges, two of which are: (i) the number of potential passengers in high-speed operations is relatively low compared to the distances travelled, which calls for low-cost solutions accounting for the fact that high-speed trains today operate on existing tracks with mixed traffic, and (ii) heavy-haul operations must endure a harsh climate and mixed traffic and bear high labour costs, all of which call for reliable solutions that can be maintained with a lean organization. Also, Sweden's railway system consists of many single track lines and many stretches are operated close to peak capacity. Thus, if technical problems arise there will be a need to quickly identify the root causes and implement countermeasures. This calls for an understanding of damage mechanisms and a quantification of the gains provided by different countermeasures. The focus in project MU18 has been on defects and discontinuities in the wheel-rail system which affect the risk of fatigue and fracture of components such as wheels, rails and insulated joints. The present work has benefitted from several previous and parallel CHARMEC projects.

The initial study within the project concerned the probability of rail breaks under impact loads on the Iron Ore Line in northern Sweden, which was selected because of its well-defined operational characteristics. The influence of wheel flat impacts at random positions on the growth of existing rail cracks and on subsequent rail breaks was investigated.

Numerical simulations have also been performed to study plastic deformation and fatigue impact at an insulated rail joint. In parallel, the degradation of insulated joints under revenue operations has been continuously followed in-field at Falkenberg on the West Coast Line in Sweden.

To evaluate the risk of subsurface cracking in a wheel, the Dang Van equivalent stress under Hertzian contacts has been employed. Subsurface initiated rolling contact fatigue cracks start in the vicinity of material defects. The results show how a combination of rail corrugation and high train speeds has a significant impact on the probability of fatigue. A sensitivity analysis reveals a strong influence of both the fatigue strength and the material defect distribution.

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

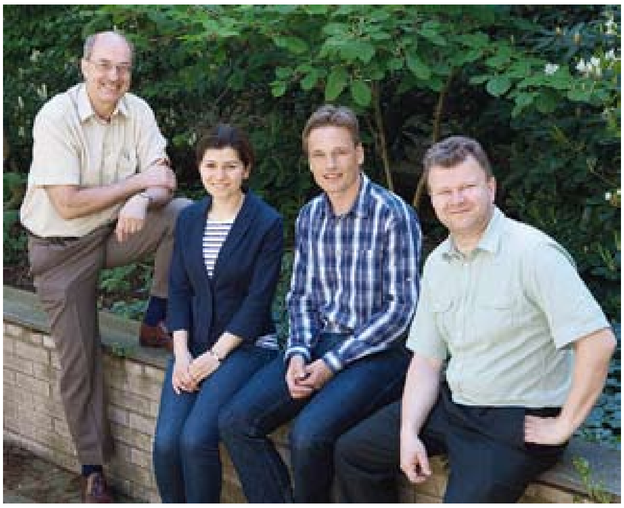


Sketch of out-of-round wheel passing a rail section with head check crack and tensile thermal stresses because of low temperature

MU19. MATERIAL ANISOTROPY AND RCF OF RAILS AND SWITCHES

Materialanisotropi och rullkontaktutmattning av räler och växlar
Materialanisotropie und Rollkontaktermüdung von Schienen und Weichen
Anisotropie des matériaux et fatigue sous charge roulante des rails et des aiguilles

Project leader and supervisor	Professor Magnus Ekh, Applied Mechanics/ Division of Material and Computational Mechanics
Assistant supervisors	Professor Kenneth Runesson and Professor Anders Ekberg, Applied Mechanics
Doctoral candidate	Ms Nasim Larijani (from 2009-06-22; Lic Eng May 2012; PhD June 2014)
Period	2009-06-22 – 2014-06-30
Chalmers budget (excluding university basic resources)	Stage 5: kSEK 100 Stage 6: kSEK 2250 Stage 7: kSEK 1825
Industrial interests in-kind budget	Stage 5: kSEK 50 + 100 + 100 Stage 6: kSEK 50 + 100 + 400 Stage 7: kSEK 25 + 50 + 200 *(SL + Trafikverket + voestalpine)*



PhD student Nasim Larijani (doctorate earned in June 2014) and her supervisors Professor Magnus Ekh (second from the right), Professor Kenneth Runesson (left) and Docent (now Professor) Anders Ekberg

One of the main sources of damage to rails and switches involving rolling contact fatigue (RCF) is the large plastic deformations that accumulate in the surface layer of these components (from manufacturing, frictional rolling contact and wear/grinding). In components made of pearlitic carbon steel these deformations induce anisotropic mechanical properties. The objective of project MU19 was to investigate the effect of this anisotropy on the RCF properties of pearlitic steel components. The project drew on several previous CHARMEC projects, such as MU6, MU11, MU14 and MU17, and there has been close co-operation with ongoing work in projects MU20 and MU24.

In the first part of project MU19, constitutive models to predict the evolution of anisotropy in the rail material were investigated, based on the findings from project MU14. The models were further improved and tuned to fit experimental data. Experimental data from wire-drawing tests, high pressure torsion tests and microcompression tests were used. The high pressure torsion tests and the microcompression tests were performed at Erich Schmid Institute of Materials Science at University of Leoben in Austria. Numerical results agree well with experimental data demonstrating the high potential of the proposed hybrid micro-macromechanical material model in analyses including large deformations of pearlitic steel. The microcompression tests were used to calibrate two material models for individual pearlitic colonies. The macroscopic response of a 3D microstructure model of pearlitic steel, using both colony models, was then compared with that of the proposed hybrid material model. It was concluded that the proposed hybrid material model gives qualitatively similar results as those obtained from the 3D microstructure. The stress levels obtained from the hybrid model were a bit lower but the computational efficiency of the hybrid model excels that of the other models.

In the second part of the project, investigations were carried out (in collaboration with project MU24) on cracks in the deformed surface layer of rails with field samples from tracks at two different locations in Sweden. The cracks were repeatedly ground and photographed. The pictures were then joined digitally to create 3D images. The thickness of the anisotropic surface layer was estimated through microhardness measurements. Changes in the microstructure of the layer in the lateral and rolling directions and their effects on formation and propagation of cracks were studied. The same type of study was carried out on a sample from the full-scale test rig at voestalpine Schienen in Austria.

Based on microstructural investigations, an anisotropic fracture surface model was proposed to account for the directional dependence of resistance against crack propagation. The fracture surface model was employed in a computational framework (developed in project MU20) such that propagation of planar cracks can be simulated. The simulation results showed that the degree of anisotropy in the surface layer has a significant influence on the crack propagation path. It was concluded that for an isotropic surface

MU19. (cont'd)

layer the crack propagates towards the surface while for a sufficient amount of anisotropy the crack deviates into the bulk material. The latter case is more detrimental since it can cause transversal rail fracture. In addition, it was found that the crack path direction is very sensitive to small changes in the anisotropic fracture resistance.

The MU19 project was completed with Nasim Larijani's successful defence in public of her doctoral dissertation (see below) on 10 June 2014. The faculty-appointed external examiner of the dissertation was Professor Stefanie Reese from RWTH Aachen University in Germany. Project MU19 has continuously been presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen and CHARMEC, see page 118. Nasim Larijani has now taken up employment with the consultancy FS Dynamics in Gothenburg.

Nasim Larijani, Göran Johansson and Magnus Ekh: Hybrid micro-macromechanical modeling of anisotropy evolution in pearlitic steel, *European Journal of Mechanics – A/Solids*, vol 38, 2013, pp 38–47

Nasim Larijani, Jim Brouzoulis, Martin Schilke and Magnus Ekh: The effect of anisotropy on crack propagation in pearlitic rail steel, *Proceedings 17th Nordic Seminar on Railway Technology,* Tammsvik (Sweden) October 2012, 1+24pp (Summary and PowerPoint presentation. Also listed under projects MU20 and MU24)

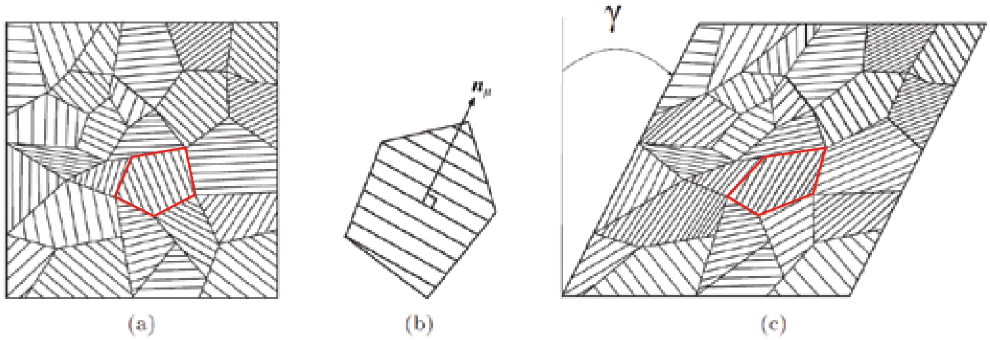
Nasim Larijani, Jim Brouzoulis, Martin Schilke and Magnus Ekh: The effect of anisotropy on crack propagation in pearlitic rail steel, *Wear*, vol 314, nos 1–2, 2014, pp 57–68 (revised article from conference *CM2012*. Also listed under projects MU20 and MU24)

Martin Schilke, Nasim Larijani and Christer Persson: Interaction between cracks and microstructure in three dimensions for rolling contact fatigue in railway rails, *Fatigue & Fracture of Engineering Materials & Structures*, vol 37, no 3, 2014, pp 280–289 (also listed under project MU24)

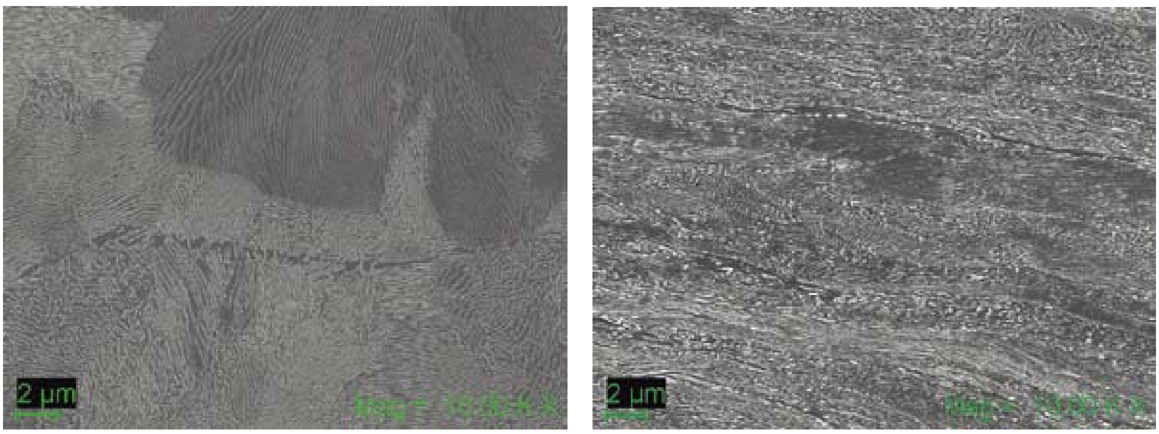
Nasim Larijani, Christoph Kammerhofer and Magnus Ekh: Simulation of high pressure torsion tests of pearlitic steel, *Journal of Materials Processing Technology*, vol 223, 2015, pp 337–343

Magnus Ekh, Nasim Larijani, Erik Lindfeldt, Marlene Kapp and Reinhard Pippan: A comparison of homogenization approaches for modelling the mechanical behaviour of pearlitic steel (submitted for international publication)

Nasim Larijani: Anisotropy in pearlitic steel subjected to rolling contact fatigue – modelling and experiments, Doctoral Dissertation, *Chalmers Applied Mechanics*, Gothenburg June 2014, 106 pp (Summary and five appended papers)



Sketches in project MU19 showing (a) a two-dimensional representative volume element (RVE) of an undeformed pearlitic structure, (b) a single colony with aligned cementite lamellae with normal direction, and (c) a two-dimensional RVE of a pearlitic structure deformed by pure shear



Scanning Electron Microscope (SEM) micrographs of pearlitic structure in surface layer of a used rail at a depth of 2 mm (left) and 100 µm (right) as studied in project MU19

MU20. WEAR IMPACT ON RCF OF RAILS

Nötningens inverkan på rullkontaktutmattning av räler
Einfluss des Verschleisses auf Rollkontaktermüdung von Schienen
Influence de l'usure sur fatigue sous charge roulante des rails

PhD student Jim Brouzoulis (left; doctorate earned in October 2012) and his supervisors Professor Magnus Ekh (right) and Docent (now Professor) Fredrik Larsson. For a photo of Anders Ekberg, see page 49

The MU20 project was concluded with Jim Brouzoulis' successful defence in public of his doctoral dissertation in October 2012. Professor Magnus Ekh, Docent (now Professor) Fredrik Larsson and Docent (now Professor) Anders Ekberg were supervisors.The title of the dissertation is "Numerical simulation of crack growth and wear in rails". The faculty-appointed external examiner of the dissertation was Professor Andreas Menzel from the Institute of Mechanics at TU Dortmund (Germany). Jim Brouzoulis has now taken up a position as Assistant Professor at Chalmers Applied Mechanics/Division of Material and Computational Mechanics.

The deterioration of rails and wheels is an important issue in railway maintenance engineering. Rail damage manifests itself in different forms at the wheel–rail contact, such as wear, plastic deformation, and rolling contact fatigue (RCF). In project MU20 the interaction between wear and RCF of rails was investigated and focused on two main issues: (i) the influence of wear on RCF characteristics, and (ii) strategies for rail profile updating, including automatic control of the prediction quality. The project was a continuation of several previous CHARMEC projects such as TS5, MU6, MU11 and MU12.

Apart from influencing the dynamic train–track interaction, as studied in other CHARMEC projects, the wear of rails influences RCF through the removal of incipient cracks, so-called crack truncation, and a continuous change of the contact geometry. These effects may be either beneficial or detrimental and it is important to discern them through modelling and simulation. A numerical procedure was developed to take into account this change of contact geometry due to wear and plastic deformations in the test-rig at voestalpine Schienen in Leoben. The procedure included simulations of the wheel-rail dynamics using the multibody simulation software GENSYS (co-operation with Peter Torstensson in TS11) together with finite element simulations of the plastic deformations. Quantitatively good agreement was obtained between simulations and results from the experiments at the test rig in terms of worn-off area and shape of the worn profile.

Furthermore, a numerical tool in terms of a 2D finite element model was developed to simulate crack growth in rails. The concept of material forces was adopted and used as the crack propagation quantity. The wear was accounted for through element removal and remeshing technique. In railway rails an anisotropic surface layer is often present due to large deformations. The influence of this highly deformed (anisotropic) surface layer on the crack propagation was studied in co-operation with project MU19. The results showed that the anisotropy has a large influence on the crack growth direction and needs to be accounted for in order to simulate crack growth accurately. See also CHARMEC´s Triennial Report for Stage 6.

Jim Brouzoulis and Magnus Ekh: Crack propagation in rails under rolling contact fatigue loading conditions based on material forces, *International Journal of Fatigue*, vol 45, 2012, pp 98–105

Nasim Larijani, Jim Brouzoulis, Martin Schilke and Magnus Ekh: The effect of anisotropy on crack propagation in pearlitic rail steel, *ibidem*, pp 432–441 (also listed under projects MU19 and MU24)

Nasim Larijani, Jim Brouzoulis, Martin Schilke and Magnus Ekh: The effect of anisotropy on crack propagation in pearlitic rail steel, *Proceedings 17th Nordic Seminar on Railway Technology*, Tammsvik (Sweden) October 2012, 1+24 pp (Summary and PowerPoint presentation. Also listed under projects MU19 and MU24)

Jim Brouzoulis: Elasto-plastic crack growth in rails based on material forces, Technical Report, *Chalmers Applied Mechanics*, Gothenburg 2012, 24 pp

Jim Brouzoulis and Magnus Ekh: Crack propagation in rails under rolling contact fatigue loading conditions based on material forces, *International Journal of Fatigue*, vol 45, 2012, pp 98–105

Jim Brouzoulis, Peter Torstensson, Richard Stock and Magnus Ekh: Wear impact on rolling contact fatigue and crack growth in rails, *Wear*, vol 314, nos 1–2, 2014, pp 13–19 (revised article from conference *CM2012*)

Nasim Larijani, Jim Brouzoulis, Martin Schilke and Magnus Ekh: The effect of anisotropy on crack propagation in pearlitic rail steel, *ibidem*, pp 57–68 (revised article from conference *CM2012*. Also listed under projects MU19 and MU24)

MU21. THERMAL IMPACT ON RCF OF WHEELS

Termisk inverkan på rullkontaktutmattning av hjul
Auswirkung thermischer Prozesse auf die Rollkontaktermüdung von Rädern
Effet thermique sur la fatigue sous charge roulante des roues

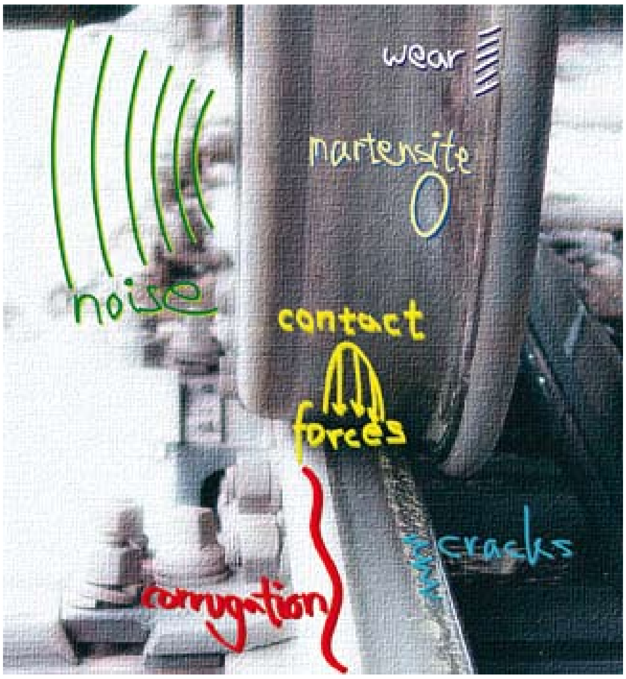
Project leader and supervisor	Professor Anders Ekberg, Applied Mechanics / Division of Dynamics
Assistant supervisors	Docent Elena Kabo, Professor Magnus Ekh and Dr Tore Vernersson, Applied Mechanics
Doctoral candidate	Mr Håkan Hansson, MSc (2008-01-01 – 2008-09-19) Ms Sara Caprioli (from 2009-06-01; Lic Eng December 2011; PhD January 2015)
Period	2008-01-01– 2015-01-31
Chalmers budget (excluding university basic resources)	Stage 5: kSEK 700 Stage 6: kSEK 2650 Stage 7: kSEK 1860
Industrial interests in-kind budget	Stage 5: kSEK 50 + 200 + 100 Stage 6: kSEK 50 + 200 + 100 Stage 7: kSEK 100 + 150 + 50 *(Bombardier Transportation + Green Cargo + SweMaint)*

For photos of the supervisors in project MU21, see pages 63 and 72

Rolling contact fatigue (RCF) of both rails and wheels is a widespread and serious damage phenomenon. On the wheel, RCF can lead to surface or subsurface initiated cracks that may propagate and lead to detachment of part(s) of the wheel tread followed by operational failure and, in the worst case, derailment of the train. RCF of railway wheels is the subject of several previous and ongoing CHARMEC projects, including MU4, MU9, MU10, MU18, MU22 and MU27. Thermal loading of railway wheels may also cause wheel degradation. This influence has been studied in projects SD1, SD4, and SD7. The current project, MU21, focused on railway wheels under the interaction of mechanical loading (due to rolling and/or sliding wheel–rail contact) and thermal loading (due to tread braking and/or wheel–rail friction). The heating affects the material properties (decreased yield limit, increased ductility, higher propensity for wear etc) and may induce detrimental residual stresses and/or surface cracks during cooling.

Moderate thermal loading may cause shallow radial cracking of the wheel tread. These cracks may promote subsequent formation and growth of RCF cracks either through increasing deformation and related crack formation in the bulk material between the thermal cracks (i), or due to shallow thermal cracks acting as initiators for subsequent crack growth due to rolling contact loading (ii). Regarding the first mechanism (i), the results of a comparison between RCF and thermal cracks indicated that thermal cracks of depth 0.1 mm have a negligible effect, whereas cracks of depth 1.0 mm significantly decrease the bulk resistance of the wheel material. Further, it has been shown how the magnitude of stress, strain and deformation depends on the direction of applied traction. Subsequent studies on the second potential mechanism (ii) investigated whether thermal (radial) cracks are more or less detrimental (as initiators) than inclined rolling contact fatigue cracks. This has an application in the specification of maintenance actions. The studies were carried out through extensive numerical simulations where elastoplastic finite element (FE) simulations have been used to evaluate the impact of simultaneous thermal and mechanical loadings of the wheel tread.

In parallel, 3D FE analyses of crack initiation under thermomechanical loading were carried out. Results have been compared to, and showed good agreement with, the results from full-scale experiments in a test rig at the Railway Technical Research Institute (RTRI) in Tokyo (Japan). Differences between thermal (radial) and RCF (inclined) cracks of approximately equal depths have been quantified. A shallow inclination with respect to the rolling direction has been identified as the most severe case. In addition, differences between accelerating and braking wheels have been identified. Also the influence of heating during the formation of thermal cracks has been quantified.



Phenomena related to wheel–rail contact (Anders Ekberg 2003)

MU21. (cont'd)

PhD student Sara Caprioli together with Mr Steven Cervello of Lucchini RS in Italy at her licentiate seminar in December 2011

The MU21 project was completed with Sara Caprioli's successful defence in public of her doctoral dissertation (see below) on 15 January 2015. The faculty-appointed external examiner of the dissertation was Dr David Fletcher, Department of Mechanical Engineering, University of Sheffield, UK. The joint reference group for projects MU21, MU22, MU25, (MU27), MU31, and MU33 had members from Trafikverket, Bombardier Transportation (in Germany/Siegen and Sweden), Lucchini Sweden, Interfleet Technology, KTH, SJ and SL. Sara Caprioli has now taken up employment with Volvo Car Group in Gothenburg.

Tore Vernersson, Sara Caprioli, Elena Kabo, Håkan Hansson and Anders Ekberg: Wheel tread damage – a numerical study of railway wheel tread plasticity under thermomechanical loading, *IMechE Journal of Rail and Rapid Transit*, vol 224, no F5, 2010, pp 435–443 (revised article from conference *IHHA 2009*)

Sara Caprioli, Tore Vernersson and Anders Ekberg: Thermal cracking of a railway wheel tread due to tread braking – critical crack sizes and influence of repeated thermal cycles, *IMechE Journal of Rail and Rapid Transit*, vol 227, no F1, 2013, pp 10–18

Sara Caprioli and Anders Ekberg: Numerical evaluation of the material response of a railway wheel under thermomechanical braking conditions, *Wear*, vol 314, nos 1–2, 2014, pp 181–188 (revised article from conference *CM2012*)

Sara Caprioli and Anders Ekberg: Influence of short thermal cracks on the material behaviour of a railway wheel subjected to repeated rolling, *Proceedings 11th International Fatigue Congress (IFC11)*, Melbourne (Australia) March 2014 (see below)

Sara Caprioli and Anders Ekberg: Influence of short thermal cracks on the material behaviour of a railway wheel subjected to repeated rolling, *Advanced Materials Research*, vols 891–892, 2014, pp 1139–1145 (from conference *IFC11*)

Sara Caprioli: Short rolling contact fatigue and thermal cracks under frictional rolling – a comparison through simulations, *Engineering Fracture Mechanics*, vol 141, 2015, pp 260–273

Sara Caprioli: Thermal impact on rolling contact fatigue of railway wheels, Doctoral Dissertation, *Chalmers Applied Mechanics*, Gothenburg January 2015, 151 pp (Summary and six appended papers)

Ali Esmaeili, Sara Caprioli, Magnus Ekh, Anders Ekberg, Roger Lundén, Tore Vernersson, Kazuyuki Handa, Katsuyoshi Ikeuchi and Toru Miyauchi: Thermal cracking of railway wheels – a combined experimental and numerical approach, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August–September 2015), 8 pp (also listed under project MU32)

Sara Caprioli, Tore Vernersson, Kazuyuki Handa and Katsuyoshi Ikeuchi: Thermal cracking of railway wheels – towards experimental validation, *Tribology International*, vol 94, 2016, pp 409–420

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, Applied Mechanics/ Division of Dynamics
Co-workers	Docent Elena Kabo and Professor Roger Lundén, Applied Mechanics
Doctoral candidate	None (only senior researchers in this project)
Period	2007-07-01 – 2018-01-31
Chalmers budget (excluding university basic resources)	Stage 5: kSEK 700 Stage 6: kSEK 200 Stage 7: kSEK 1 300 Stage 8: kSEK 1 000
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 *(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, but 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. Anders Ekberg has supported LKAB in further investigations of wheel damage on the Iron Ore Line and SweMaint in investigations of a fractured axle. The influence of a first set of actions has been assessed in that damage rates on the Iron Ore Line have decreased significantly.

Anders Ekberg and Roger Lundén participated in the drawing up of road maps for Gröna tåget 2 (Green Train 2) and HCT Järnväg (High Capacity Transport Railways). Anders Ekberg participated in reference group meetings for the research project SWORD at KTH. Anders Ekberg was external examiner for the degree of PhD at the Viva of Gordana Vasić at the University of Newcastle, UK, on 2012-11-16. He was external examiner of the doctoral dissertation by Sagheer Abbas Ranjha of Swinburne University of Technology in Australia. Two French students were supervised by Anders Ekberg. Their project studied how the risk of rail cracks is influenced by track stiffness and was carried out in co-operation with the company Eber Dynamics. Elena Kabo supervised a BSc thesis, see below. Anders Ekberg was examiner for this thesis and the thesis "The influence of stiffness variations in railway tracks" where Sadegh Rahrovani was supervisor, see project TS9.

Anders Ekberg gave the keynote presentation "Deterioration of wheels and rails – what can and should we do about it ?" at the symposium "RailAhead" in Delft on

From the left: Docent (now Professor) Anders Ekberg, Docent Elena Kabo and Professor Roger Lundén during a close inspection. Photo taken in 2012

MU22. (cont'd)

Co-workers in projects MU22, MU26 and MU27 outside the building of Mathematical Sciences on the Chalmers campus. Photo taken in 2012

23–25 October 2013. The Delft keynote established reasons for damage epidemics and showed that secondary effects make such epidemics as safety-critical as "real" accidents. The importance of predictions accounting for the statistical scatter in operational variables was highlighted and quantified. He talked about "Railway damage epidemics – examples of causes, consequences and means of mitigation" at Nationella Konferensen i Transportforskning (National Conference on Transport Research) at Chalmers on 22–23 October 2013.

Elena Kabo and Anders Ekberg have performed a study on rail crack growth and fracture within the International Colloborative Research Initiative (ICRI) on rolling contact fatigue. This study revealed that railhead crack sizes at fracture vary greatly. Depth at transversal deviation seems to be fairly consistent also from an international perspective. Anders Ekberg participated in the International Scientific Panel at the UK research programme Track21 in Southampton on 2012-11-15 and in a meeting of the International Scientific Committee for the UK research project Track to the Future on 2015-10-08–09 in Ilminster (UK). Anders Ekberg was invited speaker at an RCF workshop in Chicago (USA) on 2014-06-16 – 18 sponsored by FRA, the Federal Railroad Administration.

Dr Motohide Matsui and Mr Yoshikazu Kanematsu from the Railway Technical Research Institute (RTRI) in Japan visited CHARMEC's Anders Ekberg and Johan Ahlström on 2014-02-04 discussing, eg, the influence of stress/strength gradient effects in rails and wheels, where RTRI have experimental results that were compared to simulations at CHARMEC. During 2014-03-13 – 04-12 Roger Lundén was a researcher in residence at RTRI in Tokyo mainly dealing with our co-operation on tread braking in which RTRI carries out experiments and CHARMEC modelling in project MU21. Roger Lundén, Anders Ekberg and Jens Nielsen participated in a seminar at RTRI on 2014-03-24 and made a study visit to a regional train workshop the next day.

Anders Ekberg and Elena Kabo together with Johan Ahlström have finalized a study on evolution of the cyclic yield limit of railway steels. A procedure to include the cyclic yield stress in shear in surface initiated RCF estimations in a more accurate manner has been developed. Wheel failures have been investigated in field.

Co-operation with Motohide Matsui of RTRI in Japan, Eric Magel of NRC in Canada, Peter Mutton of Monash University in Australia and Ajay Kapoor of Swindon University in Australia has taken place resulting in a paper for the conference CM2015, see below. Anders Ekberg and Roger Lundén chaired sessions at CM2015 and were selected as two of five guest editors for the special issue of Wear featuring papers from CM2015.

Anders Ekberg, Elena Kabo and Roger Lundén together with Jens Nielsen and Johan Ahlström have contributed to a new IHHA Best Practice Handbook with chapters on damage mechanisms and material properties of wheels and rails, as well as sections on RCF clusters, hollow wear, flange wear and wheel tread lipping.

MU22. (cont'd)

The original research plan from 2006-11-22 for project MU22 was updated 2013-06-30. Projects MU21, MU22, MU25, (MU27), MU31 and MU33 have a joint reference group, see project MU21. Efforts regarding popular science disseminations have been made. As an example to balance media reporting with scientific facts, a number of "FactFlashes" (on safety, sun-kinks, and "maintenance debt" [two parts]) have been produced and published on CHARMEC's webpage: www.charmec.chalmers.se/FactFlash

Elena Kabo, Kalle Karttunen and Anders Ekberg: Report on the investigation of a Regina wheelset, *Chalmers Applied Mechanics*, Gothenburg November 2012, 4 pp (availability restricted)

Anders Ekberg: Report on the investigation of a Regina wheelset, *Chalmers Applied Mechanics*, Gothenburg November 2012, 2 pp + appendix 2 pp (availability restricted)

Motohide Matsui, Anders Ekberg and Roger Lundén: Railway operations in Sweden and Japan – similarities and differences with particular focus on wheel–rail deterioration, *Proceedings 17th Nordic Seminar on Railway Technology*, Tammsvik (Sweden) October 2012, 1+22 pp (Summary and PowerPoint presentation)

Johan Sandström, Elena Kabo, Arne Nissen, Fredrik Jansson, Anders Ekberg and Roger Lundén: Field study of insulated rail joint degradation on Västkustbanan, *ibidem*, 1+12 pp

Alexander Andersson, Hanna Berglund, Johan Blomberg and Oscar Yman: The influence of stiffness variations in railway tracks. A study on design, construction, monitoring and maintenance procedures to obtain suitable support conditions for railway sleepers, BSc Thesis 2013:02, *Chalmers Applied Mechanics*, Gothenburg 2013, 48 pp (and 5 annexes 3+11+9+7+12 pp)

Karl Bäckstedt, Erik Karlsson, Philip Molander and Mikael Persson: Beslutsstöd för underhåll av järnvägsfordon – en studie om utökat användande av hjulskadedetektorer i det proaktiva underhållsarbetet (Decision support for maintenance of railway vehicles – a study on augmented use of wheel damage detectors in the pro-active maintenance work; in Swedish), BSc Thesis 2013:04, *Chalmers Applied Mechanics*, Gothenburg 2013, 33 pp (and 6 annexes 1+3+1+1+1+1 pp). Authors received Swedtrain's price as best railway related Student thesis work in Sweden during 2013

Anders Ekberg, Elena Kabo, Kalle Karttunen, Bernt Lindqvist, Roger Lundén, Thomas Nordmark, Jan Olovsson, Ove Salomonsson and Tore Vernersson: Identifying root causes of heavy haul wheel damage phenomena, *Proceedings International Heavy Haul Conference (IHHA 2013)*, New Delhi (India) February 2013, 8 pp (also listed under project MU27)

Anders Ekberg, Bengt Åkesson and Elena Kabo: Wheel–rail rolling contact fatigue of wheels and rails – probe, predict, prevent, *Wear*, vol 314, nos 1–2, 2014, pp 120-124 (revised article from conference *CM2012*)

Anders Ekberg, Elena Kabo, Kalle Karttunen, Bernt Lindqvist, Roger Lundén, Thomas Nordmark, Jan Olovsson, Ove Salomonsson and Tore Vernersson: Identifying the root causes of damage on the wheels of heavy haul locomotives and its mitigation, *IMechE Journal of Rail and Rapid Transit*, vol 228, no F6, 2014, pp 663–672 (revised article from conference *IHHA 2013*. Also listed under project MU27)

Anders Ekberg and Elena Kabo (editors): Surface fatigue initiated transverse defects and broken rails – an International Review, Research Report 2014:05, *Chalmers Applied Mechanics*, Gothenburg 2014, 22 pp

Mallorie Segond and Quentin Wibeaux: The influence of track stiffness on rail crack occurrence, Projet de Fin d'Études en Génie Mécanique, *Chalmers Applied Mechanics*, Gothenburg 2014, 56 pp

Anders Ekberg, Elena Kabo, Björn Pålsson and Jens Nielsen: Establishing limits for wheel loads on a scientific basis – approach, recommendations and consequences, *Proceedings 18th Nordic Seminar on Railway Technology* (Keynote Lecture), Bergen (Norway) October 2014, 1+24 pp (Summary and PowerPoint presentation)

Sveriges Radio: Tåg i tid – utopi eller redan verklighet? (Trains on time – utopia or already a reality?; in Swedish), 12 September 2014 (http://sverigesradio.se/sida/avsnitt/427738?programid=412&playepisode=427738)

Elena Kabo, Anna Dubois and Anders Ekberg: Järnvägen igår, idag, imorgon – hur forskning kan användas (The railway yesterday, today, tomorrow – how research can be used; in Swedish), *Reflexen* 2014, no 3, pp 15–17

Anders Ekberg, Elena Kabo and Jens Nielsen: Allowable wheel loads, crack sizes and inspection intervals to prevent rail breaks, *Proceedings International Heavy Haul Association Conference (IHHA 2015)*, Perth (Australia) June 2015, pp 30–38 (Authors received the IHHA's Best Paper Award in the category "Infrastructure performance and maintenance". Also listed under project TS8)

Anders Ekberg, Elena Kabo, Roger Lundén and Motohide Matsui: Stress gradient effects in surface initiated rolling contact fatigue of rails and wheels, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August – September 2015), 7 pp

Johan Ahlström, Elena Kabo and Anders Ekberg: Temperature-dependent evolution of the cyclic yield stress of railway wheel steels, *ibidem*, 8 pp (also listed under project MU30)

Eric Magel, Peter Mutton, Anders Ekberg and Ajay Kapoor: Rolling contact fatigue, wear and broken rail derailments, *ibidem*, 11 pp

Anders Ekberg and Roger Lundén: Contributions to Chapter 4 in *Guidelines to Best Practices for Heavy Haul Railway Operations (Management of the Wheel and Rail Interface)* edited by John Leeper and Roy Allen, IHHA 2015. ISBN 978-0-911382-63-1

Anders Ekberg, Elena Kabo and Roger Lundén: Contributions to Chapter 5 in the above handbook

Roger Lundén, Jens Nielsen and Anders Ekberg: The influence of corrugation on frictional stress in the rail–wheel interface, *Proceedings 3rd International Conference on Railway Technology (Railways 2016)*, Cagliari (Sardinia, Italy) April 2016, 14 pp

MU23. MATERIAL BEHAVIOUR AT RAPID THERMAL PROCESSES

Materialbeteende vid snabba termiska förlopp
Materialverhalten bei schnellen thermischen Prozessen
Comportement des matériaux sous processus thermiques rapides

The MU23 project, which was a combined senior and doctoral project, was concluded with Krste Cvetkovski's successful defence in public of his doctoral dissertation on 16 October 2012. Docent Johan Ahlström and Professor Christer Persson were supervisors. The faculty-appointed external examiner of the dissertation was Professor Dietmar Eifler from TU Kaiserslautern, Germany. The title of the dissertation is "Influence of thermal loading on mechanical properties of railway wheel steels". Krste Cvetkovski has now taken up employment at Göteborgs Spårvägar (Gothenburg Trams).

Phenomena behind thermal damage on wheels and rails can be malfunctioning anti-skid devices or irregular wheel and rail surfaces, and two-point contact between wheel and rail as is often occurring on curved track. Here, spatially concentrated and very high friction forces mean that a small material volume can be heated to austenite (at about 750°C) within a few milliseconds. During the following rapid cooling caused by the surrounding cold steel, the material in this volume can be transformed into martensite, and cracks may arise and a complex residual stress field be induced. Repeated heating of material volumes to lower (moderate) temperatures can result in progressive softening, leading to impaired material performance. Project MU23 combined experimental studies and numerical modelling to examine material aspects of combined thermal and mechanical loading.

Based on experimental findings, a model for calculation of residual stresses in martensite from local thermal pulses was formulated within the senior part of project MU23. The papers on thermal damage and residual stresses were written with the combined efforts of the doctoral student and the senior researcher, see below. The work presented at CM2012 on subsurface and surface RCF cracks in pearlitic railway wheels was extended including further work by Mats Norell, specialist in spectroscopy. The investigation of short time tempering of martensite has been finalized and published, see below.

The reference group for project MU23 included members from Bombardier Transportation (Sweden and Germany/Siegen), Interfleet Technology, Lucchini Sweden and Trafikverket. Project MU23 was continuously presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen and CHARMEC, see page 118.

Krste Cvetkovski, Johan Ahlström and Birger Karlsson: Influence of short heat pulses on properties of martensite in medium carbon steels, *Materials Science and Engineering A*, vol 561, 2012, pp 321–328

Krste Cvetkovski and Johan Ahlström: Characterisation of plastic deformation and thermal softening of the surface layer of railway passenger wheel treads, *Wear*, vol 300, nos 1–2, 2013, pp 200–204

Krste Cvetkovski, Johan Ahlström, Mats Norell and Christer Persson: Analysis of wear debris in rolling contact fatigue cracks of pearlitic railway wheels, *Wear*, vol 314, nos 1–2, 2014, pp 51–56

Krste Cvetkovski, Johan Ahlström and Christer Persson: Rapid thermomechanical tempering of iron-carbide martensite, *Material Science and Technology*, vol 30, no 14, 2014, pp 1832–1834

PhD student Krste Cvetkovski (middle; doctorate earned in October 2012) and his supervisors Docent Johan Ahlström (right) and Professor Christer Persson in project MU23. Photo taken in 2012

MU24. HIGH-STRENGTH STEELS FOR RAILWAY RAILS

Höghållfasta stål för järnvägsräls
Hochfeste Stähle für Eisenbahnschienen
Aciers à haute résistance pour les rails de chemin de fer

Project leader and supervisor	Professor Christer Persson, Materials and Manufacturing Technology
Assistant supervisor	Professor Magnus Ekh, Applied Mechanics
Doctoral candidate	Mr Martin Schilke (from 2007-10-15; Lic Eng June 2011; PhD March 2013)
Period	2007-10-01 – 2013-03-31
Chalmers budget (excluding university basic resources)	Stage 5: kSEK 1 500 Stage 6: kSEK 2 700 Stage 7: kSEK 400
Industrial interests in-kind budget	Stage 5: kSEK 100 + 300 Stage 6: kSEK 100 + 300 Stage 7: kSEK 50 + 100 *(Trafikverket + voestalpine)*

The competitiveness of railway transportation calls for longer rail life. This is a challenging demand today because the deterioration of rail materials in service can be expected to accelerate due to higher speeds and axle loads in new railway systems. The primary aim of project MU24 was to investigate crack nucleation and crack growth in high-strength rail steels under fatigue conditions. The study has been performed on both rolling contact fatigue (RCF), as developed in tests on a full-scale fatigue rig, and well-defined laboratory low-cycle fatigue (LCF) tests of the same materials.

The investigation of cracks in three dimensions was finalized together with complementary measurements on white etching layer samples. The white etching layers were found to be produced by high temperature. As for three-dimensional cracks, their general shape for different loading situations and different rail grades has been clarified. The interaction between crack and microstructure and between adjacent cracks has been investigated.

The MU24 project was completed with Martin Schilke's successful defence in public of his doctoral dissertation (see below) on 15 March 2013. The faculty-appointed external examiner of the dissertation was Dr Gunnar Baumann of Deutsche Bahn Netze. Project MU24 was continuously presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen and CHARMEC, see page 118. Martin Schilke has left Chalmers and has taken up employment with the consultancy Interfleet Technology (now SNC-Lavalin) in Gothenburg.

Nasim Larijani, Jim Brouzoulis, Martin Schilke and Magnus Ekh: The effect of anisotropy on crack propagation in pearlitic rail steel, *Proceedings 17th Nordic Seminar on Railway Technology*, Tammsvik (Sweden) October 2012, 1+24 pp (Summary and PowerPoint presentation. Also listed under projects MU19 and MU20)

Motohide Matsui: Evaluation of material deterioration of rails subjected to RCF using X-ray diffraction, *ibidem*

Nasim Larijani, Jim Brouzoulis and Martin Schilke: The effect of anisotropy on crack propagation in pearlitic rail steel, *Wear*, vol 314, nos 1–2, 2013, pp 57–68 (revised article from conference *CM2012*. Also listed under projects MU19 and MU20)

Peter Torstensson and Martin Schilke: Rail corrugation growth on small radius curves – measurements and validation of a numerical prediction model, *Wear*, vol 303, nos 1–2, 2013, pp 381–396 (also listed under project TS11)

Martin Schilke and Christer Persson: Cyclic mechanical behaviour of pearlitic, bainitic and martensitic railway steels, *Chalmers Materials and Manufacturing Technology*, Gothenburg 2013, 20 pp

Martin Schilke, Nasim Larijani and Christer Persson: Interaction between cracks and microstructure in three dimensions for rolling contact fatigue in railway rails, *Fatigue & Fracture of Engineering Materials & Structures*, vol 37, no 3, 2014, pp 280–289 (also listed under project MU19)

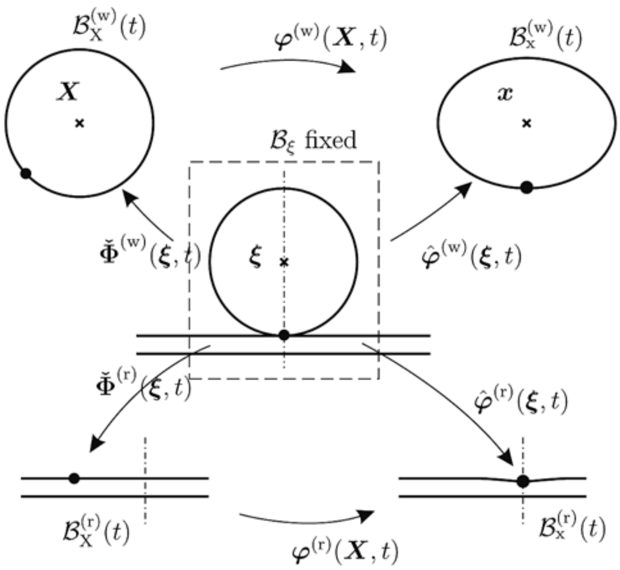
PhD student Martin Schilke (middle; doctorate earned in March 2013) and his supervisors Professor Christer Persson (right) and Professor Magnus Ekh in project MU24

MU25. THERMODYNAMICALLY COUPLED CONTACT BETWEEN WHEEL AND RAIL

Termomekaniskt kopplad kontakt mellan hjul och räl
Thermomechanisch gekoppelter Kontakt zwischen Rad und Schiene
Couplage thermodynamique du contact entre roue et rail

Project leader and supervisor	Professor Anders Ekberg, Applied Mechanics / Division of Dynamics
Assistant supervisors	Professor Fredrik Larsson and Professor Kenneth Runesson, Applied Mechanics
Doctoral candidate	Mr Andreas Draganis (from 2009-06-29; Lic Eng December 2011; PhD September 2014)
Period	2009-01-01 – 2014-09-30
Chalmers budget (excluding university basic resources)	Stage 6: kSEK 2400 Stage 7: —
Industrial interests in-kind budget	Stage 6: — Stage 7: kSEK 50 + 15 + 50 *(Bombardier Transportation + Interfleet Technology + Trafikverket)*

The project was partly financed by The Swedish Research Council, VR (through CHARMEC's budget) and partly by Chalmers Applied Mechanics, Division of Material and Computational Mechanics



Spatial (current) configuration $B_x(t)$, material configuration $B_X(t)$ and absolute (fixed) configuration B_ξ for each of two bodies w(heel) and r(ail). From the application to VR

Project MU25 investigated and developed efficient methods for modelling and computation of the thermomechanically coupled problem when two deformable bodies are in high-speed sliding contact. A typical example is a braked (and locked) railway wheel that moves along the rail. The thermomechanical coupling can potentially be of significant importance due to high contact pressure in combination with fast temperature rise. A major challenge here was to formulate a computationally efficient description of the motion of the two bodies. In particular, such a description should account for the high accuracy needed in the moving contact patch. A significant motivation for the study was the possibility to allow for refined predictions of different forms of rolling contact damage to wheels and rails.

Specific tasks of the project were: (i) establishing an appropriate description of the relative motions for contacting and mutually sliding bodies, (ii) setting up the thermomechanically coupled problem with regard to chosen reference frames for the bodies, (iii) assessing computationally efficient finite element (FE) strategies, (iv) introducing an adaptive FE strategy based on an a posteriori error estimation of various goal functionals of engineering interest, and (v) carrying out validation by comparing predictions with experimental data.

To achieve these aims, the ALE (Arbitrary Lagrangian-Eulerian) kinematical description was employed. This is a generalization of the traditional Lagrangian and Eulerian descriptions. The Lagrangian description follows when the initial configuration of the bodies is taken as the reference configuration. This means that a computational FE mesh will be fixed to material points during deformation. In the Eulerian description, the current configuration is instead chosen as the reference. This implies that a computational mesh will be fixed in space. In this description, keeping track of boundaries and history-dependent material parameters may be very difficult, while large displacements/distortions of the continuum are easily handled.

The main motivation for the project was that performance demands on current and future railway operations (in terms of loading, speeds, braking and accelerating efforts) are so high that cases where thermomechanical interaction and/or the influence of contact irregularities cannot be neglected are becoming common. Most importantly, the adopted ALE framework allows for an analysis of wheel–rail interaction over much longer stretches of track in a full dynamic analysis. This significantly extends what is possible with "traditional" FE analyses. The current work has studied the full feature set of transient, frictional contact. In particular, efforts have been made to allow for mixed control of prescribed tractive forces and/or displacements.

The MU25 project was completed with Andreas Draganis' successful defence in public of his doctoral dis-

MU25. (cont'd)

PhD student Andreas Draganis (second from the right; doctorate earned in September 2014) and his supervisors Docent (now Professor) Anders Ekberg (left), Docent (now Professor) Fredrik Larsson (second from the left) and Professor Kenneth Runesson in project MU25. Photo taken in 2009

sertation (see below) on 3 September 2014. The faculty-appointed external examiner of the dissertation was Professor Udo Nackenhorst from Leibniz University in Hanover (Germany). For the joint reference group, see under project MU21. Andreas Draganis took up employment with SKF in Gothenburg.

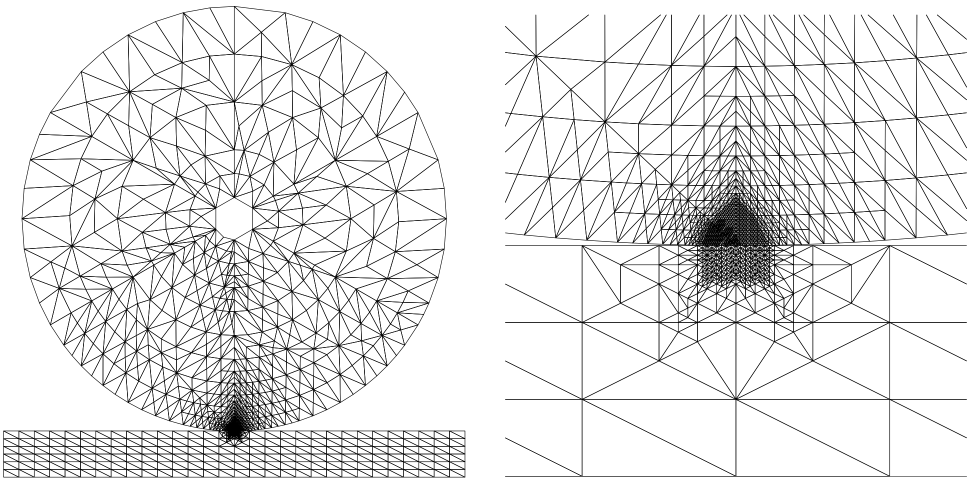
Andreas Draganis, Fredrik Larsson and Anders Ekberg: Modelling of transient thermomechanical rolling/sliding contact using an Arbitrary Lagrangian-Eulerian formulation, *Proceedings 20th International Conference on Computer Methods in Mechanics (CMM 2013)*, Poznan (Poland) August 2013, 2 pp

Andreas Draganis, Fredrik Larsson and Anders Ekberg: Finite element analysis of transient thermomechanical rolling contact using an efficient Arbitrary Lagrangian-Eulerian description, *Computational Mechanics*, vol 54, no 2, 2014, pp 389–405

Andreas Draganis: Numerical simulation of thermomechanically coupled transient rolling contact – an Arbitrary Lagrangian-Eulerian approach, Doctoral Dissertation, *Chalmers Applied Mechanics*, Gothenburg September 2014, 93 pp (Summary and four appended papers)

Andreas Draganis, Fredrik Larsson and Anders Ekberg: Finite element modelling of frictional thermomechanical rolling/sliding contact using an Arbitrary Lagrangian-Eulerian formulation, *IMechE Journal of Engineering Tribology*, vol 229, no 7, 2015, pp 870–880

Andreas Draganis: Finite element modelling of transient thermomechanical rolling contact featuring mixed control of the rigid body motion, *Journal of Tribology*, 2016, doi: 10.1115/1.4033048



Two-dimensional finite element mesh, with a zoomed-in view of the refined wheel–rail contact region, as used in project MU25

MU26. OPTIMUM INSPECTION AND MAINTENANCE OF RAILS AND WHEELS

Optimal inspektion och optimalt underhåll av räler och hjul
Optimal Besichtigung und optimaler Unterhalt von Schienen und Rädern
Inspection optimal et entretien optimale des rails et roues

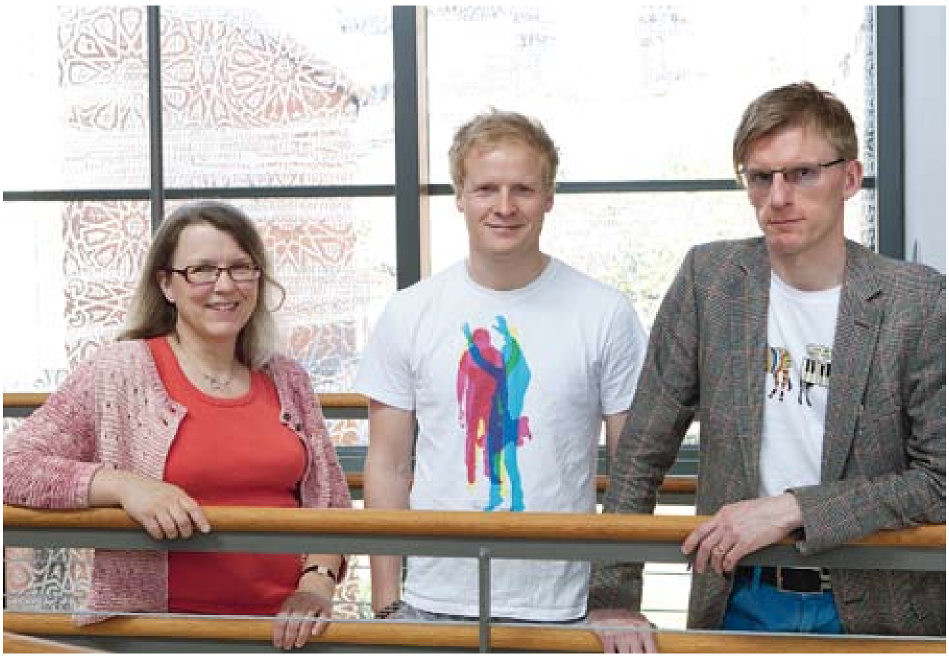
Project leader and supervisor	Docent Ann-Brith Strömberg, Mathematical Sciences / Division of Mathematics / Optimization
Assistant supervisors	ProfessorAnders Ekberg, Applied Mechanics, and Professor Michael Patriksson, Mathematical Sciences
Doctoral candidate	Mr Emil Gustavsson (from 2010-08-15; Lic Eng March 2013; PhD May 2015)
Period	2010-08-15 – 2015-06-30
Chalmers budget (excluding university basic resources)	See below
Industrial interests in-kind budget	Stage 6: — Stage 7: KSEK 15 + 50 *(Interfleet Technology + Trafikverket)*

The project is financed by the joint Department of Mathematical Sciences at Chalmers University of Technology and University of Gothenburg

Continuously increasing train speeds and axle loads lead to a higher rate of deterioration and a shorter operational life of rails and wheels, and also to an increased failure risk. These negative effects may be significantly limited through suitable design and maintenance. To improve the efficiency of maintenance and prevent extreme operational disturbances, an optimal planning of the maintenance is desirable. Project MU26 develops decision support tools for optimization (observing time periods, physical locations, and types of activities) of inspection and maintenance of rails and wheels with respect to life cycle costs, while retaining safe and profitable operations. The tools are based on mathematical models and take into account the costs of inspections and maintenance, the costs of traffic disturbances and delays, the logistics of maintenance operations, required maintenance, inspection capacity, and safety issues. The models account for the fact that degradation of rails and wheels is a progressive process. This process was studied in the parallel project MU27.

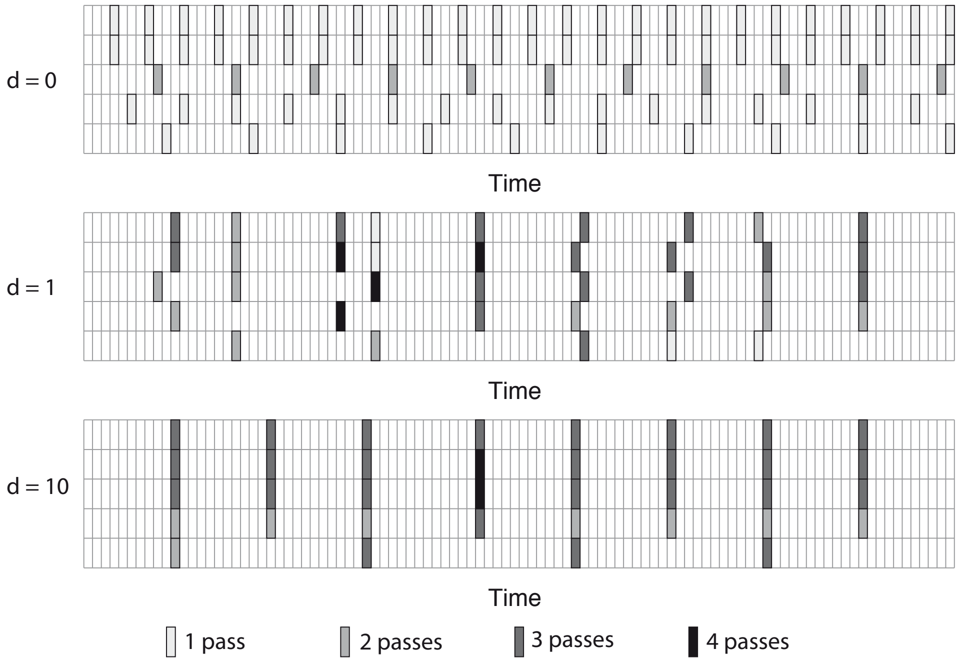
To facilitate operational planning, the effects on inspection and maintenance activities of changes in important input data, such as maintenance capacity, traffic load and budget, are being accounted for. Due to uncertainties in the input data, such as operational conditions and results from damage prediction models, the mathematical optimization models developed in project MU26 allow for stochastic input parameters.

The first part of project MU26 focused on possible strategies of maintenance scheduling for rails and wheels. Several models for maintenance planning of multicomponent systems have been developed. A study on mixed-integer optimization for the planning of preventive maintenance, including case studies on maintenance of railways (in particular rail grinding), wind turbines and aircraft engines, was finalized. Here the sizes of rail cracks are assumed to increase with the interval between grinding occasions with



PhD student Emil Gustavsson (middle; doctorate earned in May 2015) and his supervisors Docent Ann-Brith Strömberg and Professor Michael Patriksson. Photo taken in 2012. For a photo of Professor Anders Ekberg, see page 63

MU26. (cont'd)



Optimal rail grinding schedules – assuming that the degradation speed increases with time – for three distinct values of the maintenance occasion cost *d*. The term "pass" refers to "pass with the grinding machine at the maintenance occasion"

larger cracks implying a larger number of grinding passes, thus generating a higher maintenance cost. A deterministic model for crack growth is presumed and the scheduling of the rail grinding on a set of track sections is optimized.

Analysis of time data regarding rail geometry has been performed in order to obtain degradation and restoration models for the track geometry. Dr Arne Nissen from Trafikverket provided the data. A mathematical optimization model has been developed for scheduling tamping operations on ballasted track. The case study was reported in a paper, see below.

The latest stage of research work focused on the problem of recovery of primal solutions from dual subgradient schemes for mixed binary linear programs. Here numerical results indicate that the proposed methods are suitable solution strategies. A branching strategy for the branch-and-bound method, based on the same research, was developed and evaluated within a Master's thesis supervised by Emil Gustavsson, see below.

The MU26 project was completed with Emil Gustavsson's successful defence in public of his doctoral dissertation (see below) on 29 May 2015. The faculty-appointed external examiner of the dissertation was Professor Dag Haugland from the University of Bergen (Norway). The joint reference group for projects MU26 and MU27 had members from Chalmers Applied Mechanics, Chalmers Mathematical Sciences, Interfleet Technology, SP Technical Research Institute of Sweden, and Trafikverket.

Emil Gustavsson: Contributions to dual subgradient optimization and maintenance scheduling, Licentiate Thesis, *Department of Mathematical Sciences, Chalmers University of Technology and University of Gothenburg*, Gothenburg March 2013, 92 pp (Introduction and three appended papers)

Emil Gustavsson, Michael Patriksson, Ann-Brith Strömberg, Adam Wojciechowski and Magnus Önnheim: Preventive maintenance scheduling of multi-component systems with interval costs, *Computers and Industrial Engineering – Special Issue: Technology and Operations Management*, vol 76, 2014, pp 390–400

Emil Gustavsson: Scheduling tamping operations on railway tracks using mixed integer programming, *EURO Journal on Transportation and Logistics – Special Issue: Transportation Infrastructure Management*, vol 4, no 1, 2015, pp 97–112

Emil Gustavsson, Torbjörn Larsson, Michael Patriksson and Ann-Brith Strömberg: Recovery of primal solutions from dual subgradient schemes for mixed binary linear programs, *Department of Mathematical Sciences, Chalmers University of Technology and University of Gothenburg*, 2015, 32 pp

Emil Gustavsson: Topics in convex and mixed binary linear optimization, Doctoral Dissertation, *University of Gothenburg, Department of Mathematical Sciences*, Gothenburg May 2015, 147 pp (Summary and five appended papers)

Mirjam Schierscher and Pauline Aldenvik: Recovery of primal solutions from dual subgradient methods for mixed binary linear programming; a branch-and-bound approach, MSc Thesis, *Department of Mathematical Sciences, Chalmers University of Technology and University of Gothenburg*, 2015, 41 pp

Emil Gustavsson, Michael Patriksson and Ann-Brith Strömberg: Primal convergence from dual subgradient methods for convex optimization, *Mathematical Programming*, vol 150, no 2, 2015, pp 365–390

Magnus Önnheim, Emil Gustavsson, Ann-Brith Strömberg, Michael Patriksson and Torbjörn Larsson: Ergodic, primal convergence in dual subgradient schemes for convex programming, II – the case of inconsistent primal problems (submitted to *Mathematical Programming*)

MU27. PROGRESSIVE DEGRADATION OF RAILS AND WHEELS

Progressiv nedbrytning av räler och hjul
Progressive Degradierung von Schienen und Rädern
Dégradation progressive des rails et roues

Project leader and supervisor	Docent Elena Kabo, Applied Mechanics / Division of Material and Computational Mechanics
Assistant supervisors	Professor Anders Ekberg, Applied Mechanics, and Professor Michael Patriksson, Mathematical Sciences
Doctoral candidate	Mr Kalle Karttunen (from 2010-10-15; Lic Eng January 2013; PhD June 2015)
Period	2010-10-15 – 2015-10-31
Chalmers budget (excluding university basic resources)	Stage 6: KSEK 1 500 Stage 7: KSEK 3 100 Stage 8: KSEK 156
Industrial interests in-kind budget	Stage 6: — Stage 7: KSEK 15 + 50 Stage 8: — *(Interfleet Technology + Trafikverket)*

When carrying out an optimization of inspection, maintenance and operations to obtain a balance that reduces the life cycle costs, it is vital to understand and be able to quantify the deterioration of key components. To this end, project MU27 focused on the evolving deterioration of rails and wheels during operational loading. This process can be seen as a feedback loop where the progressive deterioration of track and vehicles influences the loading on rails and wheels, which in turn will influence the deterioration rate of wheels and rails etc. The project set out by identifying current degradation models and how these relate the deterioration of rails and wheels to (altered) operational conditions. The work was carried out in close co-operation with project MU26.

A correlation study between predicted tangential wheel–rail contact forces and lateral track irregularities (amplitudes, and first and second order derivatives of the irregularities with respect to the longitudinal co-ordinate) was performed. The best (although still rather poor) correlation was found between first order derivatives of lateral track irregularities and tangential wheel–rail forces. Here the curve radius had an influence with better correlation in sharper curves.

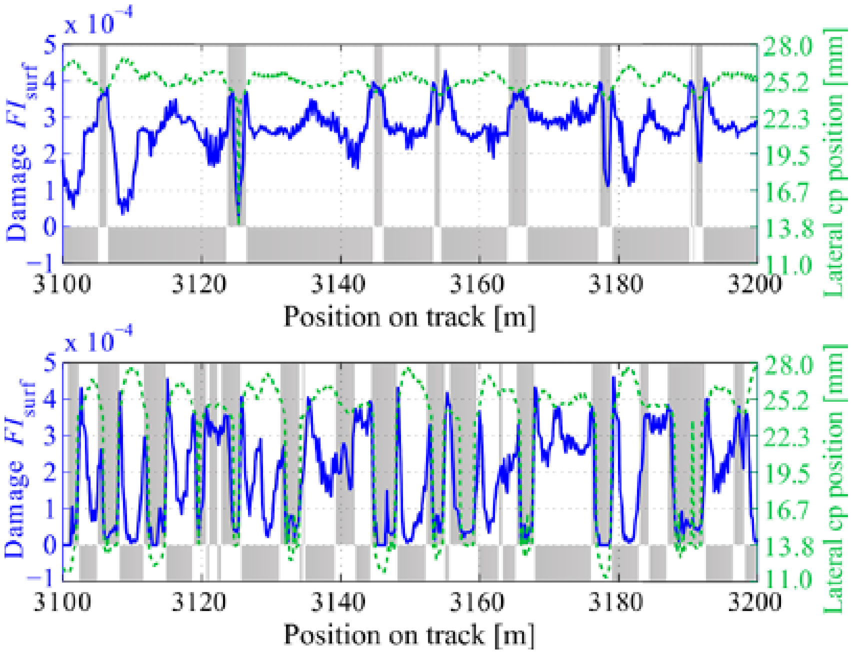
Research on the influence of hollow worn wheel profiles on rail and wheel deterioration was then performed. In a first study, a hollow worn wheel profile constructed from simple geometric shapes is employed in multibody simulations to evaluate the influence of geometry on different degradation measures. Results showed that the commonly used measure of hollow wear (i e, the depth of the hollow wear) had a very poor correlation to predicted degradation. As an example, one of the parameters that was found to have a significant influence on the material degradation was the inclination of the ellipses used to describe the geometry of the hollow wear.

The study proceeded with the identification of the most influential parameters of rail gauge corner and wheel flange root geometries on wheel and rail degradation. MATLAB scripts to parameterize measured rail and wheel profiles were developed and measured profiles were employed to determine parameter spaces for a nearly orthogonal and space filling Latin hypercube sampling. Multibody simulations were then employed to determine corresponding degradation magnitudes. Finally, meta-models of degradation were derived using linear regression. Through these meta-models degradation may be estimated directly from (parameterized) wheel and rail profiles, and track geometries. The meta-models are simple equations that allow for very speedy evaluations. They have been verified against full dynamic simulations and have been employed in a BSc project (see below) to rank the deterioration of actual rail profiles along the Swedish main line between Stockholm and Gothenburg.

Kalle Karttunen presented his licentiate thesis (see below) on 17 June 2013 with Dr Roger Enblom of Bombardier Transportation and KTH introducing the discussion at the licentiate seminar. The MU27 project was completed

PhD student Kalle Karttunen (second from the left; doctorate earned in June 2015) and his supervisors Docent Elena Kabo (right) and Docent (now Professor) Anders Ekberg (left) together with Professor Roger Lundén. Photo taken in 2012. For a photo of Professor Michael Patriksson, see page 61

MU27. (cont'd)



Predicted response of the outer wheel on the leading axle of a freight wagon with Y25 bogies negotiating a 438 metre radius curve. The solid line indicates predicted RCF damage (scale on the left axis) and the dotted line lateral position of wheel/rail contact point (scale on the right axis). Grey areas indicate predicted RCF (positive on the left vertical axis) or wear (negative) according to a wear number based criterion

with Kalle Karttunen's successful defence in public of his doctoral dissertation on 11 Juni 2015, see below. The faculty-appointed external examiner of the dissertation was Professor Rolf Dollevoet from TU Delft in The Netherlands. For the joint reference group, see under projects MU26 and MU21. Kalle Karttunen has now taken up employment with Trafikverket in Gothenburg.

Kalle Karttunen, Elena Kabo and Anders Ekberg: Numerical studies of the influence of laterally deteriorated track geometry on track shift forces and rolling contact fatigue in freight operations, *Proceedings 17th Nordic Seminar on Railway Technology*, Tammsvik (Sweden) October 2012, 1+22 pp (Summary and PowerPoint presentation)

Kalle Karttunen, Elena Kabo and Anders Ekberg: A numerical study of the influence of lateral geometry irregularities on mechanical deterioration of freight tracks, *IMechE Journal of Rail and Rapid Transit*, vol 226, no F6, 2012, pp 575–586

Kalle Karttunen: Mechanical track deterioration due to lateral geometry irregularities, Licentiate Thesis, *Chalmers Applied Mechanics*, Gothenburg January 2012, 54 pp (Summary and two appended papers)

Kalle Karttunen: How track geometry deterioration affects track deterioration, *Transportforum*, Linköping (Sweden) January 2013, 1 p

Anders Ekberg, Elena Kabo, Kalle Karttunen, Bernt Lindqvist, Roger Lundén, Thomas Nordmark, Jan Olovsson, Ove Salomonsson and Tore Vernersson: Identifying root causes of heavy haul wheel damage phenomena, *Proceedings International Heavy Haul Conference (IHHA 2013)*, New Delhi (India) February 2013, 8 pp (also listed under project MU22)

Kalle Karttunen, Elena Kabo and Anders Ekberg: The influence of track geometry irregularities on rolling contact fatigue, *Wear*, vol 314, nos 1–2, 2014, pp 78–86 (revised article from conference *CM2012*)

Kalle Karttunen, Elena Kabo and Anders Ekberg: Numerical assessment of the influence of worn wheel tread geometry on rail and wheel, *Wear*, vol 317, nos 1–2, 2014, pp 77–91

Anders Ekberg, Elena Kabo, Kalle Karttunen, Bernt Lindqvist, Roger Lundén, Thomas Nordmark, Jan Olovsson, Ove Salomonsson and Tore Vernersson: Identifying the root causes of damage on the wheels of heavy haul locomotives and its mitigation, *IMechE Journal of Rail and Rapid Transit*, vol 228, no F6, 2014, pp 663–672 (revised article from conference *IHHA 2013*. Also listed under project MU22)

Kalle Karttunen: Optimised IORE wheels – comparison of profiles and meta-models for worn wheel profile geometries, Gothenburg June 2014, 12 pp (internal report for LKAB)

Kalle Karttunen, Elena Kabo and Anders Ekberg: Influential geometric factors on gauge corner deterioration, *Proceedings 18th Nordic Seminar on Railway Technology*, Bergen (Norway) October 2014, 1+20 pp (Summary and PowerPoint presentation)

Kalle Karttunen: Influence of rail, wheel and track geometries on wheel and rail degradation, Doctoral Dissertation, *Chalmers Applied Mechanics*, Gothenburg May 2015, 122 pp (Summary and five appended papers)

Kalle Karttunen, Elena Kabo and Anders Ekberg: Gauge corner and flange root degradation estimated from rail, wheel and track geometry, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August – September 2015, 8 pp

Karl-Johan Bengtsson, Erik Kvarnström, Carl Möller and Oscar Sundlo: Nedbrytningsmått för järnvägshjul och räl (Deterioration measures for railway wheels and rails; in Swedish), *Chalmers Applied Mechanics*, BSc Thesis 2015:03, 29 pp (and 3 annexes 3+1+4 pp); http://publications.lib.chalmers.se/records/fulltext/220580/220580.pdf

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

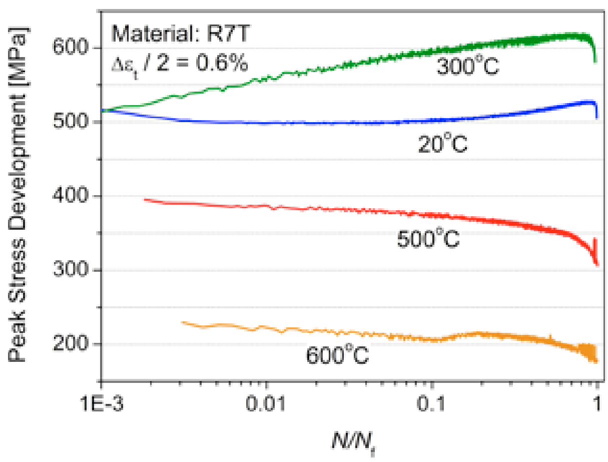
Project leader and supervisor	Docent Johan Ahlström, Senior Lecturer, Materials and Manufacturing Technology
Assistant supervisors	Professor Christer Persson, Materials and Manufacturing Technology, and Professor Magnus Ekh, Applied Mechanics
Doctoral candidate	Mr Dimitrios Nikas, MSc (from 2012-08-15; Lic Eng June 2016)
Period	2013-08-15 – 2015-06-30 (– 2018-08-14)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 2 200 Stage 8: kSEK 3 450
Industrial interests in-kind budget	Stage 7: kSEK 100 + 50 + 200 Stage 8: kSEK 100 + 50 + 200 *(Bombardier Transportation + Lucchini Sweden + voestalpine)*

PhD student Dimitrios Nikas (middle; licentiate gained in June 2016) and his supervisors Docent Johan Ahlström (right) and Professor Christer Persson in project MU28. In the new bi-axial rig, a test bar is exposed to torsional prestraining

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 for design of the components as well as for tuning of traction and braking systems. In this project, material properties under realistic conditions will be 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. Also examinations with alternating thermal and mechanical loads (thermomechanical fatigue) will be performed. Both virgin material and the anisotropic surface layer of used material will be investigated. The overall aim is to arrive at a better understanding of material behaviour under service conditions and to enable implementation and calibration of realistic material 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 R8T 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 appears. It was found that the cyclically prestrained material softens with 30 % after annealing at 600 °C. Microstructural evaluation showed that spheroidization of the pearlite started to become visible at 450 °C for the undeformed R8T material and at around 400 °C for the prestrained material and that it correlates with the measured change in hardness.

A set of low cycle fatigue (LCF) experiments at elevated temperatures has been made with the wheel steel R7T. This will help with the calibration of the material model that is developed in project MU32. The cyclic hardening and softening observed after elevated temperature exposure agrees with the static hardening and softening observed for the R8T material. Additional LCF experiments with hold times showed a rapid recovery in mechanical behaviour after the hold time finished. Only the very first cycle after each hold time deviates much; thereafter stresses lie within a few percent of the stabilised stress-strain loop before the



Measured peak stress development during low cycle fatigue tests at different temperatures in project MU28

MU28. (cont'd)

hold time. Initial hold times show less viscous behaviour compared to hold times after cyclic deformation.

Another study using EBSD technique was done for material R8T 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 initial formation of the pearlite, while ferrite grains have a more uniform orientation. Spheroidised 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. Dimitrios Nikas presented his licentiate thesis (see below) at a seminar on 10 June 2016 where Professor Ru Peng of Linköping University introduced the discussion.

The joint reference group for projects MU28, MU29, MU30, and MU32 has members from Trafikverket, Bombardier Transportation (Germany/Siegen and Sweden), Lucchini Sweden, Interfleet Technology /SNC-Lavalin, SJ and SL. Project MU28 is continuously being presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen, VAE and CHARMEC, see page 118. The research plan for project MU28 is dated 2013-03-23.

Dimitrios Nikas and Johan Ahlström: Thermal deterioration of railway wheel steels, *Proceedings 35th Risø International Symposium on Materials Science*, Risø (Denmark) 2014, pp 411–420 (also listed under project MU30)

Dimitrios Nikas and Johan Ahlström: Characterisation of microstructural changes in near pearlitic steels using orientation imaging microscopy – influence of pre-deformation on local sensitivity to thermal degradation, *Proceedings 36th Risø International Symposium on Materials Science*, Risø (Denmark) September 2015, IOP Conf. Ser.: Mater. Sci. Eng. 89 012039. Available at URL: doi:10.1088/1757-899X/89/1/012039

Ali Esmaeili, Tore Vernersson, Dimitrios Nikas and Magnus Ekh: High temperature tread braking simulations employing advanced modelling of wheel materials, *International Heavy Haul Association Conference (IHHA 2015),* Perth (Australia) June 2015, 8 pp (also listed under project MU32)

Dimitrios Nikas, Johan Ahlström and Amir Malakizadi: Mechanical properties and fatigue behavior of railway wheel steels as influenced by mechanical and thermal loading, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August – September 2015, 8 pp (also listed under project MU30)

Dimitrios Nikas: Effect of temperature on mechanical properties of railway wheel steels, Licentiate Thesis, *Chalmers Materials and Manufacturing Technology*, Gothenburg June 2016, 62 pp (Summary and two appended papers)

MU29. DAMAGE IN WHEEL AND RAIL MATERIALS

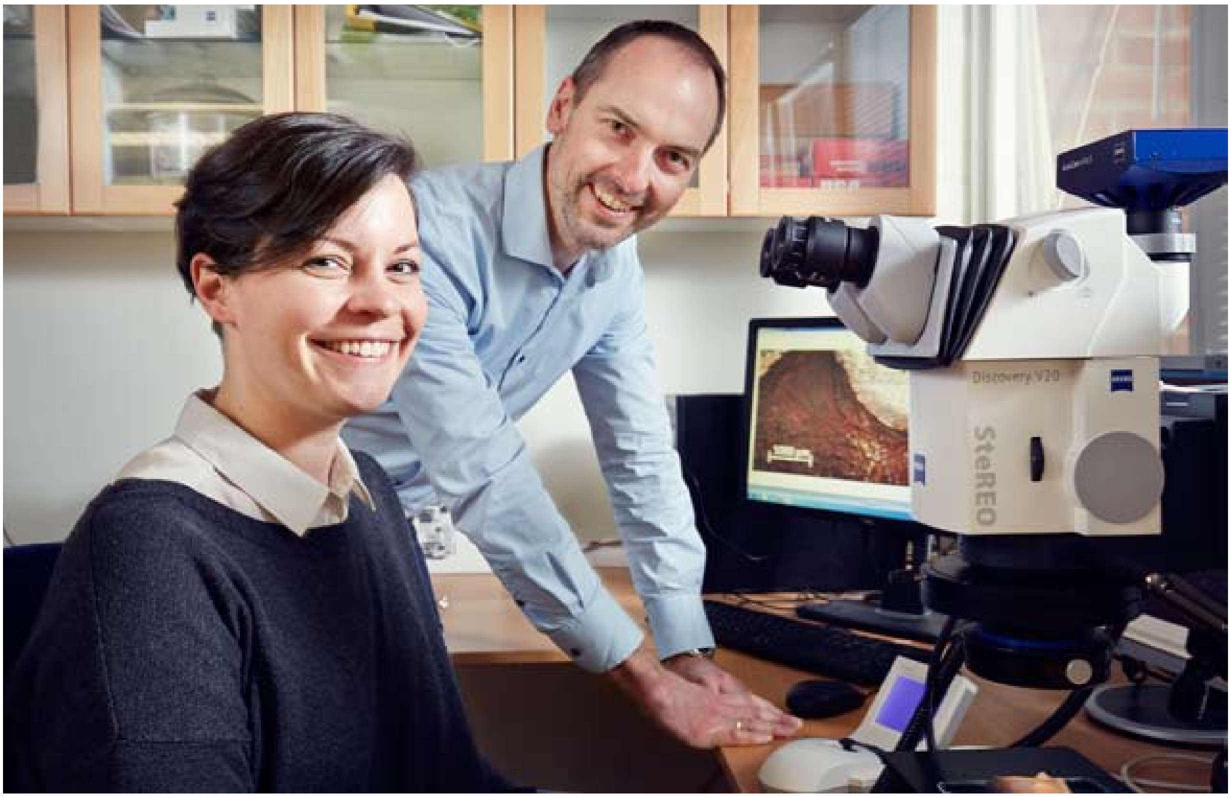
Skador i hjul- och rälmaterial
Schäden in Rad- und Schienenwerkstoffen
Endommagements des matériaux des roues et rails

Project leader and supervisor	Docent Johan Ahlström, Senior Lecturer, Materials and Manufacturing Technology
Assistant supervisor	Professor Christer Persson, Materials and Manufacturing Technology
Doctoral candidate	Ms Casey Jessop, BSc (from 2014-02-10)
Period	2014-02-10 – 2015-06-30 (– 2019-02-28)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 570 Stage 8: KSEK 3 450
Industrial interests in-kind budget	Stage 7: KSEK 100 + 15 + 50 + 50 + 200 Stage 8: KSEK 100 + 15 + 50 + 0 + 200 *(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. Understanding the mechanisms of crack initiation and crack propagation is therefore crucial. This includes how climatic conditions alter the friction between crack faces, and the influence of the material properties. Field samples will be studied and laboratory experiments be done in order better to understand crack initiation and crack growth. Using a biaxial testing machine with a climate chamber, cracks will be propagated under realistic loading conditions at varying climatic conditions. The findings from project MU29 can help to formulate, calibrate and verify suitable 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 taken from 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 geometry. Combining the exposures from a range of angles using geometrical reconstruction, a method was developed to render a 3D representation

MU29. (cont'd)



PhD student Casey Jessop and her supervisor Docent Johan Ahlström in project MU29.
A squat sample is examined in a stereo microscope, see also photo on page 69

of the complex crack network. Metallographic sectioning was carried out to determine the accuracy of prediction of the geometrical reconstruction. The 3D reconstruction was obtained and comparisons to metallographic sectioning showed accurate geometry at the medium depths, though the crack tips were not visible due to limitations of the radiography in terms of detecting tightly closed cracks. Also, the actual crack extends 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 to judge whether or not a rail section needs to be replaced, as it is non-precise in estimating the crack extension. In case the crack is too tightly closed, or oriented in an unfavourable angle for detection, the method might fail to detect or misjudge the extension of the crack network.

Further characterization studies on the squat crack network were done using other methods (optical, stereo and scanning electron microscopy, as well as topography) 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 the others. It was found that a combination of the methods could provide an accurate description of the network geometry. A study visit to several sites where RCF damage was present was made in co-operation with project MU31.

For the joint reference group, see under project MU28. Project MU29 is continuously being presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen, VAE and CHARMEC, see page 118. The research plan for project MU29 is dated 2013-03-23.

Johan Ahlström, Casey Jessop, Lars Hammar and Christer Persson: 3D characterisation of RCF crack networks, *Proceedings 2nd International Symposium of Fatigue Design and Material Defects (FDMD2) EDP Sciences*, Paris June 2014 (also listed under project MU30)

Casey Jessop, Johan Ahlström and Lars Hammar: 3D characterization of squat crack networks using high-resolution X-ray radiography, *Proceedings 35th Risø International Symposium on Materials Science*, Risø (Denmark) 2014, pp 339–348 (also listed under project MU30)

Johan Ahlström: VINNOVA slutrapport för Forskningsnära Verifiering (VINNOVA final report for Verification of Research Results; in Swedish). Available from Johan Ahlström

Casey Jessop, Johan Ahlström and Lars Hammar: 3D characterization of RCF crack networks, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August-September 2015, 10 pp

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	Docent Johan Ahlström, Senior Lecturer, Materials and Manufacturing Technology
Doctoral candidate	None (only senior researcher in this project)
Period	2013-04-01 – 2015-06-30 (– 2018-03-31)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 290 Stage 8: KSEK 1 500
Industrial interests in-kind budget	Stage 7: KSEK 50 + 15 + 50 + 50 + 200 Stage 8: KSEK 50 + 15 + 50 + 0 + 200 *(Bombardier Transportation + Interfleet Technology/SNC-Lavalin + Lucchini Sweden + Trafikverket + voestalpine)*

This senior research project is 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. The project will also provide Finite Element (FE) support to the experimental part of the doctoral projects regarding, for example, stress states in specimens. In collaboration with senior researchers at Chalmers Applied Mechanics, the experimental results from projects MU28 and MU29 will be implemented into material models of suitable complexity for the problems at hand.

The research work on thermal damage is intended to model what occurs in the wheel surface layer on repeated slipping due to, for example, malfunctioning WSP devices. The localized discontinuities in material strength and the large stress gradients are supposed to form a possible initiation site for RCF cluster cracks and squat-type cracks. The calculated residual stress fields and altered material properties after thermal loadings can be used as a starting condition for crack modelling.

An additional "seed project" on x-ray radiography of damaged wheels and rails was initiated and run as a prestudy for MU29. The aim was to examine the potential to extract 3D information on crack geometry before cutting a damaged wheel or rail. Rails provided by voestalpine Schienen have been examined. An application for funding to investigate the potential for commercialization of the technique was approved by "Innovationskontor Väst".

The Department of Materials and Manufacturing Technology at Chalmers hosted a guest researcher from Technical University of Denmark (DTU) during one week as a first step towards an increased co-operation. We supported DTU and Banedanmark (Rail Net Denmark) in an application to the Danish Science Foundation for a project regarding damage in switches and crossings. The project, called IntelliSwitch, was approved, and Johan Ahlström takes part as an international expert; part of this effort is to co-supervise a PhD student at DTU. The co-operation will give possibilities to follow in depth the characterization of deformed surface layers of rails using x-ray tomography and advanced electron microscopy; also synchrotron measurements of the residual stress state in used rails are planned for.

Johan Ahlström together with Anders Ekberg, Elena Kabo, Roger Lundén and Jens Nielsen contributed to a new IHHA Best Practice Handbook in chapters on material properties of wheels and rails.

A couple of tools for analysis of experimental results have been developed. 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 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 of the research results 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.

The process of purchasing a new biaxial test frame was initiated. After the evaluation of tenders a contract was signed with MTS. Preparations for installation of the new biaxial test frame, especially for cooling systems, were completed. The equipment was much delayed from the producer (MTS), but arrived in the autumn 2015.

For the joint reference group, see under project MU28. Project MU30 is continuously being presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen, VAE and CHARMEC, see page 118. The research plan for project MU30 is dated 2013-03-23.

MU30. (cont'd)

Johan Ahlström: LCF loop shape in near pearlitic steels – influence of temperature, *Proceedings 7th International Conference on Low Cycle Fatigue (LCF7)*, Aachen (Germany) September 2013, DVM 2013, pp 81–86

Johan Ahlström, Casey Jessop, Lars Hammar and Christer Persson: 3D characterisation of RCF crack networks, *Proceedings 2nd International Symposium of Fatigue Design and Material Defects (FDMD2) EDP Sciences*, Paris June 2014 (also listed under project MU29)

Johan Ahlström: Residual stresses in martensite after multiple heating events, *Proceedings 5th International Conference on Thermal Process Modeling and Computer Simulation (ICTPMCS5)*, Orlando FL (USA) June 2014, 10 pp

Johan Ahlström: Residual stresses in martensite after multiple heating events, *Proceedings 35th Risø International Symposium on Materials Science*, Risø (Denmark) 2014, pp 201–212

Casey Jessop, Johan Ahlström and Lars Hammar: 3D characterization of squat crack networks using high-resolution X-ray radiography, *ibidem*, pp 339–348 (also listed under project MU29)

Dimitrios Nikas and Johan Ahlström: Thermal deterioration of railway wheel steels, *ibidem*, pp 411–420 (also listed under project MU28)

Johan Ahlström: Crack initiation caused by repeated local heating events – modelling of possible mechanisms, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August-September 2015, 7 pp

Dimitrios Nikas, Johan Ahlström and Amir Malakizadi: Mechanical properties and fatigue behavior of railway wheel steels as influenced by mechanical and thermal loadings, *ibidem*, 8 pp (also listed under project MU28)

Johan Ahlström, Elena Kabo and Anders Ekberg: Temperature-dependent evolution of the cyclic yield stress of railway wheel steels, *ibidem*, 8 pp (also listed under project MU22)

MU31. SQUATS IN RAILS AND RCF CLUSTERS ON WHEELS

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

Project leader and supervisor	Docent Elena Kabo, Applied Mechanics / Division of Material and Computational Mechanics
Assistant supervisors	Professor Fredrik Larsson, Professor Anders Ekberg and Dr Peter Torstensson, Assistant Professor, Applied Mechanics
Doctoral candidate	Mr Robin Andersson (from 2013-04-08; Lic Eng June 2015)
Period	2013-04-08 – 2015-06-30 (– 2018-04-30)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 2325 Stage 8: KSEK 2850
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 (see, e g, project EU10) there is still a fundamental lack of knowledge of underlying mechanisms, influencing factors and (cost)efficient mitigation measures.

Project MU31 aims 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 sets out from, and

Squat found on a Stockholm metro line rail in June 2015.
Photo by Robin Andersson

MU31. (cont'd)

Docent Elena Kabo and PhD student Robin Andersson (standing; his licentiate gained in June 2015) and Professor Fredrik Larsson (left), Professor Anders Ekberg (second from the right) and Dr (now Assistant Professor) Peter Torstensson in project MU31

continuously compares results against, operational experiences. Focusing on understanding and quantifying the phenomena, the project incorporates detailed studies of the parametric influence of operational parameters on plastic deformation, crack formation and crack growth from local defects. To this end, increased dynamic loads and contact stresses due to surface irregularities etc have been considered.

Simulations in 2D with RAVEN (an in-house code developed by Peter Torstensson in projects TS11 and TS16) have been used to perform a parametric study regarding the influence of single surface irregularities (length and depth) as well as operational parameters (wheel–rail friction, creep, position relative to a sleeper and speed) on RCF impact (here quantified by peak magnitudes of contact pressure, shear stress, normal force and shear force). The RCF impact measures have also been compared with corresponding impact measures from a corrugated rail. The most important (combination of) parameters for each RCF impact measure have been identified. For the parameters studied, the RCF impact is in general larger for single surface irregularities than for corrugation. It has been shown that even very shallow dimples can have a large influence on the RCF impact, but also that the depth is irrelevant for short dimples. The qualitative results agree between the 2D and 3D simulations.

A study has been conducted where 2D FE analyses were performed to evaluate the influence of, e g, dimples and varying friction conditions in the context of squat initiation. The study has shown how the size of an initial rail dimple is important for the RCF impact. Furthermore, it was found that the varying wheel–rail friction might play an important role for the overall RCF impact on both smooth rails and rails with an initial dimple-like surface irregularity. Robin Andersson presented his licentiate thesis (see below) at a seminar on 4 June 2015 where Dr Rikard Nilsson of SL introduced the discussion. Robin Andersson has made a study visit to Strukton Rail AB in Stockholm in June 2015 and made field inspections of squats on Stockholm's metro line tracks.

For the joint reference group, see under project MU21. Project MU31 is continuously being presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen, VAE and CHARMEC, see page 118. The research plan for project MU31 is dated 2013-04-04. The project has support from Elena Kabo and Anders Ekberg also through project MU22.

Robin Andersson, Peter Torstensson, Elena Kabo and Fredrik Larsson: The influence of rail surface irregularities on contact forces and local stresses, *Vehicle System Dynamics*, vol 53, no 1, 2015, pp 68–87 (also listed under project TS16)

Robin Andersson: Surface defects in rails – potential influence of operational parameters on squat initiation, Licentiate Thesis, *Chalmers Applied Mechanics*, Gothenburg June 2015, 79 pp (Summary and three appended papers)

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, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August – September 2015, 9 pp (also listed under project TS16)

Robin Andersson, Peter Torstensson, Elena Kabo and Fredrik Larsson: An efficient approach to analyse rail surface irregularities accounting for dynamic train–track interaction and inelastic deformations, *Vehicle System Dynamics*, vol 53, no 11, 2015, pp 1667–1685

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, Applied Mechanics / Division of Material and Computational Mechanics
Assistant supervisors	Dr Tore Vernersson, Applied Mechanics, and Docent Johan Ahlström, Materials and Manufacturing Technology
Doctoral candidate	Mr Ali Esmaeili, MSc (from 2013-12-13)
Period	2013-12-13 – 2015-06-30 (– 2018-12-13)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1 470 Stage 8: KSEK 3 000
Industrial interests in-kind budget	Stage 7: KSEK 100+100+100+50+200 Stage 8: KSEK 100+100+100+0+200 *(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. The temperature may increase due to frictional heat generated between wheel and rail or generated between wheel and brake blocks at tread braking. This further increases the complexity of the loading situation. Also additional material responses and deterioration phenomena may come into play. The main goal of project MU32 is to improve modelling of the cyclic behaviour of wheel and rail materials subjected to mechanical and thermal loadings. The project will be conducted in close collaboration with project MU28. In MU28 tests will be performed on pearlitic steels at elevated (and possibly varying) temperatures for uniaxial as well as compression–torsional loading. The resulting knowledge on how the material behaves in realistic loading situations can be used in the current project to formulate, calibrate and validate material models. The project will also interact with project SD10 where simulations of the contact between brake block and wheel including temperature elevation will be studied.

A subroutine for a viscoplastic constitutive model with the capability to model cyclic hardening/softening and viscous behaviour has been programmed. An arbitrary number of backstresses may be used with the purpose to capture the cyclic hardening characteristics during many loading cycles. The parameters of the viscoplastic model have been identified based on experimental low cycle fatigue tests with hold time (performed within projects MU28 and SD10) of the pearlitic wheel steel R7T. These tests were performed at different temperatures ranging from room temperature up to 625°C and for the strain amplitudes 0.6 % and 1.0 %. Already at 300 °C, the experiments with hold time display viscous effects. The results of the parameter identification show that the cyclic hardening can be satisfactorily captured with the current model formulation. However, two viscous effects have been observed in the experiments with R7T. The first is due to a change of the cyclic loading rate and the second is due to relaxation during the hold time. The current model formulation cannot capture both of these effects and must therefore be improved. Furthermore, simulations of combined rolling contact and thermal loading show that strain rates in the order of 10^3 1/s can be expected. The current viscoplastic model cannot predict the material behaviour at these high strain rates in a realistic fashion and therefore further improvement is required.

Thermomechanical Finite Element (FE) analyses of wheel – rail and brake block – wheel interaction have been performed with the commercial FE package ABAQUS utilizing the developed material subroutine. The thermal model was previously developed and calibrated for freight and metro applications within project SD10. A numerical approach in a joint paper presented at CM2015, see below, includes FE simulations of the full-scale brake rig tests conducted at the Railway Technical Research Institute (RTRI) in Tokyo (Japan). Here the wheel tread material is subjected to simultaneous mechanical loading from the wheel–rail contact and thermal loading from braking. Drag braking simulations (pure thermal loading) for both a low-stress and an S-shaped wheel have been conducted using both a plastic and a viscoplastic material model. As expected, the simulations for the S-shaped wheel are more sensitive to the choice of material model than those for the low-stress wheel, since the former is subjected to larger thermal stresses during braking. Substantial differences are found already at a maximum tread temperature of 400 °C for the S-shaped wheel, see the IHHA 2015 paper.

For the joint reference group, see under project MU28. The research plan for project MU32 is dated 2013-12-13.

MU32. (cont'd)

Ali Esmaeili, Tore Vernersson, Dimitrios Nikas and Magnus Ekh: High temperature tread braking simulations employing advanced modelling of wheel materials, *Proceedings International Heavy Haul Association Conference (IHHA 2015)*, Perth (Australia) June 2015, 8 pp (also listed under project MU28)

Ali Esmaeili, Sara Caprioli, Anders Ekberg, Magnus Ekh, Roger Lundén, Tore Vernersson, Kazuyuki Handa, Katsuyoshi Ikeuchi, Toru Miyaushi and Johan Ahlström: Thermomechanical cracking of railway wheel treads – a combined experimental and numerical approach, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August – September 2015, 8 pp (also listed under project MU21)

PhD student Ali Esmaeili (left) and his supervisors Professor Magnus Ekh (second from the right), Docent Johan Ahlström (right) and Dr Tore Vernersson

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, Applied Mechanics / Division of Material and Computational Mechanics
Assistant supervisors	Professor Kenneth Runesson and Professor Anders Ekberg, Applied Mechanics
Doctoral candidate	Mr Dimosthenis Floros, MSc (from 2014-01-15)
Period	2014-01-15 – 2015-06-30 (– 2019-01-14)
Chalmers budget (excluding university basic resources)	Stage 7: KSEK 1350 Stage 8: KSEK 3000
Industrial interests in-kind budget	Stage 7: KSEK 50 + 50 + 200 Stage 8: KSEK 0 + 0 + 200 *(SL + Trafikverket + voestalpine)*

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) 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 research in the project sets out from results of previous projects (e g, MU17, MU20 and MU22). In addition, crack propagation characteristics (rate, direction etc) from the literature and parallel CHARMEC projects will be employed to calibrate and validate candidate criteria. Project MU33 aims at the development of a numerical tool for qualitative and quantitative assessment of the evolution of RCF cracks accounting for various parameters such as 3D crack geometry, anisotropy, large inelastic deformations and wear rates.

PhD student Dimosthenis Floros (middle) and his supervisors Professor Fredrik Larsson (left) and Professor Kenneth Runesson in project MU33

In the previous CHARMEC projects MU17 and MU20, RCF cracks were analysed within the concept of material forces. An extended literature survey together with a state-of-the-art description of the theory has now been compiled.

Results from project MU17 have been reproduced in an independent numerical implementation. A 2D finite element model, accounting for geometric and material non-linearities, has been developed as a basis for the evaluation of different crack propagation criteria, e g, within the concept of material forces. Particular emphasis has been devoted to the discrete representation of singularities induced by the crack tip (e g, plastic strains).

The work has been continued with an investigation of the suitability of different fatigue crack models. To this end, a 3D numerical model of cracked tubular specimens subjected to tension and torsion has been developed. Elasto-plastic analyses have been carried out in order to study the effect of (static or variable) torsion on crack growth. The first results from 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.

For the joint reference group, see under project MU21. Project MU33 is continuously being presented and discussed during biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen, VAE and CHARMEC, see page 118. The research plan for project MU33 is dated 2014-04-03.

Dimosthenis Floros, Fredrik Larsson and Kenneth Runesson: On the evaluation of material forces in fracture mechanics, *Proceedings 27th Nordic Seminar on Computational Mechanics (NSCM-27)*, Stockholm October 2014, pp 196–199

MU34. INFLUENCE OF ANISOTROPY ON ROLLING CONTACT FATIGUE CRACKS

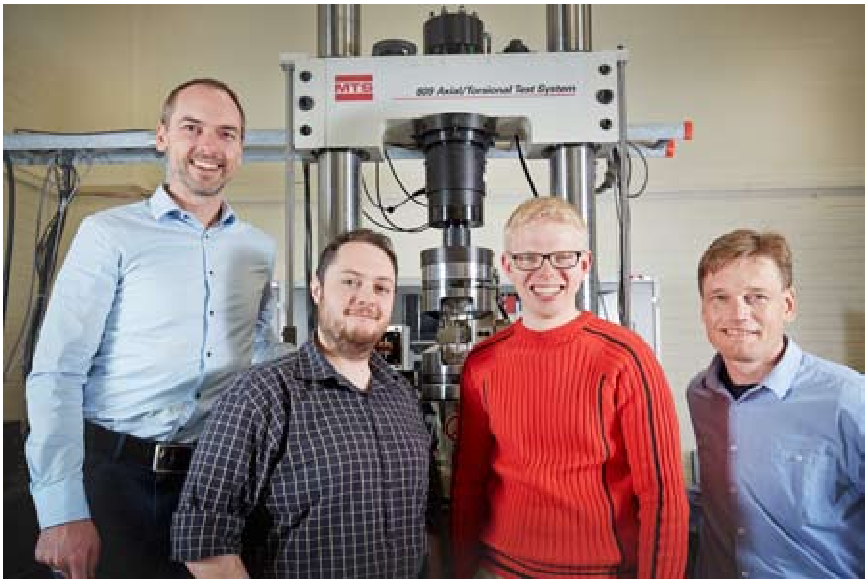
Inverkan av anisotropi på utmattningsprickor under rullkontakt
Einfluss von Anisotropie auf Ermüdungsrisse unter Rollkontakt
Influence de l´anisotropie sur les fissures en fatigue de contact de roulement

Project leader and supervisor	Professor Magnus Ekh, Applied Mechanics / Division of Material and Computational Mechanics
Assistant supervisors	Docent Johan Ahlström, Senior Lecturer, Materials and Manufacturing Technology, and Dr Jim Brouzoulis, Assistant Professor (Swedish: forskarassistent), Applied Mechanics
Doctoral candidate	Mr Knut Andreas Meyer, MSc (from 2015-05-18)
Period	2015-05-18 – 2015-06-30 (– 2019-12-31)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 150 Stage 8: kSEK 3300
Industrial interests in-kind budget	Stage 7: kSEK 25 + 5 + 110 Stage 8: kSEK 0 + 0 + 110 *(SL + Trafikverket + voestalpine)*

Rolling Contact Fatigue (RCF) crack initiation is often connected to the accumulation of plastic deformation in the surface layer of rail and wheel. The behaviour and strength of this highly-deformed layer are thus key properties of a rail or wheel material. The analyses of microhardness and geometry of the surface layer of a rail with head check cracks (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 high-pressure torsion tests and micropillar tests performed at Erich Schmid Institute in Leoben (Austria). However, the experimental data were limited and the tests do not fully mimic the real traffic situation for a surface layer of rails and wheels with repeated loadings, multiaxial stress conditions and severe plastic deformations.

A new biaxial testing machine at the Department of Materials and Manufacturing Technology will make it possible to perform laboratory tests on rail and wheel materials in more realistic loading conditions than earlier. Aims of the current project are (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, 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 microstructure development in different rail materials subjected to realistic traffic loading conditions.

During the workshop in June 2015 with voestalpine Schienen it was decided that the initial focus of the project should be on the R260 pearlitic steel, and that material for testing will be delivered to Chalmers from voestalpine Schienen. Project MU34 will be further presented and discussed during coming biannual workshops with participants from University of Leoben (Austria), voestalpine Schienen, VAE and CHARMEC, see page 118. The research plan for project MU34 is dated 2014-01-30.



PhD student Knut Andreas Meyer (second from the right) and his supervisors Professor Magnus Ekh (right), Docent Johan Ahlström (left) and Dr Jim Brouzoulis. New biaxial testing machine in the background

SD1. BRAKING OF FREIGHT TRAINS – A SYSTEMS APPROACH

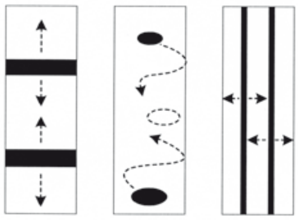
Bromsning av godståg – en systemstudie
Bremsen von Güterzügen – eine Systemstudie
Freinage de trains fret – étude de systèmes

The SD1 project was completed with Daniel Thuresson's successful defence in public of his doctoral dissertation in October 2006. The faculty-appointed external examiner of the dissertation was Professor Andrew Day from the School of Engineering, Design & Technology at the University of Bradford in West Yorkshire, UK. The title of the dissertation is "Thermomechanics of block brakes". The research in project SD1 was supervised by Professor Göran Gerbert of Chalmers Machine and Vehicle Design.

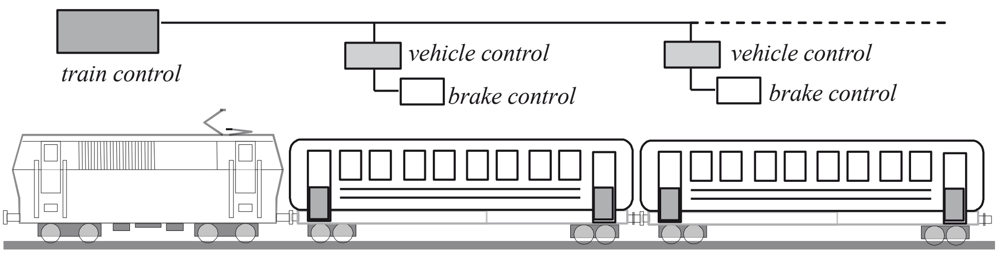
Project SD1 was aimed at describing the interaction between block and wheel by use of simple (but physically correct) models. The phenomenon known as ThermoElastic Instability (TEI) was found to be the main driving force in terms of excessive pressure and temperature. TEI on a friction material appears as moving contact points caused by the interaction between wear and thermal expansion.

Temperature measurements on the full-scale Lucchini/CHARMEC block brake test rig at Surahammar (see pages 76, 78 and 86) were performed. Both measurements and simulations showed an unstable temperature distribution. Cast-iron brake blocks were found to be more prone to TEI than blocks made of sinter and composition materials. See also CHARMEC's Triennial Reports for Stages 2, 3 and 4. The reference group for project SD1 consisted of representatives of Faiveley Transport and Green Cargo.

PhD student Daniel Thuresson (right; doctorate earned in October 2006) and his supervisor Professor Göran Gerbert in project SD1. Photo taken in 2000 at a brake rig in the laboratory of Chalmers Machine and Vehicle Design



Sketches of the shape and size of moving contact areas on a sliding brake block when ThermoElastic Instability (TEI) occurs. Contact pressure and temperature are high over the black areas

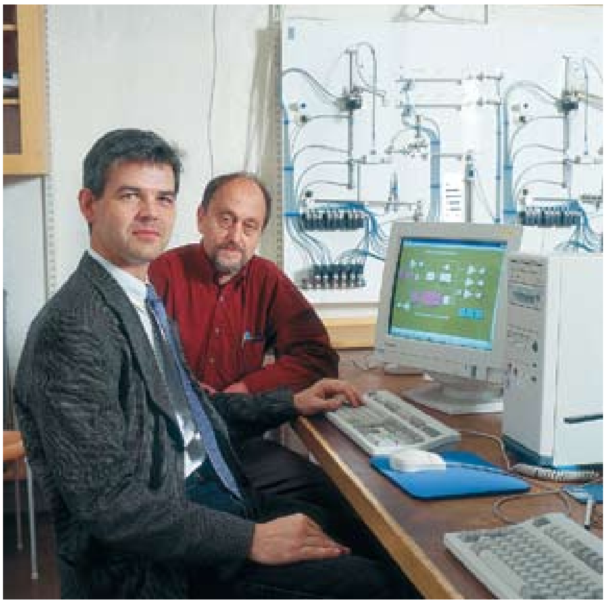


Brake control architecture studied in project SD3

SD2. SONAR PULSES FOR BRAKING CONTROL

Ljudpulser för styrning av bromsar
Schallpulse für die Steuerung von Bremsen
Contrôle de freins par pulsions sonores

The SD2 project was completed in June 2000 with a series of reports by Hans Sandholt and Bengt Schmidtbauer, see CHARMEC's Triennial Report for Stage 2. Acoustic communication (sonar transmission) through the main pneumatic brake line of a trainset (modulation of the pressure signal) was studied theoretically, numerically and experimentally. Scale-model experiments were performed at Chalmers and full-scale experiments with brake lines (including hoses, accumulators etc) up to 1200 m in length at the SAB WABCO (now Faiveley Transport) brake system simulator in Piossasco, Italy, as well as on stationary and rolling freight trains in Sweden. Sensors, actuators and software were developed. The experiments verified the theoretical/ numerical models. The conclusion reached in project SD2 was that transmitting usable information in the pressurized brake line is possible, but only at a low bandwidth (5 to 10 Hz). The described sonar transmission of braking signals still awaits commercial implementation.



Lecturer Hans Sandholt, MSc, (left) and Professor Bengt Schmidtbauer in project SD2 at a SIMULINK experiment being set up in 2000 at Chalmers Mechatronics. Photo taken in 2000

Simulation of stop braking, drag braking and complete braking programs (sequences recorded infield) 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

SD3. COMPUTER CONTROL OF BRAKING SYSTEMS FOR FREIGHT TRAINS

Datorstyrning av bromsar till godståg
Rechnersteuerung der Bremssysteme von Güterzügen
Contrôle par ordinateur des systèmes de freinage de trains fret

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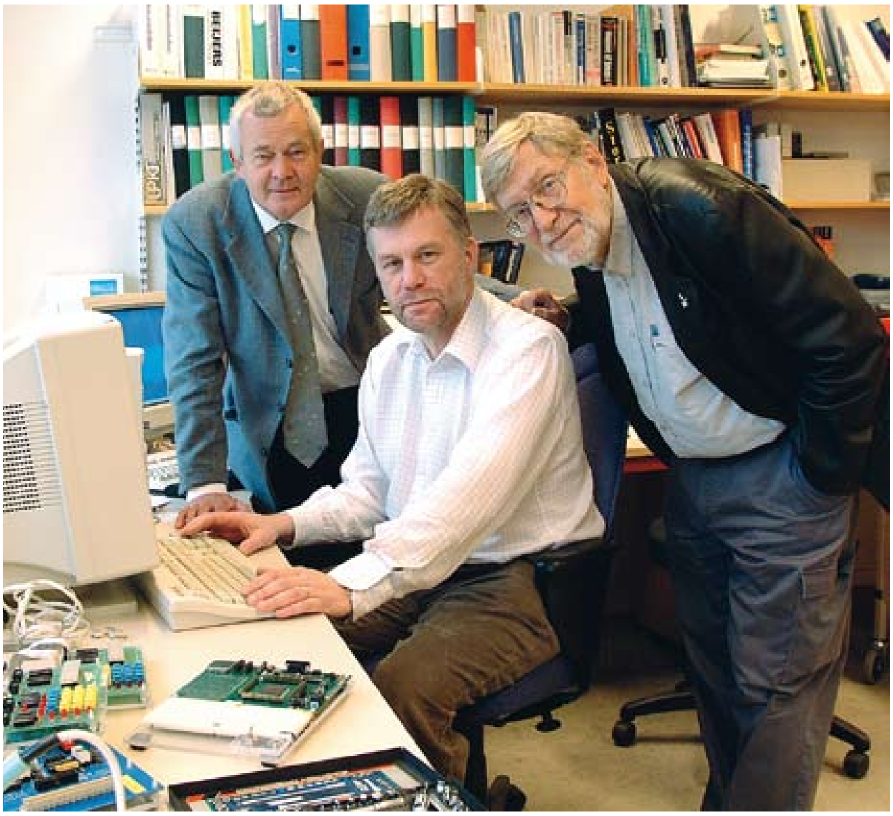
The SD3 project was completed with Roger Johansson's successful defence in public of his doctoral dissertation in June 2005. The faculty-appointed external examiner of the dissertation was Professor Martin Törngren from the Division of Mechatronics in the Department of Machine Design at the Royal Institute of Technology (KTH) in Stockholm, Sweden. The title of the dissertation is "On distributed control-by-wire systems for critical applications". The research in project SD3 was led by Mr Håkan Edler, MSc, and scientifically supervised by Professor Jan Torin of Chalmers Computer Science and Engineering.

Computers are being used to control processes of the most varying types and the applications are often spread over several computers in a network. Each computer can then be placed close to sensors and actuators to gather data and process them close to sources and sinks. Traditional electrical and mechanical interfaces can be replaced by data communication in the networks. Such distributed real-time systems provide many advantages in terms of speed, flexibility and safety/security. One example is train brakes, where a distributed computer system can give shorter response times and better means of controlling braking processes than pneumatic systems. See sketch on page 75.

An important issue in project SD3 was how to achieve a satisfactory level of safety with the then commercially available technology. Ways were found to construct reliable systems with the help of computer software, and methods were developed for verifying the reliability of these systems. A simple and robust electronic system as an add-on to the existing control system was designed and constructed.

The reference group for project SD3 included members from Faiveley Transport, Green Cargo, Halmstad University (Sweden) and SP Technical Research Institute of Sweden. See also CHARMEC's Triennial Reports for Stages 2, 3 and 4.



PhD student Roger Johansson (centre; doctorate earned in June 2005) and his project leader Mr Håkan Edler, MSc (left) and supervisor Professor Jan Torin in project SD3. Photo taken in 2003

SD4. CONTROL OF BLOCK BRAKING

Reglering av blockbromsning
Steuerung von Klotzbremsen
Contrôle du freinage à sabot

The SD4 project was completed with Tore Vernersson's successful defence in public of his doctoral dissertation in June 2006. The faculty-appointed external examiner of the dissertation was Professor Andrew Day from the School of Engineering, Design & Technology at the University of Bradford in West Yorkshire, UK (same as for project SD1). The title of the dissertation is "Tread braking of railway wheels – noise-related tread roughness and dimensioning wheel temperatures". Professor Roger Lundén of Chalmers Applied Mechanics supervised the research in project SD4.

Project SD4 aimed to improve knowledge and control of the heat distribution between block and wheel with a focus on wheel behaviour. Thermal phenomena were studied for various braking histories using computer simulations together with experimental data for forged wheels on the Lucchini/CHARMEC inertia dynamometer at Surahammar.

The tendency of cast-iron brake blocks to generate high roughness levels on wheel treads has propelled a general shift in the railway industry to other materials that do not generate disturbing roughness levels. However, this change of block material affects the heat partitioning between wheel and block. It was observed in project SD4 that excessive heating of the wheel may cause damage and result in problems with axial deflection of the wheel rim (change of wheelset gauge), and that high tensile stresses in the wheel rim after its cooling down can lead to the initiation and growth of transverse cracks on the running surface. A thermal model of railway tread braking was developed for use in design calculations (continued in project SP15) of wheel and block temperatures, including the cooling influence from the rail, so-called rail chill. The rail chill was found to have a considerable influence on the wheel temperature for long brake cycles.

Photo of an experimental test set-up at Surahammar with a tread-braked wheel in rolling contact with a "rail-wheel". One slotted composition block (configuration 1Bg) is used, see figure on page 82

A general observation in project SD4 was that the stiffness of the brake block support is important for wheel behaviour during a brake cycle. A stiff support together with a stiff block material (such as cast iron or sinter material) will make both the axial rim deflections and rim temperatures oscillate due to an unstable thermoelastic interaction between the block(s) and the wheel tread. A more flexible mounting was found to eliminate these phenomena.

Field test campaigns were run on the Velim test track in the Czech Republic and on the Coal Link in the Republic of South Africa. See also CHARMEC's Triennial Reports for Stages 3, 4 and 5. The reference group for project SD4 included members from SAB WABCO / Faiveley Transport and Interfleet Technology.

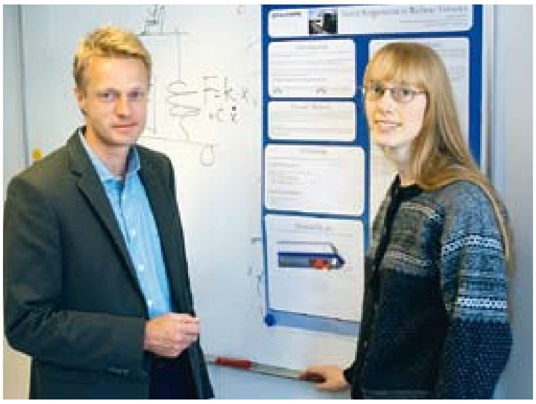
Dr Tore Vernersson (left; doctorate earned in June 2006), his co-worker Mr Hans Johansson (centre), Research Engineer, and his supervisor Professor Roger Lundén in project SD4. Photo taken in 2006

SD5. ACTIVE AND SEMI-ACTIVE SYSTEMS IN RAILWAY VEHICLES

Aktiva och semiaktiva system i järnvägsfordon
Aktive und halbaktive Systeme in Eisenbahnfahrzeugen
Systèmes actifs et semi-actifs dans des véhicules ferroviaires

A mathematical model of a railway car was built by doctoral candidate Jessica Fagerlund using the MultiBody System (MBS) software SIMPACK to study a possible active control of the vertical secondary suspension. Track irregularities were imported to the model and simulations were performed. The resulting car body accelerations and deflections were studied as well as different ride indices. Professor Jonas Sjöberg from Chalmers Signals and Systems together with Professor Thomas Abrahamsson from Chalmers Applied Mechanics supervised the research in project SD5. See also CHARMEC's Triennial Reports for Stages 3, 4 and 5.

Jessica Fagerlund presented her licentiate thesis at a seminar on 8 June 2009 where Dr Anna-Karin Christensson from University West in Trollhättan (Sweden) introduced the discussion. The title of the thesis is "Towards active car body suspension in railway vehicles".



PhD student Jessica Fagerlund (licentiate gained in June 2009) and her supervisor Professor Jonas Sjöberg in project SD5. Photo taken in 2006

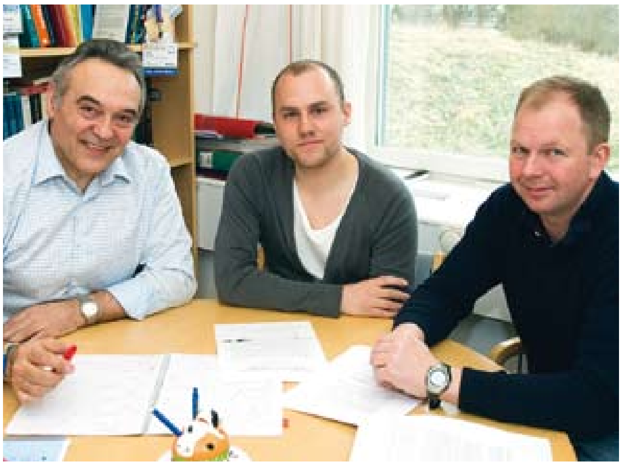
SD6. ADAPTRONICS FOR BOGIES AND OTHER RAILWAY COMPONENTS

Adaptronik för boggier och andra järnvägskomponenter
Adaptronik für Drehgestelle und andere Komponenten der Eisenbahn
Adaptronique pour des bogies et d'autres composants de chemin de fer

Active components are becoming accepted for railway vehicles and the improved suspension performance thereby being introduced will result in a better ride quality in passenger trains. Semi-active and active technologies and different control strategies have been studied by the doctoral candidate Albin Johnsson in project SD6. Hardware components of special interest were electromechanical elements and MagnetoRheological (MR) dampers. Multiobjective optimization was used in the project to find the best combinations of damping parameters for the primary and secondary bogie suspensions.

Performance objectives for safety, ride quality and wear were introduced and results presented in terms of Pareto fronts (trade-off curves in the performance objective space) as well as Pareto sets (trade-off curves in the design parameter space). These curves provide valuable information for choosing an optimal setting. Professor Viktor Berbyuk together with Docent (now Professor) Mikael Enelund, both from Chalmers Applied Mechanics, supervised the work. The project was financed by Family Ekman's Research Donation.

Work in the same area as in project SD6 has continued in the new project SD9. Albin Johnsson presented his licentiate thesis at a seminar on 24 February 2011 where Professor Sebastian Stichel of the Royal Institute of Technology (KTH) in Stockholm acted as discussion initiator. Albin Johnsson left Chalmers at the end of March 2011.



PhD student Albin Johnsson (middle; licentiate gained in February 2011) and his supervisors Professor Viktor Berbyuk (left) and Docent (now Professor) Mikael Enelund from project SD6. Photo taken in 2009. For a more recent photo of Viktor Berbyuk and Mikael Enelund, see page 83

SD7. THERMAL CAPACITY OF TREAD BRAKED RAILWAY WHEELS

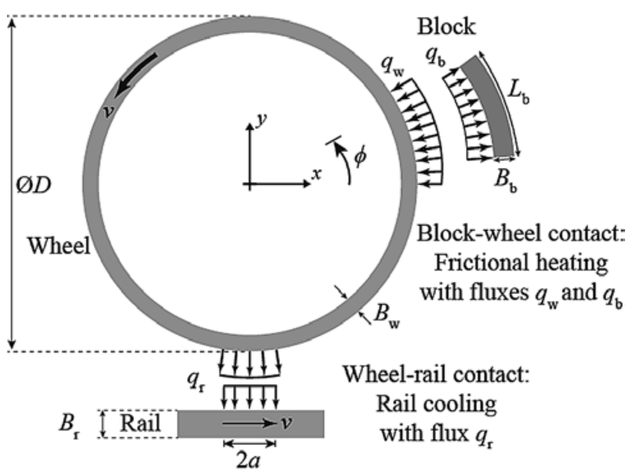
Termisk kapacitet hos blockbromsade järnvägshjul
Thermische Kapazität von Eisenbahnrädern mit Klotzbremsen
Capacité thermique des roues ferroviaires avec freins à sabot

Project leaders and supervisors	Professor Roger Lundén and Dr Tore Vernersson, Applied Mechanics / Division of Dynamics
Doctoral candidate	Mr Shahab Teimourimanesh (from 2008-09-22; Lic Eng February 2012; PhD March 2014)
Period	2008-09-01 – 2014-03-31
Chalmers budget (excluding university basic resources)	Stage 5: kSEK 600 Stage 6: kSEK 2 900 Stage 7: kSEK 1 700
Industrial interests in-kind budget	Stage 5: kSEK 100+300+50+200+0 Stage 6: kSEK 100+300+50+400+0 Stage 7: kSEK 100+100+15+200+25 *(Bombardier Transportation + Faiveley Transport + Interfleet Technology + Lucchini Sweden + SL)*

The thermal capacity of the wheels puts a limit to railway tread braking systems. In project SD7, the range of studied applications varied from light, medium and heavy metros to mainline coaches and freight locomotives with focus, however, on wheels for metros where frequent stop braking occurs. Except for the drag braking cases described in the European standard EN 13979-1, there are no known standards in the public domain relating to the thermal capacity limits for wheels. The aim of project SD7 was to develop methods and to provide data that can form a basis for future design guidelines for wheels subjected to repeated stop braking conditions; naturally still considering events of overheating and related in-service rejection criteria (e g, maximum residual stress levels and wheelset gauge changes). Temperature effects on tread damage were not dealt with in this work but in project MU21 "Thermal impact on RCF of wheels".

Important aspects of the thermal capacity of tread braked railway wheels were initially assessed in a literature survey. Then two different railway wheel designs, with typical characteristics of freight and metro wheels, were numerically studied with respect to standard design criteria for load cases of drag braking and stop braking. The influence of brake block materials, thermal parameters and distribution of brake contact pressure on the wheel temperatures was investigated. A general result was that hot spots only have a minor influence on the global heat partitioning in the wheel-block-rail system even though the hot spots have a major impact on local temperatures. Brake rig experiments and a field test campaign were performed to measure wheel and brake block temperatures during different service conditions for a metro line. Simulation and calibration tools were employed in order to facilitate a comparison between measured temperatures. The results emphasized the importance of knowing the convection cooling parameters for different wagons if prolonged braking action is to be considered.

Finally, a modelling framework for assessing wheel damage was proposed and developed that was suitable for typical metro and suburban operations. In a parametric study, the influence of various loading levels and of other important factors on temperatures, axial flange deflection, residual stresses and the fatigue life of the wheels was studied. It was found that the mechanical and thermal loading types have different influences on the web damage and on the estimated fatigue life depending on load cases and wheel design. For the two studied wheel types, it was found that locations on the wheel web that show severe damage from mechanical loads are not influenced more than marginally by damage from thermal loads. Wheels with an S-shaped web were found to have several advantages over wheels with a slightly inclined-straight web when it comes to the thermomechanical performance at tread braking. Disadvantages of S-shaped wheels could be that they have a somewhat higher weight and that they are more costly to produce. It is concluded that the most important criteria that should be assessed at repeated stop braking are still the traditionally used ones: axial flange deflections and residual stresses. In addition, the strength of the wheel–axle assembly could be an important issue at tread braking of wheels with straight webs.



Example of computational model used in project SD7

SD7. (cont'd)

Shanghai metro train in the field test campaign of project SD7 in May 2010 (photo by Markus Meinel of Faiveley Transport Nordic)

The SD7 project was concluded with Shahab Teimourimanesh's successful defence in public of his doctoral dissertation (see below) on 7 March 2014. The faculty-appointed external examiner of the dissertation was Dr Marco Tirovic, Reader at Cranfield University in the UK. The joint reference group for projects SD7 and SD8 had members from Bombardier Transportation (in Siegen/Germany, Sweden and UK), Faiveley Transport Nordic and Interfleet Technology.

Shahab Teimourimanesh: Fatigue analysis of ORE wheel from Neufchâteau accident, *Chalmers Applied Mechanics*, Gothenburg 2013, 26 pp

Shahab Teimourimanesh, Tore Vernersson and Roger Lundén: Modelling of temperatures during railway tread braking: Influence of contact conditions and rail cooling effect, *IMechE Journal of Rail and Rapid Transit*, vol 228, no F1, 2014, pp 93-109

Shahab Teimourimanesh, Tore Vernersson, Roger Lundén, Fredrik Blennow and Markus Meinel: Tread braking of railway wheels – temperatures generated by a metro train, *IMechE Journal of Rail and Rapid Transit*, vol 228, no F2, 2014, pp 210-221

Shahab Teimourimanesh: Thermal capacity of railway wheels – temperatures, residual stresses and fatigue damage with special focus on metro applications, Doctoral Dissertation, *Chalmers Applied Mechanics*, Gothenburg January 2014, 146 pp (Summary and six appended papers)

Saeed Abbasi, Shahab Teimourimanesh, Tore Vernersson, Ulf Sellgren, Ulf Olofsson and Roger Lundén: Temperature and thermoelastic instability at tread braking using cast iron friction material, *Wear*, vol 314, nos 1-2, 2014, pp 171-180 (revised article from conference *CM2012*)

Shahab Teimourimanesh: Industrial exploitation aspects of the doctoral thesis in project SD7 "Thermal capacity of tread braked railway wheels", *Chalmers Applied Mechanics*, Gothenburg August 2014, 13 pp

Shahab Teimourimanesh, Tore Vernersson and Roger Lundén: Thermal capacity of tread-braked railway wheels - Part 1: Modelling, *IMechE Journal of Rail and Rapid Transit*, vol 230, no F3, 2015, pp 784-797

Shahab Teimourimanesh, Tore Vernersson and Roger Lundén: Thermal capacity of tread-braked railway wheels. - Part 2: Applications, *ibidem*, pp 798-812

SD8. WEAR OF DISC BRAKES AND BLOCK BRAKES

Slitage hos skivbromsar och blockbromsar
Verschleiss von Scheibenbremsen und Klotzbremsen
Usure des freins à disque et des freins à sabot

The research in project SD8 was carried out by Dr Tore Vernersson and Professor Roger Lundén. A comprehensive study of the thermomechanical interaction and wear in disc brakes and block brakes has been made. Here, the properties of friction materials in brake pads and brake blocks, with their often complex dependence on, e g, temperature and pressure, are important. So are also the geometrical design and mechanical stiffness of the interacting brake components since they determine the movements of pads and blocks. The brake design thus controls both the deformations due to static brake loads and the thermal deformations due to temperature gradients and temperature differences in the components.

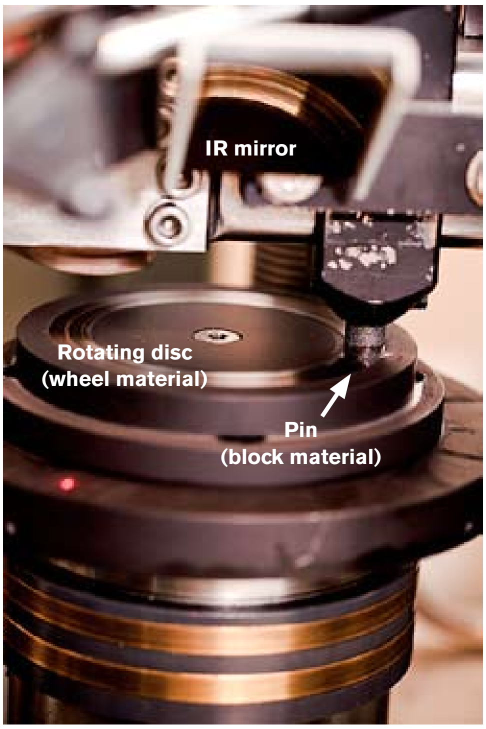
The overall aim of project SD8 was to reduce weights and life cycle costs, and to improve braking performance. Mathematical and numerical models were developed and calibrated to data from laboratory experiments and field studies. The models deliver the total amount of wear of pads and blocks for a train in revenue traffic and also the wear variation both temporally and spatially. Ultimately,

SD8. (cont'd)

PhD student Shahab Teimourimanesh (left; doctorate earned in March 2014) of project SD7 together with Dr Tore Vernersson (second from the left) and Professor Roger Lundén (right), both active in the two projects SD7 and SD8. The fourth person is PhD student Gaël Le Gigan (doctorate earned in December 2015) who worked in an associated project with VINNOVA and Scania CV AB on disc brakes for trucks, see page 123. Studied are a rubbing thermocouple, a railway brake block and a truck brake disc. Photo taken in 2012

the models should enable an optimization of the full brake system for minimization of wear and hence of the maintenance costs. Flytoget in Norway and SL Metro C20 together with the X10p train on Roslagsbanan in Stockholm were chosen as reference cases for axle-mounted disc brakes and tread brakes, respectively.

Laboratory studies of the wear of friction materials were performed in co-operation with the KTH Department of Machine Design. Here, a novel set-up was used in a pin-on-disc tester employing an external induction heating system to control the disc temperature. The temperature dependence of the wear was investigated for constant disc temperatures of up to 600 °C for organic composite, cast iron and sinter materials.

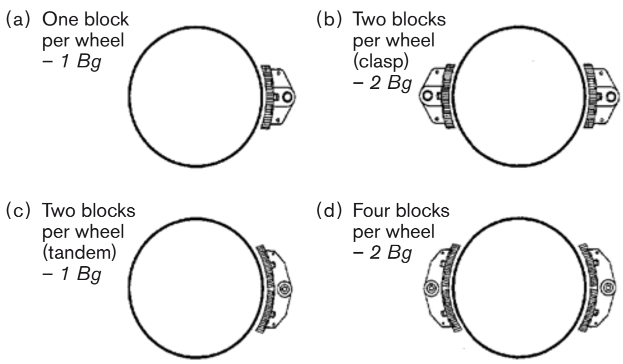


Part of equipment used in experiments at KTH in project SD8

The wear resulting from stop braking on a route containing multiple sequential brake cycles was numerically studied using a temperature-dependent wear model. It was found that a high mounting stiffness may cause the frictional contact to be localized towards one of the edges of the brake block and brake pad, and that such a brake cycle may double the amount of wear compared to a brake cycle which has a more conformal contact (which is the case when using a low mounting stiffness). The wear on generic routes containing 30 stops was studied for varying distances between stations and with different braking efforts.

The joint reference group for projects SD7 and SD8 had members from Bombardier Transportation (in Siegen/Germany, Sweden and UK), Faiveley Transport Nordic and Interfleet Technology. See also CHARMEC's Triennial Report for Stage 6.

Tore Vernersson and Roger Lundén: Wear of brake blocks for in-service conditions – influence of the level of modelling, *Wear*, vol 314, nos 1-2, 2014, pp 125-131 (revised article from conference *CM2012*)



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

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 leaders and supervisors	Professor Viktor Berbyuk and Professor Mikael Enelund, Applied Mechanics / Division of Dynamics
Doctoral candidate	Mr Milad Mousavi (from 2011-11-01; Lic Eng June 2014)
Period	2011-07-01 – 2016-10-31
Chalmers budget (excluding university basic resources)	Stage 6: kSEK 865 Stage 7: kSEK 2 790 Stage 8: kSEK 1 350
Industrial interests in-kind budget	Stage 6: kSEK — Stage 7: kSEK 200 + 15 + 50 Stage 8: kSEK 200 + 15 + 0 *(Bombardier Transportation + Interfleet Technology/SNC-Lavalin + Trafikverket)*

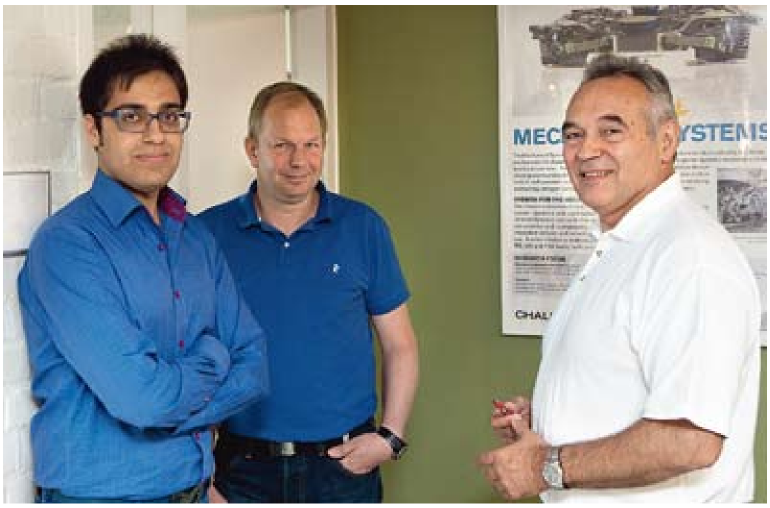
The project is financed by Family Ekman's Research Donation (through CHARMEC's budget)

The bogie system transmits forces between train and track. With increasing requirements on the performance of railway vehicles, the demands on their bogies will also increase. Not only need the bogie guarantee the running stability of the trains but it should also ensure passenger comfort and minimize rolling contact wear and fatigue of rails and wheels. Such conflicting demands on bogies are difficult to meet with the aid of traditional passive solutions, a fact which has led to active solutions. In project SD9, the focus is on a combination of multiobjective optimization of the bogie suspension and active control. In addition, appropriate actuation technologies should be developed.

Main aims and objectives are: (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 (DOF) 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 mostly using existing railway standards. A global sensitivity analysis has been carried out to identify the design parameters that have the most important influences on the objective functions. Such an analysis significantly reduced the number of input design parameters for optimization.

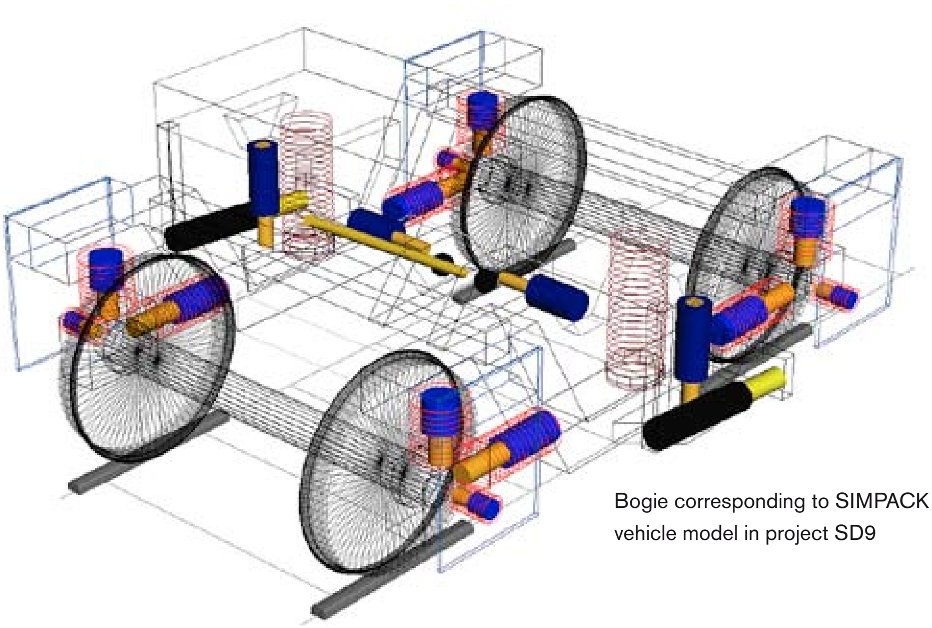
After reference model assessments, with MATLAB-SIMPACK co-simulations and system response analyses under different operational scenarios, the research has continued towards solving the global sensitivity analysis problems of the bogie dynamic behaviour with respect to suspension components. The main goal was to identify those suspension elements which have the most important effects on bogie dynamics. Based on the multiplicative version of a dimensional reduction method, an efficient algorithm has been developed for global sensitivity analysis of high-speed trains. The algorithm was successfully applied to the one-car vehicle model developed in the multibody dynamics software SIMPACK.



PhD student Milad Mousavi (left; licentiate gained in June 2014) and his supervisors Professor Viktor Berbyuk (right) and Professor Mikael Enelund from project SD9. Photo taken in 2012

Milad Mousavi presented his licentiate thesis (see below) at a seminar on 5 June 2014 with Professor Sebastian Stichel of KTH introducing the discussion. The work has continued towards solving several multiobjective optimization problems for the one-car railway vehicle model devel-

SD9. (cont'd)



Bogie corresponding to SIMPACK vehicle model in project SD9

oped in SIMPACK. Different problems such as multiobjective optimization of bogie suspension with respect to safety (to boost speed on curves) and wear/comfort Pareto optimization have been scrutinized. A target was to raise current train speeds up to those associated with track plane accelerations of 1.5 m/s^2. The optimization was performed in three levels which improved the computational efficiency. Results showed that with the aid of the optimized values of design parameters it is possible to run the vehicle at higher speeds and shorten journey times as well as 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 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. Furthermore, a robust controller has been designed and electromechanical actuators and sensors have been employed to implement the active control scheme in a practical manner. Finally, a compensation technique has been proposed to attenuate the actuator dynamic effects and improve the active control efficiency.

The reference group for project SD9 has 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.

Milad Mousavi, Viktor Berbyuk, Mikael Enelund and Rickard Persson: Towards multiobjective optimization of a rail vehicle, *Proceedings 17th Nordic Seminar on Railway Technology*, Tammsvik (Sweden) October 2012, 1+24 pp (Summary and PowerPoint presentation)

Milad Mousavi and Viktor Berbyuk: Optimization of a bogie primary suspension damping to reduce wear in railway operations, *Proceedings 6th ECCOMAS Thematic Conference on Multibody Dynamics*, Zagreb (Croatia) July 2013, pp 1025–1034

Milad Mousavi and Viktor Berbyuk: Multiobjective optimization of a railway vehicle dampers using genetic algorithm, *Proceedings ASME 9th International Conference on Multibody Systems, Nonlinear Dynamics and Control*, Portland OR (USA) August 2013, 10 pp

Milad Mousavi and Viktor Berbyuk: Application of semi-active control strategies in bogie primary suspension system, *Proceedings 2nd International Conference on Railway Technology*, Ajaccio (France) April 2014, Paper 318, 20 pp

Milad Mousavi: Towards adaptive bogie design, Licentiate Thesis, *Chalmers Applied Mechanics*, Gothenburg June 2014, 106 pp (Summary and four appended papers)

Milad Mousavi and Viktor Berbyuk: Bogie suspension effects on high speed train dynamics, *Proceedings 18th Nordic Seminar on Railway Technology*, Bergen (Norway) October 2014, 1+19 pp (Summary and PowerPoint presentation)

Milad Mousavi and Viktor Berbyuk: Global sensitivity analysis of bogie dynamics with respect to suspension components, *Multibody System Dynamics*, doi: 10.1007/s11044-015-9497-0, 30 pp (in printing 2016)

Milad Mousavi and Viktor Berbyuk: Variance-based wheel/rail contact sensitivity analysis in respect of wheelset dynamics, *Proceedings ASME 2015 International Design Engineering Technical Conferences and Computers & Information in Engineering Conference*, Boston MA (USA) August 2015, Paper DETC2015-47342, 7 pp

Milad Mousavi and Viktor Berbyuk: Multiobjective optimization of bogie suspension to boost speed on curves, *Vehicle System Dynamics*, vol 54, no 1, 2016, pp 58–85

Milad Mousavi, Viktor Berbyuk and Rickard Persson: Wear/comfort Pareto optimisation of bogie suspension, *Vehicle System Dynamics*, doi: 10.1080/00423114.2016.1180405, 24 pp (in printing)

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 leaders and supervisors	Professor Roger Lundén and Dr Tore Vernersson, Applied Mechanics / Division of Dynamics
Doctoral candidate	Mr Mandeep Singh Walia, MSc (from 2014-09-01)
Period	2013-03-01 – 2018-06-30 (– 2019-08-31)
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 1 565 Stage 8: kSEK 4 200
Industrial interests in-kind budget	Stage 7: kSEK 100+200+15+100+50 Stage 8: kSEK 100+200+15+100+50 *(Bombardier Transportation + Faiveley Transport + 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.

Important aspects of the railway braking were initially assessed in a literature survey, see below. A study was then launched that continues the work of the previous project MU21 "Thermal impact on RCF of wheels" in order to find limits for braking with respect to tread damage. This work is 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. It will constitute the completion of the work initiated in project MU21 and further presented at the CM2015 conference, see below. In short, brake rig rolling contact experiments performed at RTRI are compared to and 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, including a so-called rail-wheel in contact with the tread braked wheel, 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.

PhD student Mandeep Singh Walia (left) and his supervisors Professor Roger Lundén (right) and Dr Tore Vernersson with an IR camera in project SD10

The brake rig at Lucchini Sweden previously used in brake related CHARMEC projects has been decommissioned. However, there are ongoing efforts to re-establish this rig which had the major advantage of being readily available for CHARMEC projects. Ideas for an updated version are modernized control and measuring systems and possibly also inclusion of a system for simultaneous tractive rolling contact experiments.

The reference group for project SD10 has members from Bombardier Transportation (in Siegen/Germany, Sweden and UK), Faiveley Transport Nordic and Interfleet Technology / SNC-Lavalin.

Mandeep Singh Walia: Enhanced mechanical braking systems for modern trains – state-of-the-art survey, *Chalmers Applied Mechanics / CHARMEC*, Gothenburg 2015, 21 pp

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, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August–September 2015, 6 pp

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

EU1. EUROSABOT

EuroSABOT – Sound attenuation by optimised tread brakes
Schallverminderung durch optimierte Klotzbremsen
Atténuation du bruit par l´optimisation des freins à sabot

For a photo of project leader Roger Lundén and his co-worker Hans Johansson, see page 78

EuroSABOT had a total budgeted project cost of kEUR 3 724 and budgeted EU funding of kEUR 1 858. Chalmers/CHARMEC's share of the EU funding was kEUR 164 and our commitment to the project was 13 man-months. EuroSABOT ran between 1 March 1996 and 31 August 1999. The project was co-ordinated by AEA Technology Rail BV (Paul de Vos).

Tread braked railway vehicles radiate a high rolling sound caused by the fact that brake blocks generate roughness (waviness, corrugation) on the wheel tread, which induces vibrations and noise. The aim of EuroSABOT and project EU1 was to develop new and better brake blocks that caused less roughness on the wheel tread than cast iron blocks. CHARMEC's work was carried out in close collaboration with project VB2. A great deal of experimental work was done on the brake rig (inertia dynamometer) at Surahammar (now Lucchini Sweden) where our Hans Johansson assisted, see page 76.

Professor Roger Lundén led project EU1. See also CHARMEC's Triennial Report for Stage 2.

Photo of a cast-iron brake block in operation on the test rig at Surahammar in projects SD1 and EU1

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

EU2. SILENT FREIGHT

Silent Freight – Development of new technologies for low noise freight wagons
Entwicklung neuer Technologien für leise Güterwagen
Développement de nouvelles technologies pour des wagons fret silencieux

For a photo of project leader Jens Nielsen, see page 16

Silent Freight had a total budgeted project cost of kEUR 3 196 and budgeted EU funding of kEUR 1 700. Chalmers/CHARMEC's share of the EU funding was kEUR 91 and our commitment to the project was 17 man-months. Silent Freight ran between 1 February 1996 and 31 December 1999. The project was co-ordinated by ERRI (William Bird).

The objective of Silent Freight and the EU2 project was to reduce the noise level of rolling stock used in freight traffic by 10 dB(A). CHARMEC's contribution was to investigate whether a proposal put forward by us for a standard wheel with a perforated wheel disc could be a cost-effective solution, and applicable on existing types of freight wagon wheels.

The sound radiation from prototypes of perforated wheels was calculated with the commercial computer program SYSNOISE and measured in the test rig at Surahammar. The outcome of the EU2 project was that acoustic short-circuiting (between the front and rear sides of the vibrating wheel disc) via suitable holes is effective for a frequency range of up to about 1000 Hz. A prototype wheelset manufactured by Adtranz Wheelset (now Lucchini Sweden) was used in the final field tests at Velim in the Czech Republic in May-June 1999.

Docent (now Professor) Jens Nielsen led the EU2 project. See also CHARMEC's Triennial Report for Stage 2.

Computer model of the perforated wheel in project EU2. The wheel was studied both numerically and experimentally

EU3. SILENT TRACK

Silent Track – Development of new technologies for low noise railway infrastructure
Entwicklung neuer Technologien für leise Eisenbahninfrastruktur
Développement de nouvelles technologies pour des infrastructures ferroviaires silencieuses

For a photo of project leader Jens Nielsen, see page 16

Silent Track had a total budgeted project cost of KEUR 3747 and budgeted EU funding of KEUR 2075. Chalmers/CHARMEC's share of the EU funding was KEUR 150 and our commitment to the project was 28.5 man-months. Silent Track ran between 1 January 1997 and 29 February 2000. The project was co-ordinated by ERRI (William Bird).

The aim of Silent Track and project EU3 was to reduce the noise level from tracks with freight traffic by 10 dB(A). CHARMEC's contribution was to further develop the DIFF model (see project TS1) in order to study the origin of corrugation on the railhead, and to propose a new sleeper with reduced radiated sound power. A simulation of corrugation growth in DIFF was calibrated and verified against measurements of wave formation on rails used on Dutch railways. In collaboration with Abetong Teknik (a subcontractor in Silent Track), new optimized two-block sleepers were developed and manufactured, and were also used in the full-scale tests at Velim in the Czech Republic in May-June 1999.

Docent (now Professor) Jens Nielsen led project EU3. See also CHARMEC's Triennial Reports for Stages 2 and 3.

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

EU4. ICON

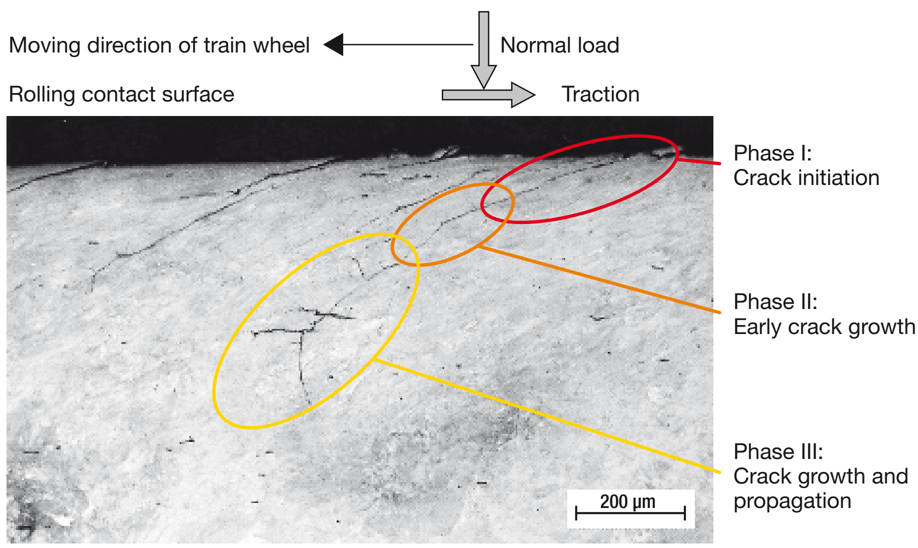
ICON – Integrated study of rolling contact fatigue
Integrierte Studie über Ermüdung durch Rollkontakt
Étude intégrée de la fatigue due au contact roulant

For a photo of project leader Lennart Josefson, see page 41

ICON had a total budgeted project cost of KEUR 1832 and budgeted EU funding of KEUR 1300. Chalmers/CHARMEC's share of the EU funding was KEUR 96 and our commitment to the project was 16 man-months. ICON ran between 1 January 1997 and 31 December 1999. The project was co-ordinated by ERRI (David Cannon).

The aim of ICON and project EU4 was to develop and verify a calculation model that would describe the initiation and early growth of cracks on the railhead. The activities in projects EU4 and MU6 were closely co-ordinated, see under the latter project.

Professor Lennart Josefson led project EU4. See also CHARMEC's Triennial Report for Stage 2.



Three phases of crack development in the railhead under rolling contact load as simulated in a so-called twin disc laboratory experiment in project EU4. The experiment was performed at the Otto-von-Guericke University in Magdeburg, Germany

EU5. EUROBALT II

EUROBALT II – European research for an optimised ballasted track
Europäische Forschung zur Optimierung von Gleisen auf Schotter
Recherche européenne pour l'optimisation des voies ferrées ballastées

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For photos of project leaders Tore Dahlberg and Roger Lundén, see page 85 in CHARMEC's Triennal Report for Stage 6 and page 82 in the present report

EUROBALT II had a total budgeted project cost of KEUR 4154 and budgeted EU funding of KEUR 2320. Chalmers/CHARMEC's share of the EU funding was KEUR 207 and our commitment to the project was 34 man-months. EUROBALT II ran between 1 September 1997 and 31 August 2000. The project was co-ordinated by SNCF (Jean-Pierre Huille).

CHARMEC's task in the EU5 project was to develop a calculation model that would reproduce and predict the dynamic interaction between the train and the ballasted track. Our DIFF calculation model was expanded, see project TS1. A resonance frequency between 20 and 30 Hz in the ballast/subgrade was included. Professor Tore Dahlberg and Professor Roger Lundén led the EU5 project. See also CHARMEC's Triennial Reports for Stages 2 and 3.

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

EU6. HIPERWHEEL

HIPERWHEEL – Development of an innovative high-performance railway wheelset
Entwicklung eines innovativen leistungsstarken Radsatzes
Développement d'un essieu monté innovant à haute performance

For photos of project leader Roger Lundén and his co-workers Jens Nielsen and Anders Ekberg, see pages 25, 60 and 82

The HIPERWHEEL project of the Fifth Framework Programme comprised a total of 280 man-months, a budgeted project cost of KEUR 3690 and budgeted EU funding of KEUR 1979. Chalmers/CHARMEC's share of the EU funding was KEUR 141 and our commitment to the project was 13 man-months. HIPERWHEEL ran between 1 April 2000 and 30 September 2004. The project was co-ordinated by Centro Ricerche Fiat (Kamel Bel Knani).

CHARMEC's main responsibility was to study damage mechanisms. One result of HIPERWHEEL was a new wheelset with 25% lower weight where the disc was made of aluminium and the rim of high-strength steel. Professor Roger Lundén with co-workers Docent (now Professor) Jens Nielsen and Dr (now Professor) Anders Ekberg ran the EU6 project. See also CHARMEC's Triennial Reports for Stages 3 and 4. CHARMEC's European partners in HIPERWHEEL are listed in the latter report.

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

EU7. INFRASTAR

INFRASTAR – Improving railway infrastructure productivity by sustainable two-material rail development
Verbesserte Produktivität der Eisenbahninfrastruktur durch Entwicklung haltbarer Schienen aus zwei Werkstoffen
Amélioration de la productivité de l´infrastructure ferroviaire par le développement des rails durables composés de deux matériaux

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The INFRASTAR project of the Fifth Framework Programme comprised a total of 140 man-months with a budgeted project cost of KEUR 1780 and budgeted EU funding of KEUR 1080. Chalmers/CHARMEC's share of the EU funding was KEUR 181 and our commitment to the project was 20 man-months. INFRASTAR ran between 1 May 2000 and 31 October 2003 and was co-ordinated by AEA Technology Rail (Martin Hiensch).

The application of an extra surface layer to the railhead by melting of powder onto the surface by means of a laser beam was investigated. See also project MU7 and CHARMEC's Triennial Reports for Stages 3 and 4. CHARMEC's European partners in INFRASTAR are listed in the latter report. Professor Lennart Josefson and Professor Roger Lundén with co-workers Docent (now Professor) Jens Nielsen, Dr (now Professor) Jonas Ringsberg and Professor Birger Karlsson ran the EU7 project.

EU8. ERS

ERS – Euro Rolling Silently

The ERS project of the Fifth Framework Programme comprised a total of 317 man-months with a budgeted project cost of KEUR 5880 and budgeted EU funding of KEUR 2470. Chalmers/CHARMEC's share of the EU funding was KEUR 206 and our commitment to ERS was 20 man-months. ERS ran between 1 September 2002 and 31 August 2005 and was co-ordinated by SNCF (Jacques Raison).

The aim of the ERS project was to develop new "LL" type brake blocks for tread braked freight wagons. Without modifying the wagons, the blocks would replace the existing cast iron blocks of grade P10 (i e, a retrofit solution was requested).

The thermomechanical capability of two freight wagon wheels (VMS from Valdunes and RAFIL from Radsatzfabrik Ilsenburg) was evaluated. Temperature results from brake bench tests were used for calibrating axisymmetric finite element models, including both wheel and brake block. Tests performed on the Lucchini / CHARMEC inertia dynamometer at Surahammar included an investigation of the effect of rail chill (cooling of the rolling wheel through its contact with the rail, see project SD4).

Professor Roger Lundén with co-workers Mr Martin Helgen (MSc), Docent Jan Henrik Sällström and Mr (now Dr) Tore Vernersson ran the EU8 project. See also CHARMEC's Triennial Reports for Stages 3 and 4. CHARMEC's European partners in ERS are listed in the latter report.

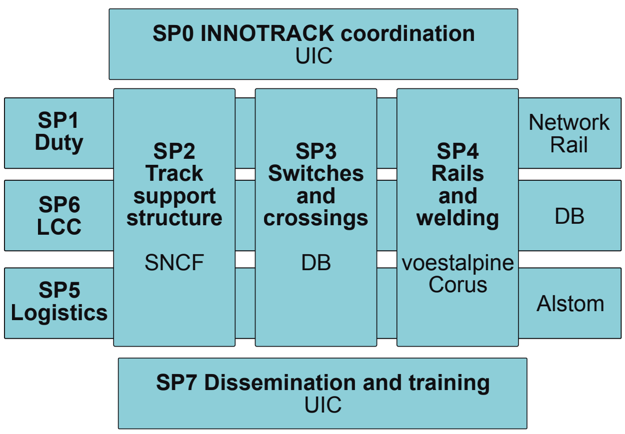
EU9. EURNEX

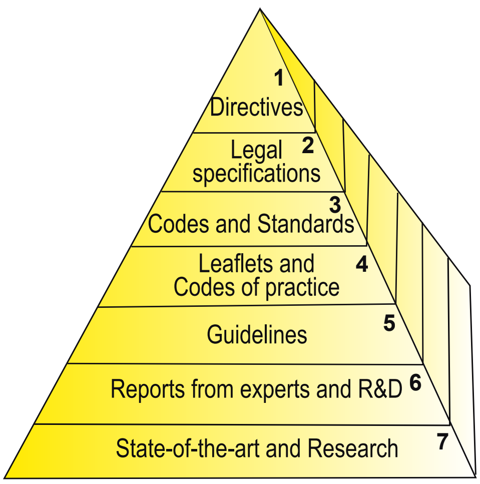
EURNEX – European Rail Research Network of Excellence

For a photo of Roger Lundén and Anders Ekberg, see page 63

EURNEX was financed during 2004-2007 by the EU under the Sixth Framework Programme, see www.eurnex.net. The EURNEX Association was founded on 30 October 2007 to continue the EURNEX idea. The activities are co-ordinated by FAV in Berlin (FAV stands for Forschungs- und Anwendungsverbund Verkehrssystemtechnik), which also co-ordinated the previous EU project. Chalmers/CHARMEC was a member of the EURNEX Association until 31 December 2013.

Professor Roger Lundén and Docent (now Professor) Anders Ekberg led the work in the EU9 project. See also CHARMEC's Triennal Reports of Stages 4, 5 and 6. As EURNEX (the Network of Excellence) evolved up to 31 December 2007, an organization based on ten "Poles of Excellence" was established. Anders Ekberg was the leader of Pole 8, which dealt with "Infrastructure and Signalling".





INNOTRACK project organization with subprojects and responsible partners, and hierarchy of regulations in the European rail sector. From INNOTRACK Concluding Technical Report

EU10. INNOTRACK

INNOTRACK – Innovative Track Systems

Chalmers/CHARMEC was a partner in INNOTRACK, an Integrated Project (IP) under the Sixth Framework Programme: Thematic Priority 6 – Sustainable Development, Global Change and Ecosystems. The aim of INNOTRACK was to deliver innovative products, processes and methodologies in order to achieve the ERRAC targets of increased quantities and quality of rail transport on conventional lines with mixed traffic. INNOTRACK is said to be the first European project with comprehensive co-operation between infrastructure managers and the supply industry regarding the complete track construction, with the aim to reduce the rate of track degradation and maintenance intervention. INNOTRACK comprised a total of 1266 man-months with a budgeted project cost of MEUR 18.6 (including budgeted EU funding of MEUR 10.0). The 36 partners (from 10 countries) in INNOTRACK are listed in CHARMEC's Triennial Report for Stage 4. Banverket's (now Trafikverket) Björn Paulsson was the Project Manager, representing the UIC and based in their office in Paris. CHARMEC's Anders Ekberg was the technical and scientific co-ordinator for the entire INNOTRACK project, see page 89. CHARMEC's part of INNOTRACK comprised 44 man-months with a budgeted project cost of KEUR 663 from EU and additional funding of KSEK 5345 from CHARMEC, and was led by Professor Roger Lundén.

The results of the INNOTRACK project have been reported in 144 "deliverables". CHARMEC was the lead contractor for 6 of these and contributed to others. A Concluding Technical Report summarizing the overall results of INNOTRACK has been compiled by us. INNOTRACK formally ended on 31 December 2009 and later activities have focused on dissemination and implementation (see also projects SP21 and SP22). For co-ordination at the European level, an INNOTRACK Implementation Group was formed with Anders Ekberg participating. He and Björn Paulsson have also participated in the UIC Track Expert Group (TEG) with the dissemination and quality assurance of project results.

INNOTRACK's project manager Björn Paulsson (left) and technical and scientific co-ordinator Anders Ekberg outside the UIC office in Paris. Photo taken in 2009

The Executive Summary of the INNOTRACK Concluding Technical Report has been translated into German, French, Swedish and Russian with CHARMEC being involved in the translations into Swedish and Russian. Regarding dissemination activities (co-)organized by CHARMEC, we may mention a public seminar on INNOTRACK with emphasis on the work carried out by us at Chalmers, a workshop on results regarding switches & crossings including a visit to installed demonstrators in Eslöv (Sweden), and a press conference at VINNOVA in Stockholm. A special issue of IMechE Journal of Rail and Rapid Transit (vol 224, no F4, 2010, pp 237-335) provides an overview of the scientific aspects of INNOTRACK. See also CHARMEC's Triennial Reports for Stages 5 and 6.

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

EU11. QCITY

Quiet City Transport

This was an Integrated Project (IP) under the Sixth Framework Programme: Thematic Priority 6 – Sustainable Development, Global Change and Ecosystems. Banverket (now Trafikverket) was a partner (one of 27 from 10 countries) and transferred work in QCITY to CHARMEC and to our Professor Jens Nielsen, as reported in project SP10. QCITY ran from 1 February 2005 to 31 January 2009. The co-ordinator of project QCITY was Nils-Åke Nilsson from Acoustic Control ACL AB (now part of Tyréns AB in Stockholm, Sweden). See www.qcity.org.

EU12. RIVAS

RIVAS – Railway Induced Vibration Abatement Solutions

Project leader	Professor Jens Nielsen, Applied Mechanics / Division of Dynamics
Period	2011-01-01 – 2013-12-31
Budget EU	kEUR 283
Budget CHARMEC	Stage 6: kSEK 180 Stage 7: kSEK 47

For a photo of Jens Nielsen, see page 28

RIVAS was a Collaborative Project within the European Union's Seventh Framework Programme under the activity code "Attenuation of ground-borne vibration affecting residents near railway lines". It aimed to contribute to technologies for efficient control of the exposure of people to vibration and vibration-induced noise caused by rail traffic. RIVAS focused on low-frequency vibration from surface lines, which is a concern mainly for freight traffic. However, results are also applicable to suburban, regional and high-speed operations.

Key deliverables include protocols for the evaluation of annoyance and exposure to vibrations, for the assessment and monitoring of the performance of antivibration measures, and for the characterization of vibration properties of soils. Mitigation measures for both ballasted track and slab track were studied. Guidelines have been presented for track and vehicle maintenance, for design of transmission mitigation measures, and for low-vibration vehicles, see www.RIVAS-project.eu.

The 26 partners (from 9 countries) in RIVAS were ADIF (Spain), Alstom (France), Bombardier Transportation (Sweden), BAM (Germany), CSTB (France), CEDEX (Spain), Chalmers/CHARMEC (Sweden), DB (Germany), D2S (Belgium), Eiffage Rail (Germany), KU Leuven (Belgium), Keller (Germany), Lucchini RS (Italy), Pandrol (UK), Rail One (Germany), RATP (France), Sateba (France), SATIS (NL), SBB (Switzerland), SNCF (France), Trafikverket (Sweden), TÜV Rheinland (Germany), UIC, UNIFE, University of Southampton/ISVR (UK), and VibraTec (France).

The 8 work packages of RIVAS were WP1 Assessment and monitoring procedures (led by DB), WP2 Mitigation measures at source (Alstom), WP3 Mitigation measures on track (SNCF), WP4 Mitigation measures on transmission/propagation (KU Leuven), WP5 Mitigation measures on vehicles (Bombardier Transportation), WP6 Dissemination, exploitation and training (UIC), WP7 Administrative management (TÜV Rheinland), and WP8 Technical co-ordination (UIC). Bernd Asmussen and Wolfgang Behr, DB/UIC, co-ordinated the full RIVAS project. It comprised a total of 483 man-months with a budgeted project cost of MEUR 8.3 (including budgeted EU funding of MEUR 5.2) and ran during 36 months starting on 2011-01-01. The commitment of Chalmers/CHARMEC was 20 man-months related to WP2, WP3 and WP5. The kick-off meeting for RIVAS was held at UIC in Paris on 2011-02-02. RIVAS Description of Work is dated 2010-11-29. Chalmers was the task leader for WP2.1 Vibration effect of track irregularities and WP5.3 Design of low vibration vehicles, and was responsible for Deliverables D2.1, D2.5, D5.4 and D5.5.

CHARMEC worked on simulation of train induced ground vibrations. Here also the influence of vehicle design parameters was assessed. Chalmers was responsible for a guideline for the design and maintenance of railway vehicles leading to reduced generation of ground-borne vibration. The unsprung mass and wheel out-of-roundness (OOR) are key vehicle related parameters determining the generation of ground-borne vibration. Guidelines on reducing the unsprung mass were presented, including alternative wheelset designs and the design concept and suspension of the mechanical drive system. To reduce ground-borne vibration, the following measures for rolling stock need to be implemented: (1) network based monitoring stations for wheel tread conditions to trigger condition based wheel maintenance, (2) improved brake system design, wheel slide protection and wheel material quality to avoid wheel flats and other discrete wheel tread defects, (3) reduction of unsprung mass, in particular for locomotives, by application of suspended drive design concepts, and (4) radial steering of wheelsets to reduce wear and wheel polygonalisation on small radius curves.

EU12. (cont'd)

The influence of different types of track irregularities and wheel out-of-roundness has been assessed through numerical simulations. In collaboration with KU Leuven in Belgium, a hybrid model for the prediction of ground-borne vibrations due to discrete wheel and rail irregularities was developed. The hybrid model combines the simulation of vertical wheel–rail contact force in the time domain and calculation of ground-borne vibration in the frequency-wavenumber domain considering a layered soil model. The model has been demonstrated by investigating the influence of wheel flat size and vehicle speed on maximum vertical wheel–rail contact force and ground vibration. Further, a benchmark was performed to compare predicted contact forces and vibrations between the CHARMEC in-house software DIFF and software developed by ISVR in UK and KU Leuven, which have a different focus. These indicated good agreement and described how the models could be modified and tuned to extend the prediction accuracy and obtain maximum interoperability between the codes.

An overview of various methods to measure track irregularities in loaded or unloaded conditions has been compiled. It was noted that none of the existing systems measures track irregularities in the complete wavelength interval relevant for ground-borne vibration and noise. The influence of tamping, unsprung mass and wheel out-of-roundness on ground vibrations has been measured in field trials. These indicated that freight locomotives induce the maximum vibration levels.

Results from RIVAS have been disseminated, e g, at the 11th International Workshop on Railway Noise in Uddevalla 2013 and at the 18th Nordic Seminar on Railway Technology in Bergen 2014.

Jens Nielsen, Geert Lombaert and Stijn François: A hybrid model for the prediction of ground-borne vibration due to discrete wheel/rail irregularities, *Journal of Sound and Vibration*, vol 345, 2015, pp 103-120

Jens Nielsen, Adam Mirza, Steven Cervello, Philipp Huber, Roger Müller, Brice Nélain and Philipp Ruest: Reducing train-induced ground-borne vibration by vehicle design and maintenance, *International Journal of Rail Transportation*, vol 3, no 1, 2015, pp 17-39

Adam Mirza, Anders Frid and Jens Nielsen: Reduction of train induced ground vibration by vehicle design, In Jens Nielsen et al (editors): *Noise and Vibration Mitigation for Rail Transportation Systems, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, vol 126 (revised article from workshop *IWRN11*), Springer, 2015, pp 523-530

Roger Müller, Jens Nielsen, Brice Nélain and Armin Zemp: Ground-borne vibration mitigation measures for turnouts: state-of-the-art and field tests, *ibidem*, pp 547-554

Jens Nielsen: RIVAS – Railway Induced Vibration Abatement Solutions, *Proceedings 18th Nordic Seminar on Railway Technology*, Bergen (Norway) October 2014, 1+21 pp (Summary and PowerPoint presentation)

Deliverables RIVAS

Jens Nielsen, Roger Müller, Matthias Krüger, Thomas Lölgen, Pablo Mora and Pau Gratacos: Classification of wheel out-of-roundness conditions with respect to vibration emission, D2.2, August 2012, 91 pp

Jens Nielsen, Eric Berggren, Thomas Lölgen, Roger Müller, Bert Stallaert and Lise Pesqueux: Overview of methods for measurement of track irregularities important for ground-borne vibration, D2.5, July 2013, 49 pp

Roger Müller, Pau Gratacos, Pablo Mora, Jens Nielsen, Joseph Feng and Steven Cervello: Definition of wheel maintenance measures for reducing ground vibration, D2.7, October 2013, 86 pp

Joseph Feng, Jens Nielsen, Bert Stallaert and Eric Berggren: Validation of track maintenance measures, D2.8, December 2013, 36 pp and 2 annexes, (28 pp + 29 pp)

Roger Müller, Brice Nelain, Jens Nielsen and Estelle Bongini: Description of the vibration generation mechanism of turnouts and the development of cost effective mitigation measures, D3.6, January 2013, 129 pp

Roger Müller, Baldrik Faure, Estelle Bongini, Armin Zemp, Jens Nielsen and Björn Pålsson: Ground vibration from turnouts: numerical and experimental tests for identification of the main influencing sources/factors, D3.12, December 2013, 51 pp

Jens Nielsen, Adam Mirza, Steven Cervello, Anders Frid, Roger Müller, Brice Nelain and Philipp Ruest: Train induced ground vibration – optimised rolling stock mitigation measures and their parameters, D5.4, February 2013, 81 pp

Jens Nielsen, Adam Mirza, Philipp Ruest, Philipp Huber, Steven Cervello, Roger Müller and Brice Nelain: Guideline for the design of vehicles generating reduced ground vibration, D5.5, December 2013, 46 pp

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

EU13. D-RAIL

D-RAIL – Development of the Future Rail Freight System to Reduce the Occurrences and Impact of Derailment

Project leader	Professor Anders Ekberg, Applied Mechanics / Division of Dynamics
Co-workers	Professor Roger Lundén, Dr Björn Pålsson, Docent Elena Kabo, Professor Jens Nielsen and Dr Tore Vernersson, all of Applied Mechanics
Period	2011-10-01 – 2014-09-30
Budget EU	keur 250
Budget CHARMEC	Stage 6: ksek 200 Stage 7: ksek 454 + 486

From the left: Dr Tore Vernersson, Docent (now Professor) Anders Ekberg, Mr (now Dr) Björn Pålsson, Docent Elena Kabo, Professor Jens Nielsen and Professor Roger Lundén, all of them being active in project EU13. Photo is taken in Chalmersska Huset (the Chalmers House) at Södra Hamngatan 11 in Gothenburg in 2012

d-rail was a "small or medium-scale focused research project" within the Seventh Framework Programme, with a total budget of Meur 4.77 of which Meur 3.00 were the requested eu funding. d-rail focused on freight traffic, identifying root causes of derailment of particular significance to freight vehicles. A key question was how independent minor faults (e g, a slight track twist and a failing bearing) could combine to cause a derailment. d-rail extended the study to include expected demands on the rail freight system forecast for 2050.

Causes of derailment and pertinent frequency/impact were quantified and investigated in detail to further the understanding of mechanisms and conditions under which derailments may occur. In tandem with the above analysis, current monitoring systems and vehicle identification technologies (wayside and vehicle-mounted) and developing technologies were assessed with respect to their ability to identify developing faults and potential dangers. Where current systems were shown to be deficient, requirements for future monitoring systems were specified. Integration of alarm limits, monitoring systems and vehicles across national borders and network boundaries were examined, and deployment plans based on rams and lcc analyses were outlined. Field testing and validation were made at vuz's test track in the Czech Republic.

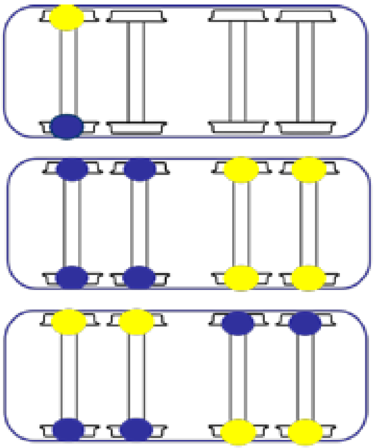
The project d-rail was jointly co-ordinated by uic and University of Newcastle with Anders Ekberg of charmec acting as scientific and technical co-ordinator, with financial support from vinnova. The outcome of d-rail has provided input to standards, regulations and international contracts. See www.d-rail-project.eu for more information and public reports.

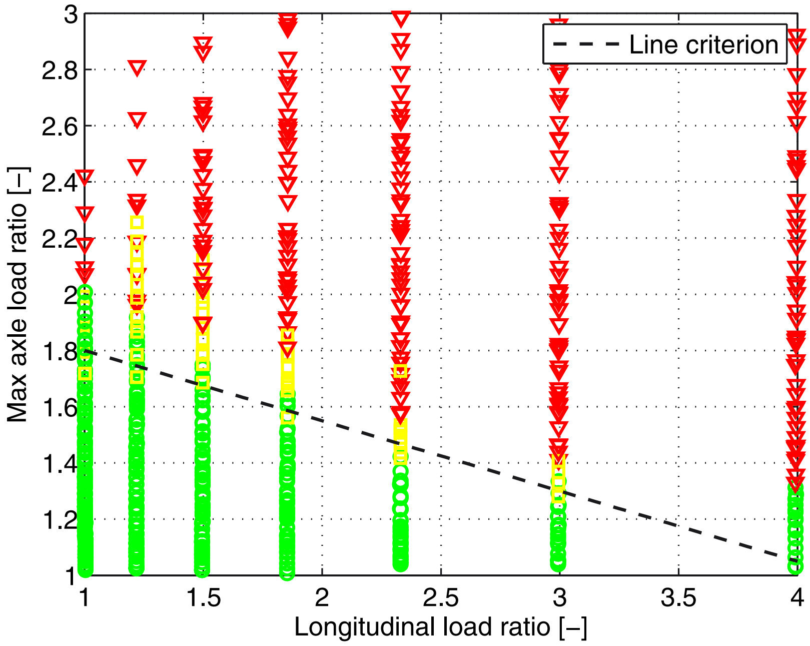
The 20 partners (from 9 countries) in d-rail were University of Newcastle (uk), uic, rssb (Rail Safety and Standards Board, uk), Technische Universität Wien (Austria), Panteia (nl), Chalmers/charmec (Sweden), Politecnico di Milano (Italy), mmu (Manchester Metropolitan University, uk; later replaced by Huddersfield University, uk), Lucchini rs (Italy), MerMec (Italy), Faiveley Transport (Italy), Telsys (Germany), Oltis (Czech Republic), vuz (Czech Republic), db (Germany), Harsco Rail (us), sbb (Switzerland), öbb (Austria), sncf (France) and Trafikverket (Sweden).

d-rail was divided into 9 work packages: wp1 Derailment impact (led by uic), wp2 Freight demand and operation (led by University of Newcastle), wp3 Derailment analysis and prevention (led by sncf), wp4 Inspection and monitoring techniques (led by MerMec), wp5 Integration of monitoring techniques (led by db), wp6 Field testing and evaluation (led by vuz), wp7 Operational assessment and recommendation (led by db), wp8 Dissemination & exploitation (led by uic), and wp9 Project co-ordination (led by uic and University of Newcastle). charmec worked (number of man-months in parentheses) in wp3 (18), wp6 (4), wp7 (2) and wp8 (1). A total of 25 Deliverables were produced with charmec being the lead contractor for three of them.

At charmec, the risk of derailment was studied for freight traffic in the switch of a small-radius turnout setting out from a parameter screening including 25 vehicle and track parameters. A "bad case" combination of vehicle and turnout was defined, the most influential parameters identified and a derailment limit as a function of these parameters established. Some of this work was performed during our Björn Pålsson's stay as visiting researcher in March – April 2013 at the University of Huddersfield, uk. In our work on wheel breaks, two generic wheel designs

EU13. (cont'd)





Definition of different types of load imbalances studied in project EU13. Criterion for allowed imbalance. Scenarios that have been analysed are marked red (lead to derailment), yellow (flange climbing) or are green (no risk of derailment)

subjected to excessive thermal and mechanical loads were assessed using fatigue and thermomechanical criteria. Further, cracking of the wheel web was studied in detail. The results of the above investigations have been compiled in Deliverables D3.2 and D3.3, see below.

The influence of lateral bending on the risk of rail fracture caused by foot cracks has been investigated through numerical simulations by our Elena Kabo supported by full-scale measurements at the VUZ test facility. The good match between field measurements and simulations allows for better failure predictions regarding foot cracks. CHARMEC has also contributed with technical input to the LCC and RAMS evaluation of D-RAIL solutions and to the overall quality assurance of the project. We have reviewed most of the D-RAIL reports.

Results have been disseminated on several occasions. Some of the more important ones are the 17th International Wheelset Congress in Kiev 2013, the Wayside Train Monitoring Systems conference in Frankfurt 2013, the UIC Track Expert Group meeting in Eslöv 2013 and the final dissemination seminar in Stockholm 2014.

Tore Vernersson, Roger Lundén, Elena Kabo and Anders Ekberg: Wheel fracture – sensitivity to extreme loads for two generic wheel designs, *Proceedings 17th International Wheelset Congress (IWC17)*, Kiev (Ukraine) September 2013, pp 38–47

Anders Ekberg and Björn Paulsson: D-RAIL – konsten att inte spåra ur (D-RAIL – the art of not derailing; in Swedish), Research Report 2015:07, *Chalmers Applied Mechanics*, Gothenburg 2015, 22 pp (and 2 annexes, 1+1 pp)

Deliverables D-RAIL

Francesco Braghin (editor): Analysis and mitigation of derailment, assessment and commercial impact, D3.2, 2013, 283 pp (+ 1 annex, 18 pp). Chalmers responsible for Chapter 4 "Derailments in switches & crossings", Chapter 6 "Derailments due to wheel failures" and Chapter 7 "Derailments due to rail failures"

Anders Ekberg (editor): Guidelines on derailment analysis and prevention, D3.3, 2013, 38 pp. Chalmers responsible for the overall report, and for Chapter 3 "Derailment in switches & crossings", Chapter 4 "Derailment due to wheel failures" and Chapter 5 "Derailments due to rail failures"

Lukas Hejzlar (editor): Analysis of tests for the validation of numerical simulations, D6.1, 2014, 36 pp (+ 2 annexes, 1+13 pp). Chalmers responsible for Section 3 "Numerical analyses"

Wali Nawabi (editor): Existing derailment RAMS and economic studies and D-RAIL approach, D7.1, 2014, 59 pp. Chalmers responsible for Section 3.1.1 "Current status regarding derailments" and Section 3.3.1 "Potential modifications to infrastructure/vehicle/ regulations/ maintenance etc to minimize derailment risks"

Wali Nawabi (editor): RAMS analysis and recommendation (technical focus), D7.2, 2014, 116 pp (+ 3 annexes, 5+6+4 pp). Chalmers responsible for Section 2.3.3 "Top derailment causes" and Section 3.4 "Use of monitoring systems in maintenance procedures", and parts of Section 2.3.8 "Considering of EU-related projects"

Björn Paulsson and Anders Ekberg: Scientific and technical review by acknowledged scientists and railway experts, D7.5, 2014, 11 pp. Trafikverket and Chalmers responsible for this report

Björn Paulsson and Anders Ekberg: Dissemination and implementation of D-RAIL results, D8.3, 2014, 15 pp. Trafikverket and Chalmers responsible for this report

François Defossez (editor): Exploitation of results from D-RAIL, D8.4, 2014, 17 pp. Chalmers responsible for parts of Section 2 "D-RAIL Exploitable results"

EU14. Capacity4Rail

Capacity4Rail – Capacity for Rail

Project leader	Professor Anders Ekberg, Applied Mechanics / Division of Dynamics
Co-workers	Professor Roger Lundén, Docent Elena Kabo, Professor Jens Nielsen, Dr Björn Pålsson and Dr Peter Torstensson, all of Applied Mechanics
Period	2013-10-01 – 2017-09-30
Budget EU	kEUR 217 + 54
Budget CHARMEC	Stage 7: kSEK 300 Stage 8: kSEK 200

Capacity4Rail (SST.2013.2-2) is 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 are the requested EU funding. Capacity4Rail aims 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 is co-ordinated by the UIC and has 46 partners listed on www.capacity4rail.eu.

Capacity4Rail is 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 are then divided into work packages. CHARMEC will work (number of Man-Months in parentheses) in WP1.3 Switches & crossings (S&C) for future railways (11 MM) [responsible for Deliverable D1.3.2 due month 30] and WP4.1 (3.5 MM) [WP leader and responsible for Deliverable D4.1.2 due month 36]. In addition CHARMEC will contribute in Task 1.1.4 (4.5 MM) "Upgrade infrastructure to meet new freight demand". The formal kick-off meeting for Capacity4Rail was held at the UIC in Paris on 2013-10-16.

CHARMEC's work on optimization of switches & crossings has established an approach for geometry optimization. A post-processing toolbox for evolution of damage (in terms of wear and surface initiated rolling contact fatigue) in railway turnouts has been developed and implemented. The approach together with initial simulation results have been presented at CM2015, see below.

In WP4.1 CHARMEC drafted skeletons for the first two deliverables. The operational work has focused on Deliverable D4.1.2 where operational parameters required for status assessment and prediction of future degradation rates etc are contrasted to which parameters are operationally viable to measure.

CHARMEC's contributions to Deliverable D1.1.4 on freight lines consisted in the outline of a structured approach to track upgrading. Here a three-level approach with successively refined analyses is detailed where suitable level(s) can be selected depending on the scope of the upgrading. Further, possibilities for the different analyses (both in terms of resolution and in terms of investigated phenomena) are described.

Jens Nielsen, Björn Pålsson and Peter Torstensson: Switch panel design based on simulation of accumulated rail damage in a railway turnout, *Proceedings 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs CO (USA) August – September 2015, 9 pp

Björn Paulsson (editor): Upgrading of infrastructure in order to meet new operation and market demands, Capacity4Rail Deliverable D1.1.4, 2015, 202 pp

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

EU15. WRIST

WRIST – Innovative Welding Processes for New Rail Infrastructures

Project leader	Professor Lennart Josefson, Shipping and Marine Technology
Co-worker	Dr Jim Brouzoulis, Applied Mechanics / Material and Computational Mechanics
Period	2015-05-01 – 2018-04-30
Budget EU	kEUR 417
Budget CHARMEC	Stage 8: kSEK 400

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 flexible and cost-effective joining processes for rails (orbital friction welding and aluminothermite welding) that will address the key degradation mechanisms experienced by welds in current rail infrastructure. The new processes also recognize the move of the industry towards higher train

EU15. (cont'd)

speeds and axle loads and the need to increase capacity. One particular focus of the new welding processes is to overcome the inability of current joining processes to weld together premium grade steels, such as low-carbon carbide-free bainitic grades.

WRIST is co-ordinated by the Belgian Welding Institute. In addition to Chalmers, 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 ARTTIC (France).

WRIST is divided into 9 work packages (CHARMEC Man-Months in parentheses): WP1 Requirements analysis, WP2 Further development of the new aluminothermite welding process (1 MM), WP3 Development of new orbital friction process (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 second project meeting in Maidstone (UK) on 20–21 April 2016.

Chalmers' work in WRIST officially started on 1 August 2015 and focused initially on identifying material and process parameters needed for the thermal and mechanical analyses of the two welding processes. So far initial models (thermal and mechanical) for both the orbital friction welding process and the aluminothermite process have been developed.

EU16. In2Rail

In2Rail – Innovative Intelligent Rail

Project leader	Professor Anders Ekberg, Applied Mechanics / Division of Dynamics
Co-workers	Professor Roger Lundén, Docent Elena Kabo, Professor Jens Nielsen, Dr Peter Torstensson and Dr Björn Pålsson, all of Applied Mechanics
Period	2015-05-01 – 2018-04-30
Budget EU	kEUR 502
Budget CHARMEC	Stage 8: kSEK 400

In2Rail (MG-2.1-2014) is a project within the European Union´s Horizon 2020 Programme with an EU grant of MEUR 18.0. In2Rail is 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 is co-ordinated by Network Rail (UK) and has 53 additional partners listed on the project website www.in2rail.eu.

The 13 work packages (WP) in In2Rail are 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 is involved in WP 2, 3 and 5. The formal In2Rail kick-off was held in Brussels on 2015-05-07.

CHARMEC's work in WP2 so far has focused on switch rail maintenance and operational tolerances. In WP3 our work is 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.

In WP5 CHARMEC's work analyses the influence of thermal stresses with particular focus on measuring stress-free temperature and predicting the influence of track and trackbed geometry on sun-king formation. A first report has been finalized, see below, where we have contributed with sections on thermal stress monitoring and consequences.

In2Rail Deliverable D5.1: Report on parameters influencing concept developments, 63 pp (and 5 annexes, 6+11+10+4 pp +spreadsheet)

Peter Torstensson, Giacomo Squicciarini, Matthias Krüger, Jens Nielsen and David Thompson: Hybrid model for prediction of impact noise generated at railway crossings (accepted for oral presentation at *12th International Workshop on Railway Noise (IWRN12)* in Terrigal (Australia) in September 2016)

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP1. LUCCHINI SWEDEN AB (bilateral agreement)

Bilateral agreements have been running since 1987 between Lucchini Sweden (formerly Sura Traction, ABB Sura Traction 1990-96, Adtranz Wheelset 1996-2000) and Chalmers Applied Mechanics (formerly 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. The main contact now is Erik Kihlberg, who succeeded Lennart Nordhall as President of Lucchini Sweden in April 2009.

Contact persons are also Gunnar Eriksson and Peter Jöehrs at Surahammar and personnel at the parent company Lucchini RS in Italy. Several new designs of freight and passenger wheelsets have been developed. In April and June 2012, CHARMEC gave a course for the personnel at Lucchini Sweden on materials, design, maintenance and other aspects of wheelset technology. Roger Lundén also assists Lucchini Sweden on the CEN and ERWA committees, see further page 121.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP2. NOISE FROM SWEDISH RAILWAYS

CHARMEC has been involved in Banverket's (now Trafikverket) overall efforts to reduce the noise emitted from Swedish railways since 2002. Results from projects VB4, EU2 and EU3 were utilized in project SP2. Continued work has taken place in project SP10.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP3. TRACK FORCE MEASUREMENTS ON X2

An extensive test campaign with field measurements of the track forces caused by Swedish high-speed train X2 was run in October 2002. The cash and in-kind financing (about MSEK 3.0) came from Banverket (now Trafikverket), Lucchini Sweden, SJ AB and CHARMEC.

A bogie was equipped by TrainTech Test Centre (now Interfleet Technology Test Centre) with accelerometers, measuring wheels and a data collection system. The train ran three times Stockholm–Gothenburg (Göteborg)–Stockholm, twice Stockholm–Malmö–Stockholm, and once Stockholm–Sundsvall–Stockholm. The aim was to cover the high-frequency range of the load spectrum (up to around 2000 Hz) where large contributions to peak loads may originate. CHARMEC contributed with a background analysis and calculations.

The results from SP3 have been used in TS8 and other projects. See also CHARMEC's Triennial Report for Stage 3 and under SP11 below.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP4 & SP5. VAE AG AND VOESTALPINE SCHIENEN GMBH (bilateral agreements)

For the period 1 January 2002 – 30 June 2003, bilateral agreements were reached between Chalmers/CHARMEC and Austrian switch manufacturer VAE AG (for projects TS7 and MU14) and Austrian rail producer voestalpine Schienen GmbH (for projects MU11 and MU14). From Stage 3, the two Austrian companies joined CHARMEC's Industrial Interests Group under the joint name voestalpine Bahnsysteme GmbH & CoKG.

SP6. DEVELOPMENT OF A QUIET RAIL

Utveckling av en tyst räl

From September 2000, CHARMEC had a development project aimed at the treatment and installation of rails with less noise radiation. Different shielding arrangements and absorbing materials were tested in project SP6. See CHARMEC's Triennial Report for Stage 3 and also project SP10 in the following.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP7. LATERAL TRACK STABILITY

Lateral spårstabilitet

One of the most feared phenomena in railway operations is the formation of sun-kinks on the track, a phenomenon also known as lateral buckling. Sun-kinks are caused by excessive compressive forces in the rails, owing to high temperature and restrained thermal expansion. Large and rapid lateral deflections of the track occur and may cause derailment of a passing train. The SP7 project was led by Docent (now Professor) Anders Ekberg and Dr (now Docent) Elena Kabo and several co-workers from SP Technical Research Institute of Sweden, see photo.

The resulting axial force in a rail is zero at a certain "neutral temperature". Knowledge of this temperature is important because it governs the maximum temperature that the track can sustain before sun-kinks are likely to occur. In SP7 several existing and proposed methods for measuring the axial force (and thereby the neutral temperature) in an installed rail were studied theoretically, numerically and experimentally.

Experimental setup for the "wave guide method" at the SP laboratory in project SP7. From the left: Docent (now Professor) Anders Ekberg and Dr (now Docent) Elena Kabo of Chalmers Applied Mechanics together with Dr Gunnar Kjell, Dr (now Professor) Erland Johnson, Dr Robert Lillbacka and Mr Lars Jacobsson, Lic Eng, of SP Technical Research Institute of Sweden. Photo taken in 2006

The other focus of project SP7 was on track stability with its dependence on the lateral stiffness of rails, fastenings and sleepers. Non-linear finite element (FE) simulations in 2D and 3D were performed to establish the lateral force-deflection characteristics of a single sleeper embedded in ballast and of a 100 m stretch of the full track. Finally, a "track resonance method" was launched for an experimental study of the overall risk of sun-kinks on an existing track.

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

SP8. DESIGN OF INSULATED JOINTS

Utformning av isolerskarvar

Project SP8 was led by Dr (now Docent) Elena Kabo. Work in the project was gradually shifted to projects TS8, MU18 and EU10, see under these projects.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP9. SLEEPER DESIGN FOR 30 TONNE AXLE LOAD

Sliperutformning för 30 tons axellast

The design of new concrete sleepers for the Iron Ore Line (Malmbanan) in northern Sweden was studied, at the request of Banverket (now Trafikverket), with regard to the increase in maximum axle load from 25 to 30 tonnes.

The project was led by Professor Jens Nielsen of Chalmers Applied Mechanics/CHARMEC and Dr Rikard Bolmsvik of Abetong (see project MU5). The study ran from July 2004 to June 2005 and was financed by Banverket. See also CHARMEC's Triennial Report for Stage 4 and projects SP12 and SP17 in the following.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP10. NOISE REDUCTION MEASURES AND EU PROJECT QCITY

Bullerreducerande åtgärder och EU-projektet QCITY

To comply with noise legislation and support long-term political, environmental and logistical objectives, greater understanding is needed of the emission and propagation of railway noise and the nuisance it causes to people living near railway lines. Several research projects focusing on railway noise have therefore been run at Banverket (now Trafikverket). They include (i) developing technology for frequent and regular measurement of short-wavelength rail irregularities using Banverket's STRIX car, (ii) surveying the market of noise reduction measures, (iii) introducing rail vibration absorbers at hot spots in the railway network, (iv) developing a database of models of tracks and vehicles representative of Swedish conditions to be used with the noise prediction software TWINS, (v) participating in the EU integrated project QCITY (Quiet City Transport) which comprised a total of 1041 man-months and had a budgeted EU funding of MEUR 7.40 (here Banverket was a partner with a commitment of 12 man-months plus in-kind contributions), the aim being to develop an integrated technology infrastructure for the efficient control of road and rail ambient noise, and (vi) participating in the reference group for noise projects under the Green Train Programme in Sweden, see page 117 in CHARMEC's Triennial Report for Stage 6.

The aim of project SP10 was to increase efficiency and achieve synergy effects by integrating these projects. This task was assigned to CHARMEC's Jens Nielsen, who worked part-time in the project from January 2005 to November 2009.

A field test with three different types of rail dampers (from Corus Rail, CDM and Schrey & Veit) was performed in September 2008 at the Tjörnarp test site between Höör and Hässleholm on the Southern Main Line with UIC60 rails. In addition, pass-by noise from 14 train passages (8 X60, 2 X40, 1 X12, 2 InterCity and 1 freight train) at a speed of about 70 km/h was recorded at a test track near Kungsängen northwest of Stockholm. Without a noise barrier, the X60 and X40 trains were the quietest trains measured, some 8 dB(A) quieter than the freight train. An installed low barrier was found to be most efficient in reducing TEL (Transit Exposure Level) for the X60 and X12 trains. For detailed results from Tjörnarp and Kungsängen, see CHARMEC's Triennial Report for Stage 5.

SP11. VERTICAL CONTACT FORCES OF HIGH-SPEED TRAINS

Vertikala kontaktkrafter på höghastighetståg

During 2000 and 2002, vertical contact force measurements were carried out using an X2 bogie and wheelset, see project SP3. Analysis of part of the measured data revealed that extreme loads have a large high-frequency content, and numerical simulations have indicated that these extreme loads are of vital importance in the degradation of tracks and wheels. The overall aim of project SP11 was to (i) clarify the occurrence of high-frequency vertical wheel–rail contact forces at high-speed operations on Swedish railways, and (ii) further the understanding, prediction and counteracting of cracks in wheels and rails as a consequence of rail and wheel corrugation. The SP11 project was led by Mr Per Gullers, MSc, of Interfleet Technology and Professor Roger Lundén of Chalmers Applied Mechanics. Docent (now Professor) Anders Ekberg, Professor Jens Nielsen and Docent Elena Kabo of Chalmers Applied Mechanics were co-workers.

In total, the work contained the following 10 tasks: (1) refinement of a computer-based tool to analyse measured data, (2) state-of-the-art survey of methods for measuring rail corrugation, (3) improvement of filters for force data analysis, (4) DIFF modelling of wheel–rail interaction, (5) FIERCE analysis of rolling contact fatigue (RCF), (6) development of analysis tools for handling of large data files, (7) analysis of rail corrugation data, (8) development of acceptance criteria for rail irregularities, (9) evaluation of rail irregularities in relation to Banverket's (now Trafikverket) database BIS, and (10) writing of reports. CHARMEC was involved in tasks 2, 4, 5, 8 and 10. Project SP11 was conducted through a partnership between Interfleet Technology and CHARMEC. The project was part of the Green Train (Gröna Tåget) Programme in Sweden, see page 117 in CHARMEC's Triennial Report for Stage 6.

The measurements carried out in the summer of 2007 on the Green Train at speeds up to 280 km/h have been assessed. In parallel, dynamic vehicle–track interaction at high vehicle speeds has been studied using our computer program DIFF with rotating and non-rotating Regina and X2 wheelsets being implemented (including gyroscopic and centripetal effects), see project TS12.

It was concluded that the Green Train vehicle design will be fairly sensitive to excitation by sleeper passing and probably also to the excitation by other track irregularities. The reason may be the high unsprung mass and high axle load. On one track section with severe rail corrugation, the calculated 95-percentile of the dynamic component of the vertical contact force increased by 35% when vehicle speed was raised from 200 to 280 km/h. This means that the introduction of future high-speed traffic in Sweden would make it necessary to set requirements for track design, specifying the need to choose resilient rail pads and rails with high bending stiffness, as well as for optimized geometry and material of switches and crossings. In addition, requirements on track maintenance to limit rail surface irregularities and degradation of profiles in crossings and on preserving the conditions of the ballast bed would be needed, see project SP19. See also CHARMEC's Triennial Reports for Stages 4 and 5. The reference group for project SP11 had members from Interfleet Technology and Trafikverket. For CHARMEC's work in task 5 above, see our MU projects. See also CHARMEC's Triennial Reports for Stages 4, 5 and 6.

Meeting in October 2006 of the reference group for project SP11 at the office of Interfleet Technology in Solna (Sweden). From the left: Per Gullers (Interfleet), Johan Oscarsson (Interfleet), Roger Lundén (CHARMEC), Tohmmy Bustad (Banverket), Lennart Warsén (SJ), Lars Andersson (Interfleet), Jens Nielsen (CHARMEC) and Simon Gripner (Banverket)

SP12. NEW SLEEPER SPECIFICATIONS

Nya sliperspecifikationer

Project SP12 was initiated by Banverket (now Trafikverket) and based on previous work in project SP9. The design of sleepers for 35 tonne axle load was studied. Although the current maximum axle load on the Iron Ore Line (Malmbanan) in northern Sweden is 30 tonnes, an increase to 35 tonnes may take place in the future. The work was carried out in 2006 and led by Professor Jens Nielsen of CHARMEC and Dr Rikard Bolmsvik of Abetong. The influence of wheel tread defects (wheel flats) and of non-uniform distribution of support stiffness from the ballast along the sleeper was studied. The bending moments in the sleeper at the rail seats and at the centre were calculated using CHARMEC's simulation model DIFF for dynamic interaction between train and track. The in-situ strain gauge measurements in the track at Harrträsk (close to Gällivare) in September 2006 were also utilized, see project TS9. Sleepers with cracked and non-cracked centre sections were numerically studied, and the risk of fatigue failure was evaluated using statistics gathered through Banverket's (now Trafikverket) wheel damage detector at Harrträsk.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP13. ALARM LIMITS FOR WHEEL DAMAGE

Larmgränser för hjulskador

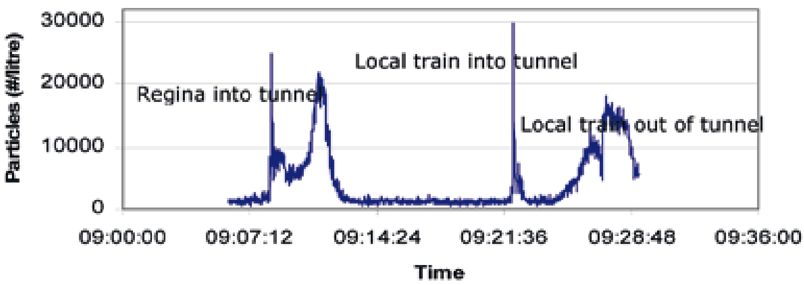
In Sweden, the criterion for removal of wheels with a flat is based on the length of the flat, which must not exceed 40 mm or 60 mm. In the latter case, immediate action is required. To find a more rational alternative, project SP13 focused on the maximum contact force that a damaged wheel may exert on the rail. In Banverket's (now Trafikverket) existing wayside detectors, the lowest alarm limit had been put at 290 kN. New alarm limits should consider the risk of rail fracture caused by a damaged wheel. The present study included existing defects in rails, residual stresses induced at welds, and deviations from the neutral temperature of the rail. Results from the field test, with a train containing several intentional and severe wheel defects, which was performed on Svealandsbanan in September 2000, have been re-analysed. Project SP13 ran from October 2006 to June 2009 and involved CHARMEC's Professor Jens Nielsen, Docent (now Professor) Anders Ekberg and Docent Elena Kabo.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP14. PARTICLE EMISSIONS AND NOISE FROM RAILWAYS

Partikelemissioner och buller från järnväg

Particle emissions will probably be one of the dominating health aspects of railway (and road) traffic in coming years. Mechanisms contributing to the emissions are the continuous wear of wheels and rails (especially on curves), the wear of brake blocks, brake pads and brake discs, and the wear of catenary wires and pantograph contact strips. Project SP14 ran from January 2007 to June 2009 and was led by Professor Erik Fridell of IVL Swedish Environmental Research Institute and CHARMEC's Anders Ekberg. The total project budget was KSEK 1525, of which Banverket (now Trafikverket) contributed KSEK 820. In this project, particle emissions and airflow were registered at the entrance/exit of a single-track tunnel at Hindås, near Gothenburg, for a large number of trains. In addition, onboard measurements of particles and noise were performed on Regina trains travelling between Gothenburg (Göteborg) and Kalmar, and between Gothenburg and Halmstad, see CHARMEC's Triennial Reports for Stages 5 and 6 and the below diagram.



Example of result from tunnel measurements at Hindås in project SP14

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP15. COMPUTER PROGRAM FOR DESIGN OF BLOCK BRAKES

Beräkningsprogram för utformning av blockbromsar

In this project, results from the previous project SD4 have been implemented in an industrially adapted computer code for the calculation of wheel and block temperatures. The code can be used to efficiently design tread braking systems for both freight and passenger trains. It can handle stop braking and drag braking, as well as intermediate periods of cooling. This makes it possible to predict the temperature history for a full train route.

The new software has been utilized in commercial projects for Faiveley Transport to calculate temperatures of wheels and brake blocks of future trains in revenue traffic on new lines. Required brake power and train speed, as calculated from data on track gradients, speed limits, axle loads and stipulated brake deceleration, are used as input to the software. The results from the software have also been used to assess the required speed limitations should some components of the total brake system of a train malfunction and other components have to deliver an increased braking effort without being overloaded.

Project SP15 ran from July 2007 to December 2008 and was led by CHARMEC's Dr Tore Vernersson and Professor Roger Lundén.

Parallel special projects – Parallella specialprojekt (SP) – Parallele Sonderprojekte – Projets spéciaux parallèles

SP16. IDENTIFICATION OF DYNAMIC PROPERTIES IN TRACK OF TIMBER SLEEPERS AND CONCRETE REPLACEMENT SLEEPERS

Identifiering av dynamiska egenskaper i spår hos träsliprar och ersättningssliprar av betong

The joint initiative for project SP16 came from Abetong and Banverket (now Trafikverket), and these two parties also shared the financing on an equal basis. As from 2018, new timber sleepers impregnated with creosote will not be allowed by the European Union, and this situation together with the need for replacing single (cracked or rotten) timber sleepers in an existing track formed the background for the project.

Properties of timber sleepers in track were measured, and based on registered data and numerical simulations, a concrete replacement sleeper was designed and tested with a positive outcome. Important issues were preserved vertical stiffness and lateral stability of the track. Dr Rikard Bolmsvik of Abetong led project SP16 and Professor Jens Nielsen and Docent Elena Kabo of CHARMEC were co-workers. Master's student Nico Burgelman assisted in the project. Patent is now pending for Abetong's TCS (Tuned Concrete Sleeper). See also CHARMEC's Triennial Report for Stage 6.

From the left: Mikael Thuresson of Abetong together with Nico Burgelman, Rikard Bolmsvik and Jens Nielsen at a visit in 2009 to Abetong's sleeper plant at Vislanda (Sweden) in project SP16

SP17. SWITCH SLEEPER SPECIFICATIONS

Växelsliperspecifikationer

Concrete line sleepers for an axle load of 35 tonnes were studied in project SP12. According to plans, Banverket (now Trafikverket) would introduce specifications for sleepers in switches (turnouts) of a track where a 35 tonne axle load is being foreseen. In particular, the required bending moment capacity of these sleepers should be determined. Project SP17 was financed by Banverket. Results from measurements at Härad on Svealandsbanan in project TS7 (see CHARMEC's Triennial Report for Stage 4) and from new measurements at Eslöv on the Southern Main Line were utilized together with numerical simulations, using the codes DIFF3D and GENSYS. The work in project SP17 was co-ordinated with that in project EU10.

Dr Rikard Bolmsvik of Abetong led the project and Professor Jens Nielsen of Chalmers Applied Mechanics / CHARMEC and Dr Elias Kassa (now Professor at NTNU in Trondheim, Norway) of Manchester Metropolitan University (UK) were co-workers in project TS7. See also CHARMEC's Triennial Report for Stage 6.

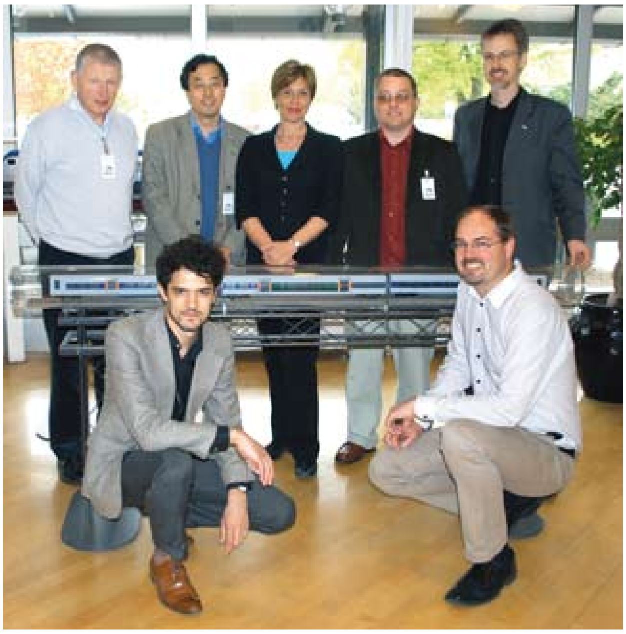
SP18. GROUND VIBRATIONS FROM RAILWAY TRAFFIC – A PRESTUDY ON THE INFLUENCE OF VEHICLE PARAMETERS

Markvibrationer från järnvägstrafik – en förstudie om inverkan av fordonsparametrar

The objective of project SP18 was to identify the most important rolling stock parameters in the process of generating and propagating ground vibrations from railways. Numerical simulations with the code SIMPACK were performed and experimental results from full-scale test runs with a Regina train were utilized. A comprehensive analysis and parametric study was also performed using the code TGV from ISVR (Institute of Sound and Vibration Research) in Southampton, UK.

The present project originated in an EU application denoted ARIV (Abatement of Railway Induced Vibrations) where Chalmers/CHARMEC and Bombardier Transportation Sweden were members of the consortium (consisting of 28 partners from 12 countries and led by Deutsche Bahn). This IP (Integrated Project) application under the Second Call within the Seventh Framework Programme was rejected. A new application under the Third Call was successful, see project EU12.

The SP18 project was led by Professor Jens Nielsen of Chalmers Applied Mechanics / CHARMEC. Co-workers were Dr Anders Frid, Ms Siv Leth, Lic Eng, and Mr Adam Mirza, MSc, all three from Bombardier Transportation Sweden, and Dr Martin Li and Mr Alexander Smekal, MSc, both from Banverket (now Trafikverket). See also CHARMEC's Triennial Reports for Stages 5 and 6.



Project SP18 meeting in May 2009 at Bombardier Transportation Sweden in Västerås: Adam Mirza (left) and Jens Nielsen in front of Siv Leth and (from the left) Alexander Smekal and Martin Li from Banverket, Chris Jones from ISVR in Southampton (UK) and Anders Frid

SP19. OPTIMUM TRACK STIFFNESS

Optimal spårstyvhet

The aim of project SP19 was to produce a specification for the selection of a suitable vertical track stiffness (optimum value and/or acceptable range of values) for a nominal track for new and upgraded lines in Sweden. Track stiffness is here defined as the ratio between the magnitude of each of a pair of static vertical (wheel) loads applied onto the two rails and the corresponding elastic rail deflection. In the optimization, wheel–rail contact forces, rolling contact fatigue (RCF), rail vibrations, normal stresses in the rails due to bending, bending moments in sleepers, deformations of fastenings, rail seat loads on sleepers and forces between sleeper and ballast were considered. RCF in the rail was calculated according to our FIERCE model, see project MU9.

Based on numerical simulations of the dynamic vehicle–track interaction using the in-house computer program DIFF, the influence of the combined subgrade/ballast bed modulus C_{sb} [(MN/m)/m^2] on wheel–rail contact forces and various track responses has been investigated considering stochastic variations of C_{sb}. Track irregularities and out-of-round wheels were accounted for by use of an extrapolated ISO 3095 spectrum with wavelengths in the 1/3 octave bands 5–400 cm (corresponding to the frequency range 25–2000 Hz at train speed 350 km/h). The vehicle model was based on the EUROFIMA vehicle with an axle load of 20 tonnes and a maximum speed of 350 km/h.

Significant dynamic contributions to track responses are generated by wheel/rail irregularities. With increasing C_{sb} the dynamic contributions to wheel–rail contact forces, to an RCF index, as well as to rail bending stresses, rail seat loads and sleeper bending moments, are increasing. The choice of an optimum level of C_{sb} becomes a compromise in order to limit all different track responses

The project was financed by Trafikverket. Professor Jens Nielsen of Chalmers Applied Mechanics/CHARMEC was project leader and Dr Martin Li from Trafikverket was co-worker. See also CHARMEC's Triennial Report for Stage 6.

SP20. CLASSIFICATION OF WHEEL DAMAGE FORMS

Klassificering av hjulskadeformer

In the development of efficient mitigation strategies for wheel damage, it is crucial that underlying causes can be tracked. In this process, a clear and detailed documentation of different observed damage forms is essential. Until now, the documentation process in Sweden has been well established and efficient when it comes to geometry deterioration. However, especially in the case of crack formation, the procedures used have been insufficient and outdated. Project SP20 was launched to improve this situation.

A survey of current reporting procedures resulted in a draft proposal that was presented and discussed during a reference group meeting of projects MU18, MU21, MU22 and MU25 on 2010-10-15. Based on the feedback, a revised version was prepared and discussed at a new meeting on 2010-12-18. Additional feedback, mainly regarding the level of detail to employ, resulted in a second revision, which was circulated among the members of a reference group from Bombardier Transportation (Germany and Sweden), Interfleet Technology and Lucchini Sweden, as well as among the members of the CHARMEC Board.

The final recommendation for the classification of wheel damage forms has been issued in both Swedish and English. All but one of the current categories in the widely used wheel damage database FORD have been kept. The new category has been assigned an entirely different code, which means that the old and the new systems can be used in parallel.

Example of observed damage on freight wheel

Docent (now Professor) Anders Ekberg of Chalmers Applied Mechanics/CHARMEC led the project and Docent Elena Kabo Chalmers Applied Mechanics/CHARMEC was co-worker. See also CHARMEC's Triennial Report for Stage 6.

SP21. OPTIMUM MATERIAL SELECTION FOR SWITCHES

Optimalt materialval för spårväxlar

Wear, accumulated plastic deformation and rolling contact fatigue (RCF) are common damage mechanisms in components of switches and crossings (S&C). An innovative methodology for the prediction of these mechanisms for a mixed traffic situation in a switch was developed in the INNOTRACK (EU10) project. It includes: (i) simulation of dynamic vehicle–track interaction considering stochastic variations in input data, (ii) simulation of wheel–rail contacts accounting for non-linear material properties and plasticity, and (iii) simulation of wear and plastic deformation in the rail during the life of the switch component.

The three different materials R350HT, MN13 and B360 have been tested at Chalmers, in the laboratory of the Department of Materials and Manufacturing Technology, for tensile strength at different temperatures and strain rates as well as low-cycle fatigue behaviour. The steels were also investigated metallurgically and metallographically, including hardness measurements and microstructural evaluations. The results from the laboratory measurements have been employed in the calibration of a non-linear material model used in the present predictions of material deterioration. A specific aim of project SP21 was to apply the simulation methodology to predict rail profile degradation in an existing crossing at Haste in Germany (on the railway line between Hanover and Hamm in Lower Saxony/Niedersachsen). The predicted degradation of the R350HT crossing was compared to field measurements after 5 and 9 weeks of mixed traffic.

The SP21 project was partially financed by Trafikverket and DB. It was led by Professors Jens Nielsen and Magnus Ekh of Chalmers Applied Mechanics. Docent Elena Kabo of Chalmers Applied Mechanics and Mr Dirk Nicklisch, Dipl-Ing from DB Systemtechnik, were co-workers. See also CHARMEC's Triennial Report for Stage 6.

SP22. IMPLEMENTING INNOTRACK RESULTS AT TRAFIKVERKET

Implementering av INNOTRACK-resultat vid Trafikverket

The EU project INNOTRACK, see our project EU10, led to a large number of implementable results, and initial analyses have indicated a potential for massive cost savings if these results were to be implemented in operational services. The current project was initiated to aid the implementation of suitable results in Sweden at Trafikverket.

A first priority list for the implementation at Trafikverket has been established and contains the following six items: Insulated joints, Wheel flats and alarm limits, Subsoil stabilization through LC piling, Switches & crossings, LCC/RAMS, and Grinding. To co-ordinate activities at the European level, an INNOTRACK Implementation Group has been formed, of which our Anders Ekberg is an active member. A three-year field study of rail joint deterioration (carried out in projects MU18 and EU10) has been reported. Conclusions from the study have played an important part in the revision of Trafikverket's regulations for insulated joints. Part of the work on switches & crossings has also been incorporated in Trafikverket's technical regulations.

Wheel flats and alarm limits are further studied in the EC funded project D-RAIL (see EU13) and the UIC funded project HRMS (see SP25). The results will add to the revision of regulations on allowed wheel flats at Trafikverket.

The SP22 project was partially financed by Trafikverket. Docent (now Professor) Anders Ekberg of Chalmers Applied Mechanics/CHARMEC was project leader and Professor Per-Olof Larsson-Kråik of LTU and Docent Elena Kabo of Chalmers Applied Mechanics/CHARMEC were co-workers. See also CHARMEC's Triennial Report for Stage 6.

Installation of inclined lime-cement (LC) columns under an existing embankment in Sweden. From INNOTRACK Concluding Technical Report

SP23. OPTIMIZED PRESTRESSED CONCRETE SLEEPER

Optimerad förspänd betongsliper

The objective of project SP23 was to discuss and quantify the different parameters and criteria that are important in the design of concrete monobloc sleepers. The output should serve as a guideline for RDSO (Research Designs & Standards Organisation under the Ministry of Railways) in India in their work to establish a revised sleeper design specification adapted to Indian railway traffic conditions. In a general sense, project SP23 aimed at rationalizing various parameters in the design methodology and manufacturing process to obtain an optimum product with prolonged life and reduced cost. In the project, international sleeper design standards were surveyed and methods for producing sleepers with a consistently high quality and low wear of the production equipment, in combination with improved ergonomic working conditions, were studied. The selection of various production sequences for stressing of wires, compacting of concrete and demoulding etc was discussed.

Sleeper optimization without the need for unreasonably conservative safety factors can be performed using a validated model for simulation of the dynamic vehicle–track interaction. The uncertainty (stochastic scatter) in the input values for each vehicle/track parameter needs to be considered. The presence of wheel/track irregularities, such as out-of-roundness, wheel flats, insulation joints and rail corrugation, may generate substantial dynamic contributions to the wheel–rail contact forces, resulting in high rail seat loads and sleeper bending moments.

The support conditions given by the track bed have a significant influence on the generated sleeper bending moments. Hence, regular and controlled maintenance of rolling stock, rails and ballast bed are prerequisites for a successful optimization of the prestressed concrete sleeper. Low rail pad stiffness leads to a reduction of sleeper bending moments. A sleeper design with a narrow central cross-section reduces the sleeper bending moment at the centre.

The existing Indian sleeper design was evaluated in relation to the rail seat bending moment prescribed by the European sleeper standard. It was shown that the capacity of the current Indian sleeper design is well above the bending requirements given in Europe for the same loading case. Recommendations on the production process to meet the demands on quality and durability according to capacity requirements set in the specification and sleeper standard are given in a report delivered to RDSO. Material selection and parameters to obtain good adhesion properties between wires and concrete are discussed and explained.

The proposed guidelines for optimization of design and production of prestressed concrete railway sleepers were presented at a meeting with Ajay Singhal and S K Awasthi of RDSO and Alok Mishra of India Ministry of Railways in Växjö, Sweden, on 25-26 July 2011. The results were also presented by the SP23 project leaders at the seminar "Optimizing Rail Track Investment & Maintenance" in Seoul (South Korea) on 21-22 November 2012, which was organized by UIC and Korea Railroad Research Institute. The seminar also included a presentation of the INNOTRACK project by Björn Paulsson and Laurent Schmitt from UIC and of research from Korea and Japan. A visit to a sleeper plant near Seoul, which is operated by one of Abetong's licensees, was organized.

The project SP23 was financed by UIC. Dr Rikard Bolmsvik of Abetong and Professor Jens Nielsen of Chalmers Applied Mechanics/CHARMEC were project leaders. See also CHARMEC's Triennial Report for Stage 6.

Meeting in July 2011 at Abetong's head office in Växjö. From the left: S K Awasthi, Jens Nielsen, Rikard Bolmsvik, Ajay Singhal, Stefan Svenningsson (Global Sales Director Abetong), Alok Mishra and Ulf Malmqvist (General Manager Abetong Infrastructure)

SP24. DERAILMENT RISKS IN SWITCHES

Urspårningsrisker i växlar

Trafikverket initiated project SP24 and it was to be financed by UIC. Plans and contract were proposed during autumn 2011 with the project divided into three stages: (i) building of a track switch model, (ii) simulations of freight trains, and (iii) simulations of passenger trains. Part of the work in the first stage was carried out during December 2011. The contract with UIC was not signed and therefore the activities were terminated. However, parts of the work that was planned for SP24 have been carried out in project EU13 (D-RAIL).

SP25. HARMONIZED MEASUREMENT SITES FOR TRACK FORCES

Standardiserade mätplatser för spårkrafter

Project leader	Professor Anders Ekberg, Applied Mechanics / Division of Dynamics
Co-workers	Docent Elena Kabo and Professor Jens Nielsen, Applied Mechanics
Period	2012-01-01 – 2014-12-31
Chalmers budget (excluding university basic resources)	Stage 6: KSEK 140 Stage 7: KSEK 446

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

The UIC project HRMS (Harmonization – running behaviour and noise measurement sites) had the objective to develop a methodology to identify safety and/or commercial risks in the running behaviour of vehicles. The project contained four work packages: WP1 Categorization of sites (which was built on the previous UIC project "Axle load checkpoints to categorize measurement sites"), WP2 Harmonization of assessment quantities and of limit values (where the focus was on creating a framework for establishing limit values of vertical wheel–rail contact forces), WP3 Noise measurements (with focus on increasing the reproducibility of noise measurements), and WP4 Standardized output for data transfer and vehicle identification.

Active partners in the project were SBB of Switzerland, ÖBB of Austria, Network Rail of UK, Trafikverket of Sweden, Infrabel of Belgium, CC Infra and Vilant of Finland, and SNCF and Inexia of France. Chalmers was the only university involved in the project and was responsible for WP2.

The work on rail breaks in HRMS set out from findings in project INNOTRACK (EU10) and in the UIC project ALC (Axle Load Checkpoints). Results from INNOTRACK were distilled to extract limit values for a "bad case" scenario (a severe, but reasonable condition in terms of load characteristics, support conditions etc). In the WP2 work on a technical and scientific basis for alarm limit values (related to the risk of rail breaks), the number of influencing parameters was reduced to only two: deviation from neutral temperature and magnitude of wheel load. The study indicated which crack sizes (in rail head and rail foot) that need to be detected and removed if rail breaks are to be avoided below defined (alarm) load magnitudes. The influence of hanging sleepers on rail breaks has been given detailed consideration. Further, a compilation has been made of additional phenomena that could/should be considered to extend the scope of the alarm limits such as a framework to deal with general overloading of vehicles.

The work on derailment due to flange climbing was carried out in parallel to the work in D-RAIL (EU13). Here the most important parameters were identified and a "bad case" scenario in terms of vehicle and track characteristics was defined. Through simulations, limit states of load imbalance that resulted in derailment were identified and suitable characteristics to quantify the load imbalance were derived. The result from WP2 is a simple criterion for allowed wheel load limit values (and related critical sizes of rail head and foot cracks). Further, high precision limit values for unbalanced loading (including a criterion for twisted frames) have been derived.

Noise monitoring systems currently operating in Europe have been surveyed and evaluated in terms of capability and compliance with respect to normative requirements (ISO3095:2013). For all existing monitoring sites, the track consists of UIC60 rails on monobloc concrete sleepers on a ballasted track bed. The rail pad vertical dynamic stiffness is relatively high on all sites (from 700 to 1000 kN/mm). This situation seems favourable since tracks with stiff rail pads contribute less to the total noise than do tracks with soft rail pads, meaning that the contribution of wheel noise to the total pass-by noise is more significant. A statistical analysis of noise levels measured at the Deutsch-Wagram

SP25. (cont'd)

monitoring station in Austria (rail pad stiffness 700 kN/mm) has been performed. Pass-by noise levels were rather insensitive to temperature variations; the maximum deviation in average noise level was 1 dB when the temperature increased from below 0°C to above 20°C. However, the influence of snow on the pass-by level is significant and depends on snow depth.

A numerical parameter study on the influence of ground surface conditions (acoustic impedance and ground surface level relative to top of rail), temperature and rail roughness on noise level at the microphone has been performed using the software TWINS. The sound pressure level is higher when the surface is reflective and grass/soil is preferred over concrete or asphalt. For ground surfaces with low sound reflection, the influence of ground surface vertical level (when varying from 0.2 to 2.0 m) on pass-by noise level is in the order of 1 dB. Rails should be maintained not to exceed the ISO3095 roughness limit spectrum to ensure that the monitoring system is sensitive to variations in wheel roughness level. Monitoring stations with soft rail pads are significantly affected by the influence of temperature on track decay rates and track related noise, meaning that a correction procedure for measured noise levels will be required. The final report (see below) has been distributed to the UIC Track expert and Train–track interaction groups.

HRMS: Harmonization – Running behaviour and noise on measurement sites, UIC, 2014, 153 pp. Chalmers/CHARMEC responsible for Section 3.2 "Categorization of measurement sites – limit values, assessment concepts" and partly responsible for Section 3.3 "Reproducibility of noise measurements"

SP26. HOLISTIC OPTIMIZATION OF TRACKS

Holistiskt optimerade spår

Project leader	Professor Jens Nielsen, Applied Mechanics / Division of Dynamics
Co-workers	Dr Eric Berggren, EBER Dynamics, Dr Rikard Bolmsvik, Abetong, and Mr Anders Hammar, Trafikverket
Period	2013-11-01 – 2017-11-01
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 1 209 Stage 8: kSEK 656

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

Dr Eric Berggren of EBER Dynamics in project SP26

The environmental impact of railways should be reduced and timber sleepers impregnated with creosote be replaced by concrete sleepers to reduce the emission of chemical products in the soil. Concrete sleepers should be optimized to minimize material consumption and cost. A key issue is to construct, maintain and assure 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 aims to reduce the life cycle cost and 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, (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, and (iii) a procedure for proactive track maintenance (methods and intervals) to improve track geometry. The new knowledge will be obtained through measurement and prediction of sleeper–ballast contact pressure and subsequent track geometry degradation.

Four test sites have been selected for monitoring of track geometry degradation and assessment of track maintenance. 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. Two sites are located on Malmbanan (the Iron Ore Line), one on the Southern Main Line near Linköping and one on the West Coast Line near Halmstad.

SP26. (cont'd)

Here geometry measurements are available from 1997 until present. Modelling of track geometry degradation has been initiated in the related CHARMEC project TS15.

Based on track recording car measurements from 1997 to 2014, standard deviations of longitudinal level and mean-to-peak values of isolated defects have been evaluated for a section on the northern route of Malmbanan. Track stiffness measured on the same section has also been assessed. A model for simulation of dynamic interaction between an iron ore wagon and a track with sudden transitions in support stiffness has been developed in DIFF. The company EBER Dynamics is developing a new method for track stiffness measurement where the influences of wheel–rail contact geometry and track deflection before and after the loaded measurement wheelset are considered. For an assessment and calibration of the method for processing of measured stiffnesses, track deflections for various non-linear support conditions have been calculated in DIFF. A method for illustration of the time history of track geometry parameters (standard deviation and mean-to-peak value) along a given track section has been proposed. Clear linear trends of track geometry degradation between track interventions (tamping/track renewal) for a section on the northern route of Malmbanan have been identified. Sudden transitions in track stiffness due to local variations in substructure properties or track infrastructure may lead to severe differential track settlement. The project description submitted to VINNOVA is dated 2013-06-25.

Jens Nielsen, Eric Berggren, Rikard Bolmsvik, Anders Hammar and Thomas Axelsson: Track geometry degradation and optimisation of sleeper support conditions on the Swedish iron ore line, *Proceedings Railway Engineering 2015*, Edinburgh (UK) June – July 2015, 12 pp (available on CD)

SP27. OPTIMIZED PRESTRESSED CONCRETE SLEEPER – PHASE II

Optimerad förspänd betongsliper – steg II

Project leader	Dr Rikard Bolmsvik, Abetong
Co-worker	Professor Jens Nielsen, Applied Mechanics
Period	2014-01-01 – 2014-12-31
Chalmers budget (excluding university basic resources)	Stage 7: kSEK 248

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

The objective of project SP27 was to continue the work for the Indian Railways that was carried out and reported in project SP23. Different parameters and criteria important in the design of concrete monobloc sleepers have been discussed and quantified. The output will serve as a guideline for RDSO (Research Designs & Standards Organisation under the Ministry of Railways in India) in their work to establish a revised sleeper design specification adapted to Indian railway traffic conditions.

For freight and passenger traffic, CHARMEC's in-house code DIFF has been used to investigate the influence of vehicle speed, sleeper design, rail pad stiffness and ballast support conditions on rail seat load and sleeper bending moments. Wheel/rail irregularities such as wheel flats and rail corrugation have been considered. A large set of simulations resulting in maxima of rail seat loads and sleeper bending moments generated by two types of traffic (freight train with axle load 25 tonnes and passenger train at speed 250 km/h) have been performed. It was concluded that a principle sleeper geometry design according to sleeper A22 (developed by Abetong) in combination with a resilient rail pad, is a good basis for an optimized sleeper design. Such a sleeper/rail pad combination provides loading conditions that increase the robustness of the sleeper, accounting for wheel and rail irregularities and poor ballast conditions including the case with a ballast shoulder at centre.

The defined values for the sleeper capacity requirements should be related to the worst scenario of vehicle/track irregularities and sleeper support conditions accepted by the infrastructure owner. Important prerequisites for sleeper optimization are the application of wheel removal alarm limits and proper preventive maintenance of rolling stock and track in order to reduce the scatter of the in-situ sleeper load environment.

The reference group for project SP27 had members from Abetong and RDSO. The project description appended to the contract with UIC was signed on 2013-11-26.

Rikard Bolmsvik and Jens Nielsen: Optimization of railway concrete sleeper design, Research Report 2014:07, *Chalmers Applied Mechanics*, Gothenburg 2014, 97 pp

ACADEMIC AWARDS

(up to June 2015)

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

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

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

Adjunct Professor

Jens Nielsen	2006-07-01

Licentiate theses and doctoral dissertations submitted by CHARMEC researchers during Stage 7

INTERNATIONAL CONFERENCES

During Stage 7 (and the months immediately following Stage 7) researchers from CHARMEC have participated in, and contributed to, the following major seminars, workshops, symposia, conferences and congresses:

The 19th International EUROMA Annual Conference in Amsterdam (The Netherlands) 1–5 July 2012

The 21st International Symposium on Mathematical Programming (ISMP 2012) in Berlin (Germany) 19–24 August 2012

The 9th International Conference of Contact Mechanics and Wear of Rail/Wheel Systems (CM2012) in Chengdu (China) 27–30 August 2012

The 25th International Conference on Noise and Vibration Engineering (ISMA2012) in Leuven (Belgium) 17–19 September 2012

The 17th Nordic Seminar in Railway Technology in Tammsvik (Sweden) 3–4 October 2012

The 10th International Heavy Haul Conference (IHHA 2013) conference in New Delhi (India) 4–6 February 2013

The 31st Conference & Exposition on Structural Dynamics (IMAC XXXI) in Garden Grove CA (USA) 11–14 February 2013

The 11th International Conference on Structural Safety & Reliability (ICOSSAR 2013) in New York NY (USA) 16–20 June 2013

The 6th ECCOMAS Thematic Conference on Multibody Dynamics in Zagreb (Croatia) 1–4 July 2013

The ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2013) in Portland OR (USA) 4–7 August 2013

The 23rd International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2013) in Qingdao (China) 19–23 August 2013

The 20th International Conference on Computer Methods in Mechanics (CMM2013) in Poznan (Poland) 27–31 August 2013

The 7th International Conference on Low Cycle Fatigue (LCF7) in Aachen (Germany) 9–11 September 2013

The 11th International Workshop on Railway Noise (IWRN11) in Uddevalla (Sweden) 9–13 September 2013

The 17th International Wheelset Congress (IWC17) in Kiev (Ukraine) 22–27 September 2013

The 3rd Braking Technology Conference and Exhibition (EuroBrake 2014) in Lille (France) 13–15 May 2014

The 24th International Symposium on Algorithms and Computation (ISAAC2013) in Hong Kong 16–18 December 2013

The 32nd Conference & Exposition on Structural Dynamics (IMAC XXXII) in Orlando FL (USA) 3–6 February 2014

The 11th International Fatigue Congress (IFC11) in Melbourne (Australia) 2–7 March 2014

The 2nd International Conference on Railway Technology: Research, Development and Maintenance (Railways 2014) in Ajaccio / Corsica (France) 8–11 April 2014

The 2nd International Symposium of Fatigue Design and Material Defects (FDMD2) in Paris (France) 11–13 June 2014

The 5th International Conference on Thermal Process Modelling and Computer Simulation (ICTPMCS5) in Orlando FL (USA) 16–18 June 2014

The 11th International Heavy Haul Association Conference (IHHA 2015) in Perth (Australia) 21–24 June 2015

The 35th Risø International Symposium on Materials Science in Risø/Roskilde (Denmark) 1–5 September 2014

The International Conference on Operations Research 2014 in Aachen (Germany) 2–5 September 2014

The 26th International Conference on Noise and Vibration Engineering (ISMA2014) in Leuven (Belgium) 15–17 September 2014

The 18th Nordic Seminar on Railway Technology in Bergen (Norway) 14–15 October 2014

The 27th Nordic Seminar on Computational Mechanics (NSCM-27) in Stockholm 22–24 October 2014

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

The 24th International Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD2015) 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

PARTNERS IN INDUSTRY

The status report that follows applies as of May 2016. 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.

Bombardier Transportation Sweden AB (2000)
Bombardier Transportation is a global manufacturer of equipment for railway operations, and a maintenance and service provider for rolling stock. The company's range of products includes passenger coaches, total transit systems, locomotives, freight cars, propulsion systems, and rail control solutions. The total number of employees is about 38 000, of whom 2 000 work in Sweden. The Swedish office in Västerås is one of the main engineering hubs for the company's Propulsion and Control Business Unit. Also located on this site are the global Bombardier Centres of Competence for Acoustics & Vibration, Vehicle Dynamics, EcoDesign, Fire Safety and Electro Magnetic Compatibility. The company's main area of interest in relation to CHARMEC is the effect of wheel–rail interaction on ride dynamics, wheel wear, wheel damage, and rolling noise. Other areas of interest include the transmission of wheel/rail-generated vibrations into the bogie and car body, the identification of contact forces, and the application of active control systems for enhanced comfort. The company also wants to increase its understanding of how the requirements for low levels of ground vibrations and external noise can be met.

Faiveley Transport Nordic AB (1997)
Faiveley Transport is one of the world's largest railway equipment suppliers with headquarters in Paris and production units in Sweden, Germany, France, Italy, the UK and several other countries. The total number of employees is around 5700, of whom 175 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 AB (2000)
This government-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 covered approximately 21 000 million gross tonne-kilometre in 2014. 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.

Interfleet Technology AB / SNC-Lavalin Rail & Transit AB (1995 and 1992)
Founded in 1911, and with offices in over 50 countries, SNC-Lavalin is one of the leading engineering and construction groups in the world and a major player in the ownership of infrastructure. SNC-Lavalin has approximately 37 000 employees. In Sweden the company is based in Stockholm/Alvik, Göteborg, Malmö, Helsingborg, Västerås, Ånge and Luleå and employs 160 people, The turnover is here about MSEK 200. 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.

Lucchini Sweden AB (1995 and 1987)
Lucchini Sweden is a railway wheelset manufacturer in Surahammar with 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 AB is a government enterprise based in Stockholm. The company's main activities are travel services under its own name, and contract rail services for regional and national transport authorities, with almost 100 000 passengers per day in total. The SJ group has around 4 200 employees, of which on-train staff and train drivers are the largest groups. Investments in 2015 amounted to MSEK 525. Current projects include extension of the technical life of the X2000 fleet by technical upgrades and interior and exterior refurbishment. 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.

AB Storstockholms Lokaltrafik / SLL Trafikförvaltningen (2003)
Stockholm Public Transport (SL) was the organization running all of the land based public transport systems in Stockholm County. From 2012 the responsibility was taken over by the Public Transport Section of Stockholm County Council (Stockholms Län). Within the Greater Stockholm Area railway network, the system caters for around 2.7 million passenger trips every day. On an ordinary weekday, approximately 800 000 people use SL services. Research areas of principal interest to SL are vibrations and noise, track and vehicle maintenance, and materials. Of particular interest are the wear and dynamics of switches (turnouts), and structure-borne noise and material fatigue problems. However, SLL has decided not to continue in CHARMEC's Stage 8.

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 17 locations in Sweden and Norway with a total of about 280 employees. The annual turnover is around MSEK 410 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 10 000 wagons with close to 30 000 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 programs.

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 6 400 employees. Trafikverket's areas of interest 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 1 1600 employees worldwide. For the financial year 1 April 2014 – 31 March 2015, the sales of the voestalpine Group (including all four divisions) amounted to MEUR 11 200. 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.

ÅF Infrastructure AB (2014)
ÅF is an engineering and consulting company with assignments in the energy, industrial and infrastructure sectors. The company has about 8000 employees and offices in more than 30 countries. The infrastructure branch of ÅF constitutes about one third of the company. ÅF Infrastructure AB became a partner in CHARMEC from 1 January 2014. However, the company has decided not to continue in Stage 8 of the centre.

RESULTS AND EFFECTS IN INDUSTRY

In May 2016, Trafikverket and our partners in the Industrial Interests Group for Stage 7, and continuing as partners also in Stage 8, 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 Sweden

CHARMEC's wheelset research projects dealing with rolling contact fatigue, damage and cracks have been essential for our understanding of the behaviour of wheels in revenue traffic. The company initiated a CHARMEC project on wheels and rails for train speeds of 250 km/h under Swedish conditions, with mixed traffic and a harsh climate. CHARMEC's work with railway noise is also important for the development of quieter trains. Our ambition to improve the vibrational and acoustic behaviour of trains is reflected in the fact that Bombardier has initiated new CHARMEC projects in this area. Bombardier's involvement in the project looking at multiobjective optimization of vehicle dynamics properties and active technology fits in with the company's objective to find even better and more cost-efficient solutions for vehicle dynamics design. We believe that the results will lead to the development of new systems and components for bogies and car bodies.

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.

Interfleet Technology / SNC-Lavalin Rail & Transit

CHARMEC has given Interfleet Technology (now 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. Interfleet Technology has employed a PhD from CHARMEC, and we see a potential for recruiting more PhDs from CHARMEC. Interfleet appreciates the valuable contact network that CHARMEC brings.

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 and 32.5 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 Stage 7, SJ increased its participation in CHARMEC projects and reference groups.

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 INNOTRACK project of the EU Sixth Framework Programme 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 8 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 new 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 and 7, 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. These studies will continue in detail in Stage 8. For VAE, the co-operation with CHARMEC has led to a better theoretical understanding of forces, stresses and material behaviour inside a turnout. Different crossing nose materials were investigated. The research of the past now allows a full combination of several models and methods to calculate the life of a turnout providing VAE with advantages in terms of design and material development.

TORE DAHLBERG 1945–2016

CHARMEC's former co-worker Tore Dahlberg died in February 2016. At Chalmers University of Technology, he took his Master of Science in Mechanical Engineering in 1970 and, after two years of voluntary work in Africa, returned to earn his doctoral degree in Solid Mechanics (Swedish: hållfasthetslära) in 1979.

In 1997 Tore Dahlberg moved to Linköping Institute of Technology where he was appointed Professor. His work for CHARMEC concerned track dynamics in both Swedish and European projects. Tore Dahlberg wrote several textbooks and published some 25 scientific papers in international journals.

SPECIAL EVENTS AND ACHIEVEMENTS

Board meetings relocated

Six of the twelve meetings of the CHARMEC Board during Stage 7 were combined with visits to organizations outside Chalmers: to Bombardier Transportation Sweden AB in Västerås on 29 November 2012; to Interfleet Technology AB in Stockholm/Solna on 25 April 2013; to Trafikverket in Stockholm/Solna on 25 November 2013; to SJ AB in Stockholm on 7 May 2014; to ÅF-Industry AB in Gothenburg on 26 November 2014, and to Lucchini Sweden AB in Surahammar on 3 June 2015.

Leaving members

With due acknowledgement from CHARMEC, long-time Board members Henrik Tengstrand of Adtranz Sweden / Bombardier Transportation Sweden (2000-2012), Håkan Anderson of voestalpine Bahnsysteme (2003-2013), Marcin Tubylewicz of Green Cargo (2008-2013), Hugo von Bahr of SJ / Interfleet Technology (1995-2014) and Hans Andersson of SP Technical Research Institute of Sweden and Chalmers University (1995-2015) left the Board during Stage 7. Earlier, Evert Andersson of KTH Railway Group (1995-1999), Stefan Östlund of KTH (1999-2009), Stefan Westberg of Abetong (1995-2008), Lennart Nordhall of Adtranz Wheelset / Lucchini Sweden (1995-2009) and Björn Paulsson of Banverket / Trafikverket (1995-2008) were among those who have left. At the start of Stage 8 on 1 July 2015, none of the Board members from the start of CHARMEC in 1995 remained.

VINNOVA

In 2013, VINNOVA (Sweden's Innovation Agency) published a report on the long-term industrial impacts of the Swedish Competence Centres based on interviews made by the Technopolis Group in the UK. It was concluded that "between 1995 and 2011, CHARMEC has altogether strongly contributed to an economic impact for society and industry that can be estimated to between 1035 and 1430 MSEK per year. During those 17 years, CHARMEC received around 230 MSEK in cash and 120 MSEK in kind contributions from governmental funders, the host university and industry".

During Stage 7, VINNOVA supported the CHARMEC projects EU13 and SP26, see pages 93 and 108, and also the associated project AP4, see below.

On the initiative of JVTC in Luleå (see below), a project to create what is known as a VINNOVA SIO agenda (Strategic Innovation Area) with the title "Robust and reliable transportation systems" was run during 2015. Several organizations contributed, including CHARMEC through Roger Lundén, to workshops led by JVTC. The SIO agenda is now published on VINNOVA's homepage (www.vinnova.se). A SIO agenda may become a VINNOVA-funded programme.

Family Ekman's Research Donation

During Stages 5, 6 and 7, funds from this donation to Chalmers University have financed projects SD6 and SD9, respectively.

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.

Trafikverket's Research and Innovation Seminars

Trafikverket annually organizes a Research and Innovation Seminar to discuss research strategies and co-operation with the research communities etc. Chalmers/CHARMEC regularly attends and contributes to these seminars.

Tomorrow´s depots for maintenance of railway vehicles

Trafikverket launched a project to create a 'road map' for developing of future maintenance depots for railway vehicles. It ran during 2013 and 2014 with participants from Chalmers/CHARMEC, KTH, University of Gothenburg and the consultancy Transrail. Members from Chalmers/CHARMEC were Ann-Brith Strömberg, Michael Patriksson, Anders Ekberg and Roger Lundén. The project was completed in 2015.

High-speed tracks in Sweden

Trafikverket is now planning sections of the future high-speed rail tracks in Sweden. Chalmers/CHARMEC has participated in several meetings with Trafikverket and other organizations to find optimal track solutions that take Swedish conditions into consideration.

Denmark, Finland and Norway

Several meetings between CHARMEC and research establishments, government agencies and private companies in our Nordic neighbour countries took place during Stage 7.

Areas of Advance

Chalmers University has profiled its research activities around eight Areas of Advance (Swedish: Styrkeområden). Two of these areas related to CHARMEC are Materials Science, in which CHARMEC provides applications that in many aspects are extreme, and Transport, in which railway mechanics issues are crucial for a competitive railway transport system. We participated in seminars arranged by the two areas. During Stage 7, CHARMEC received financial support from the two areas Energy and Materials. CHARMEC researchers also received financial support from the area Transport during Stages 6 and 7.

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. Collaboration also takes place between research groups at KTH and Chalmers, for example in projects MU31 and SD9.

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.

RTRI

Contracts between CHARMEC and the Railway Technical Research Institute (RTRI) in Tokyo (Japan) were agreed in 2011 and 2012 and involve a researcher exchange. Guests to CHARMEC from RTRI were Dr Motohide Matsui (19 February 2012 – 28 March 2013), Dr Kazuyuki Handa (7 April – 25 June 2013), Dr Hideyuki Takai and Dr Chikara Hirai (21 May 2013) and Dr Motohide Matsui and Mr Yoshikazu Kanematsu (4 February 2014). Mr Yukihiko Kimura from Nippon Steel & Sumitomo Metal Corporation visited CHARMEC on 20 October 2014.

Professor Roger Lundén's was in residence as a researcher at RTRI during the period 13 March – 12 April 2014. RTRI then invited CHARMEC to a symposium in Tokyo on 24 March 2014 where Anders Ekberg, Roger Lundén and Jens Nielsen were among the lecturers. About 40 people participated from RTRI, East Japan Railway Company, Ibaraki University and Nippon Koei.

Ministry of Enterprise and Innovation (MEEC)

In 2013 the Swedish Ministry of Enterprise and Innovation (Näringsdepartementet) signed an agreement on co-operation with Japan's Ministry of Land, Infrastructure, Tourism and Transport (MLIT) regarding high-speed rail transport. The aim is to share information on politics, laws and regulations, organization and planning of the railway sector in Sweden and Japan and to exchange experiences and technologies in specific areas of common interest. Delegations

From the left: Dr Kazuyuki Handa, (Researcher at Division of Friction Materials, RTRI), Professor Roger Lundén, Dr Norimichi Kumagai (RTRI President) and Dr Toru Miyauchi (Head of Division of Friction Materials, RTRI). Photo taken during Roger Lundén´s stay at RTRI in Tokyo in April 2014 from MEEC, Trafikverket and other organizations visited Japan in April 2014 and May 2015 for meetings and study visits. Roger Lundén participated in parts of the 2014 visit and gave a presentation on CHARMEC's research. He also took part in a study tour that involved travelling from Tokyo to Aomori (ca 700 km) on the high-speed train Hayabusa (Eagle) with visits to construction sites for high-speed lines and with demonstration of how snow is dealt with.

Also, the Ministry of Enterprise and Innovation has organized seminars for the railway sector in which people from CHARMEC participated.

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 to be included 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. Updated instructions for the semi-annual reports were issued by Anders Ekberg in September 2013. 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 its meetings 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 PRGs have been continuously updated since 2001.

Doctoral examinations

CHARMEC's eleven doctoral examinations that took place during Stage 7 are listed on page 110. So far during Stage 8, Sadegh Rahrovani in project TS14 defended his dissertation on 18 March 2016, see page 23, and Milad Mousavi in project SD9 plans to defend his in September 2016.

Implementation of research results

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

Assistant Professors

During Stage 7, Dr Astrid Pieringer, Dr Peter Torstensson and Dr Björn Pålsson were engaged as Assistant Professors (Swedish: forskarassistent) at CHARMEC. They are active in projects VB12, TS16 and TS18, respectively, and now employed for four years.

Guest researchers

Dr Sakdirat Kaewunruen from RailCorp in Sydney (Australia) visited CHARMEC on 9-27 September 2013. Professor Paul Meehan from the Department of Mechanical Engineering & Mining at the University of Queensland in Brisbane (Australia) visited us on 11-18 June 2015. He stayed for a longer period in 2005, see the Triennial Report July 2003 – June 2006. From March to July 2015, PhD student Juan Giner Navarro from the Polytechnic University of Valencia (Spain) stayed at CHARMEC, see also project TS16.

Exchange with voestalpine

voestalpine
ONE STEP AHEAD.

As previously, meetings between CHARMEC researchers and their Austrian colleagues at rail manufacturer voestalpine Schienen (VAS) in Leoben and switch manufacturer voestalpine VAE in Zeltweg were held twice a year during Stage 7. Experts were invited to these two-day meetings from the Austrian Academy of Sciences (Erich Schmidt Institute of Materials Science) and the Materials Centre Leoben, which are both linked to the University of Leoben. From 2009 people from the Competence Centre Virtuelles Fahrzeug (ViF) in Graz and from 2014 people from the Austrian Centre of Competence for Tribology (AC^{2}T) in Wiener Neustadt have also taken part. The meetings dur-

The 26th workshop with VAS, VAE, MCL and ViF from Austria was held on 7-8 June 2016 at Chalmers/CHARMEC. The island Hyppeln in the Northern Archipelago of Gothenburg was visited during the evening event on 7 June. From the left: ***Julian Wiedorn*** (MCL); ***Christof Bernsteiner*** (ViF); ***Björn Pålsson*** (CHARMEC); ***Christer Persson*** (CHARMEC); ***David Künstner*** (VAS); ***Hans Peter Brantner*** (VAS); ***Stephan Scheriau*** (VAS); ***Roger Lundén*** (CHARMEC); ***Werner Daves*** (MCL); ***Christoph Kammerhofer*** (VAS); ***Robin Andersson*** (CHARMEC); ***Johan Ahlström*** (CHARMEC); ***Peter Torstensson*** (CHARMEC); ***Uwe Ossberger*** (VAE); ***Casey Jessop*** (CHARMEC); ***Magnus Ekh*** (CHARMEC); ***Knut Andreas Meyer*** (CHARMEC); ***Rostyslav Skrypnyk*** (CHARMEC); ***Jens Nielsen*** (CHARMEC); ***Dimitrios Nikas*** (CHARMEC); ***Erik Stocker*** (VAE); ***Dimosthenis Floros*** (CHARMEC). Photo by Anders Ekberg

ing Stage 7 were held on 14-15 January 2013 in Leoben and Zeltweg, 27-28 May 2013 in Gothenburg, 13-14 January 2014 in Leoben and Zeltweg, 2-3 June 2014 in Gothenburg, 12-13 January 2015 in Leoben and Zeltweg, and 8-9 June 2015 in Gothenburg. New workshops were held on 18-19 January 2016 in Leoben and Zeltweg and 7-8 June 2016 in Gothenburg, see photo above.

ViF contract

A contract on co-operation between CHARMEC and ViF, see above, for 2013-2017 has been signed.

Abetong's testing of TCS

In co-operation with CHARMEC, see project SP16 on page 102, Abetong has developed a Tuned Concrete Sleeper (TCS) for spotwise replacement of timber sleepers. In September-October 2013, 1500 TCS were randomly installed and then continuously and successfully tested on both tangent and curved track at Silverdalen close to Hultsfred (Sweden). Trafikverket annually buys about 200 000 timber sleepers.

Part of Abetong's TCS test track at Hultsfred, Sweden

SPECIAL EVENTS … (cont'd)

Abetong's licensee meeting

CHARMEC's Anders Ekberg contributed to Abetong's international licensee meeting in Stockholm on 3-6 June 2014 with the lecture "CHARMEC – an overview of national and international research initiatives".

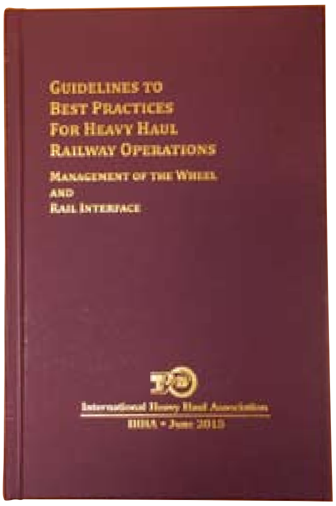
Bombardier Transportation meetings

In Siegen (Germany) on 10-11 October 2014, Anders Ekberg took part in "Opening ceremony of Bogie Technical Center" and "3rd FLEXX Bogie Operator Forum". CHARMEC has since long appreciated the commitment demonstrated by this Technical Center to our research projects, in particular the visits to CHARMEC by their senior product engineer Roger Deuce.

LKAB and Heavy Haul

Researchers from CHARMEC have assisted 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 included clarification of the reasons behind the damage and measures to manage 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.

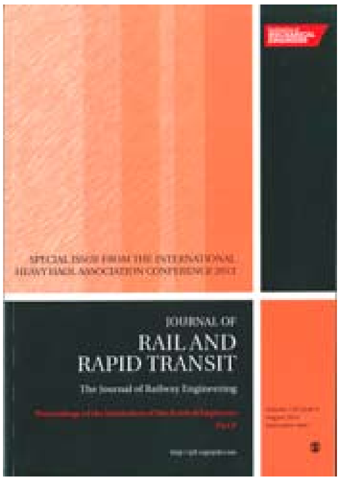
CHARMEC is a member of the local organization Nordic Heavy Haul (NHH), which in turn is a member of the International Heavy Haul Association (IHHA). IHHA organizes the International Heavy Haul Conference (IHHC) in which CHARMEC takes part.



In 2015 IHHA published the book "Guidelines to Best Practices for Heavy Haul Railway Operations: Management of the Wheel and Rail Interface". CHARMEC's Anders Ekberg, Elena Kabo, Roger Lundén, Jens Nielsen and Johan Ahlström contributed with parts of Chapter 4 on Wheel and rail materials and Chapter 5 on Wheel and rail damage mechanisms

Editorial Board of JRRT

Since 2005, Roger Lundén has been a member of the Editorial Board of the IMechE Journal of Rail and Rapid Transit. Several research results in railway mechanics from Chalmers/CHARMEC have been published in JRRT (close to 60 articles up to September 2015). IMechE stands for the Institution of Mechanical Engineers. The Editorial Board meetings of JRRT take place at the IMechE premises on Birdcage Walk in Westminster, London (UK). A Special Issue of the journal (August 2014) contains 14 papers from the IHHA Conference in 2013 with Roger Lundén being one of four Guest Editors.



Editorial Board of FFEMS

Since 2004, Roger Lundén has been a member of the Editorial Board of the international scientific journal Fatigue & Fracture of Engineering Materials & Structures (FFEMS). Several articles by CHARMEC researchers have been published in FFEMS.

Contact mechanics and Thermal stresses

A renewed graduate course on contact mechanics was given at Chalmers during Stage 7 by Professor Roger Lundén and Professor Magnus Ekh, with nine of CHARMEC's doctoral students attending. The two parts of the course were "Engineering contact mechanics" (Lundén) and "Computational contact mechanics" (Ekh). With four participants from CHARMEC, a new graduate course on thermal stresses was given by Roger Lundén and Dr Tore Vernersson during Stage 7. In the spring of 2016, the contact mechanics course was repeated with six new doctoral students attending.

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". The 31st NBIU took place in September 2015 with Jens Nielsen taking part for the 19th 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 project planning engineer in the railway sector. The programme was initiated by Banverket (now Trafikverket), falls under the Swedish National Agency for Higher Vocational Education and is organized by Folkuniversitetet. Roger Lundén serves on the advisory board, which met eight times during Stage 7.

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 (Faculty of Engineering at Lund University on 12-14 June 2013, and Linköping Institute of Technology on 10-12 June 2015). 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.

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 it has been known as the UNIFE Railway Wheels Committee. UNIFE (Union des Industries Ferroviaires Européennes) is the Union of European Railway Industries.

The aim of ERWA is to contribute to "improvements in wheels and wheelsets by focusing on safety, reliability and economic efficiency". The association's activities include "the definition, adaptation and implementation of advanced technology". During Stage 7, Roger Lundén continued to serve on ERWA's Technical Committee and took part in several meetings, most of which were held at UNIFE in Brussels (Belgium). The 13th Annual Meeting of ERWA on 20-22 May 2013 was hosted by Lucchini Sweden in Stockholm, the 14th meeting on 26-28 May 2014 by Gutehoffnungshütte Radsatz in Essen (Germany), the 15th meeting on 18-20 May 2015 by Bonatrans in Ostrava (Czech Republic) and the 16th meeting on 23-24 May 2016 by Lucchini Unipart Rail in Oxford (UK).

ERWA has assumed overall responsibility for the International Wheelset Congresses (IWC). At the 17th IWC in Kiev (Ukraine) on 22-27 September 2013, three researchers from CHARMEC took part. The IWC18 will be held in Chengdu (China) on 24-27 October 2016.

Swedtrain

Staff from CHARMEC take part in the meetings of Swedtrain, the Swedish Society of Railway Industries chaired by Klas Wåhlberg, CEO of Bombardier Transportation Sweden. Swedtrain's Research and Development Group has members from Bombardier Transportation, CHARMEC, Interfleet Technology, KTH Railway Group and JVTC at Luleå University of Technology.

The Master's students Helena Almegius, Jonatan Berg, Alexander Kärkkäinen and Susanna Lindberg from the EU13 project received the 2013 Swedtrain award for Best Master's Thesis. A corresponding prize in 2014 was won by Karl Bäckstedt, Erik Karlsson, Philip Molander and Mikael Persson from the MU22 project.

Swedtrain has a committee contributing to the network Forum for Transport Innovation (www.transportinnovation.se). CHARMEC's Anders Ekberg is active in the committee, which has delivered two road map proposals regarding railway research.

VTI

Staff from CHARMEC have taken part in the annual meetings arranged by VTI, the Swedish National Road and Transport Research Institute. At VTI's Transport Forum in Linköping (Sweden) on 9-10 January 2013, CHARMEC gave two lectures entitled "How track geometry deterioration affects track deterioration" (Kalle Karttunen) and "Cost analysis for railway transports – how should deterioration be included?" (Roger Lundén).

Göteborgs spårvägar

During Stage 7 there were several meetings between Göteborgs Spårvägar (Gothenburg Trams) and CHARMEC to discuss co-operation, particularly in the area of squeal noise related to projects TS16 and VB11.

Nordic Rail Fair

CHARMEC took part in the 10th Nordic Rail Fair at the Elmia Exhibition Centre in Jönköping (Sweden) on 8-10 October 2013. We shared a stand with KTH Railway Group, Luleå Railway Research Centre (JVTC) and the Swedish National Road and Transport Research Institute (VTI). Our research projects were displayed and printed material was distributed to visitors. The stand was sponsored by VINNOVA. We also took part in the 11th Nordic Rail Fair on 6-8 October 2015, but without VTI on the stand with us.

SPECIAL EVENTS … (cont’d)

Nordic seminars on railway technology

KTH Railway Group organized the 17th Nordic Seminar on Railway Technology at Tammsvik (close to Stockholm) on 3-4 October 2012 with about 100 participants. The 18th seminar was arranged by the Norwegian University of Science and Technology (NTNU) together with the research institute SINTEF on 14-15 October 2004 in Bergen (Norway) with about 80 participants. From CHARMEC, 14 and 9 persons, respectively, took part and gave presentations. These are listed under the project descriptions in the previous section.

CM2015

The International Conference on Contact Mechanics and Wear of Rail/Wheel Systems, held every third year, is central to CHARMEC’s activities. We took part in the 10th CM conference held in Colorado Springs (USA) on 30 August – 3 September 2015, giving 10 presentations. Roger Lundén is a member of the international committee of CM2015. Dr Stuart Grassie, chairman of the CM conferences, together with Mats Berg and Sebastian Stichel of KTH, and Anders Ekberg and Roger Lundén, are Guest Editors of a Special Issue of the scientific periodical Wear for publication of peer-reviewed CM conference papers.

Road Shows

Before CHARMEC’s new Principal Agreement, valid as of 1 July 2015, was drawn up, we staged a series of so-called Road Shows with our project leaders and researchers visiting Trafikverket and the eleven individual members of the Industrial Interests Group, see list on page 13. CHARMEC’s resources were presented and possible future projects of mutual interest were discussed.

TTCI in Chicago

Anders Ekberg was invited by the Transportation Technology Center Inc (TTCI) in North America to the RCF (Rolling Contact Fatigue) workshop “Design strategies to improve the life of heavy haul wheels” held in Chicago IL (USA) on 16-18 June 2014, giving the lecture “Heavy haul wheel performance in Northern Europe”. Information was exchanged on maintenance strategies in North America and Europe.

Indian Railways

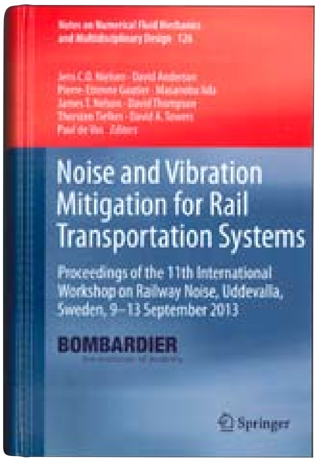
The co-operation with India’s RDSO (Research Designs & Standards Organisation, Ministry of Railways) on the design of concrete monobloc sleepers, see project SP27 on page 109, has continued during Stage 7.

UTMIS

This acronym stands for “Utmattningsnätverket i Sverige” (the Fatigue Network in Sweden) and involves people from several branches of engineering, including railway mechanics. Its activities had a seminar organized by Lennart Josefson and Anders Ekberg at Chalmers on 27-28 May 2013 at which the latter spoke about “Examples of the influence of eigenfrequencies on rolling contact fatigue of wheels and rails”.

IWRN 11

CHARMEC arranged the 11th International Workshop on Railway Noise (IWRN 11) on 9-13 September 2013 at Bohusgården in Uddevalla on the west coast of Sweden, approximately 90 km north of Gothenburg. The members of the local organizing committee were Jens Nielsen (chair), Roger Lundén, Wolfgang Kropp and Astrid Pieringer, together with Anders Frid, then of Bombardier Transportation Sweden (now ÅF-Industry). A total of 160 delegates from 19 countries in Asia, Australia, Europe and North America took part. Workshop proceedings with 84 peer-reviewed articles were edited by Jens Nielsen et al and published by Springer in Notes on Numerical Fluid Mechanics and Multidisciplinary Design, vol 126 (717 pages). IWRN11 was financially supported by Bombardier Transportation, voestalpine Schienen, Lucchini and Chalmers/CHARMEC.



Proceedings IWRN 11

EU projects

During Stage 7, together with partners, CHARMEC worked with the European RIVAS, D-RAIL and Capacity4Rail (C4R) projects and the proposed new projects TRANQUIL, WRIST, In2Rail and Shift2Rail. WRIST and In2Rail were launched in May 2015, see pages 95-96. Anders Ekberg has been the scientific and technical co-ordinator for the entire D-RAIL project, see page 93. This is the same role as the one he performed in the concluded project INNOTRACK, see page 90.

SPECIAL EVENTS … (cont'd)

IVA seminar

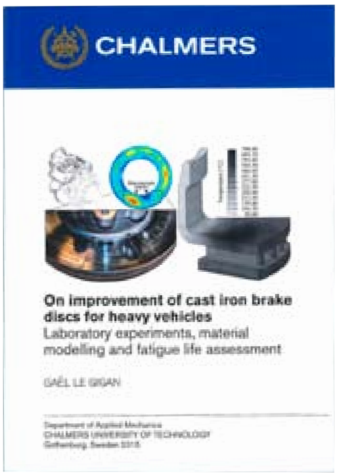
IVA, the Royal Swedish Academy of Engineering Sciences, together with NTVA, the Norwegian Academy of Technological Sciences, arranged a seminar in Gothenburg on 29 January 2015 on a future high-speed railway line Oslo-Gothenburg-Malmö-Copenhagen serving this "8-million city". Anders Ekberg from CHARMEC provided an overview of high-speed rail concepts.

FactFlashes

Under this heading, CHARMEC researchers are publishing short items accounting for some of our achievements, aimed at a wide audience.

Associated project AP4

Since April 2010 doctoral student Gaël Le Gigan from France has been working at CHARMEC in the associated project AP4, "Improved performance of brake discs". The project was financially supported by VINNOVA through the FFI (Strategic Vehicle Research and Innovation) programme and relates to brake discs used by the truck manufacturer Scania in Södertälje (Sweden). The project leader was Dr Peter Skoglund of Scania. There are strong synergy effects with our brake projects for railway vehicles, see photo on page 82. Gaël Le Gigan successfully defended his doctoral dissertation "On improvement of cast iron brake discs for heavy vehicles – laboratory experiments, material modelling and fatigue life assessment" on 3 December 2015. The faculty-appointed external examiner of the dissertation was Professor Philippe Dufrénoy, Laboratoire de Mécanique de Lille, Université Lille, France.



Doctoral degree conferment ceremony

Every year, in May or June, Chalmers stages a ceremony for the conferment of higher degrees in which those being awarded both PhDs and honorary doctorates take part. On 14 May 2016 in the Gothenburg Concert Hall, three CHARMEC doctors were awarded (out of an annual total of about 170 doctors at Chalmers University). Also one 50-year Jubilee Doctorate was conferred, see photo.

Jubilee Doctor Professor Bengt Åkesson (front), Dr Gaël Le Gigan (project AP4; second from the left), Dr Shahab Teimourimanesh (project SD7; third from the left), Dr Hamed Ronasi (project TS12; second from the right). Supervisors in projects AP4 and SD7 Professor Roger Lundén (left) and Dr Tore Vernersson (right)

FINANCIAL REPORT

This is a presentation of the cash and in-kind investments for Stage 7, 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 Trafikverket, the Industrial Interests Group and Chalmers have been calculated according to the principles stated in the Principal Agreement for Stage 7 dated 19 June 2012.

Report per party

Budgeted cash and in-kind investments per party according to the Principal Agreement for Stage 7 are presented in Table 1, including ÅF for which the contract ran from 1 January 2014. Included are also cash contributions from Chalmers, Trafikverket, UIC and VINNOVA that were not included in the Principal Agreement for Stage 7. Cash contributions from the EU are also included although they are not a formal part of CHARMEC's budget.

Cash investments

A letter dated 26 October 2012 from CHARMEC to each of the following: Trafikverket, Abetong Teknik AB, Bombardier Transportation Sweden AB, Faiveley Transport Nordic AB, Green Cargo AB, Interfleet Technology AB, Lucchini Sweden AB, SJ AB, SweMaint AB and voestalpine Metal Engineering, proposed how the payments from the partners to CHARMEC should be settled. According to the letter, CHARMEC would invoice on six different occasions: 2012-11-01, 2013-03-01, 2013-09-01, 2014-03-01, 2014-09-01 and 2015-03-01. This proposal was accepted by all partners. Special agreements on dates for payments were made for SL, since their contract had to be renewed from 1 January 2013 because of organizational changes, and for ÅF.

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 re-

Table 1. Cash and in-kind contributions (kSEK) per party during Stage 7

Party	Cash		In-kind		Total	
	Budget	Paid	Budget	Performed	Budget	Paid/Performed
Chalmers	15 180	15 180	9 800	9 800	24 980	24 980
Abetong	1 440	1 440	660	334	2 100	1 774
Bombardier	2 400	2 240	1 500	1 506	3 900	3 906
Faiveley	1 155	1 155	600	515	1 755	1 670
Green Cargo	660	660	330	0	990	660
Interfleet	180	180	150	131	330	311
Lucchini	1 485	1 485	900	1 134	2 385	2 619
SJ	660	660	–	–	660	660
SL	1 455	1 455	330	51	1 785	1 506
SweMaint	150	150	150	0	300	150
Trafikverket	17 704	17 704	1 500	690	19 204	18 394
voestalpine	2 145	2 145	2 460	2 445	4 605	4 590
ÅF	300	300	150	119	450	419
UIC	645	645	–	–	645	645
VINNOVA	1 609	1 609	–	–	1 609	1 609
EU	2 990	2 990	–	–	2 990	2 990
From Stage 6	3 792	3 792	–	–	3 792	3 792
Total	53 950	53 950	18 530	16 725	72 480	70 675

Note 1 The funding from EU does not formally belong to CHARMEC's budget
Note 2 Interfleet is now SNC-Lavalin

duced 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, of which ksek 725 kSEK are assigned to Stage 6, kSEK 2 704 to Stage 7 and the remaining amount, kSEK 1 346, to Stage 8. At the end of Stage 7, kSEK 725 + 2 704 had been invoiced.

In November 2012, it was agreed that UIC would contribute kEUR 44 to the SP25 project "Harmonized measurement sites for track forces". This amount was invoiced during Stage 7. In November 2013, it was agreed that UIC would contribute up to kEUR 35 to the SP27 project "Optimized prestressed concrete sleeper – phase II". The amount kEUR 26 was invoiced in January 2016 and has been included in the present financial report for Stage 7.

In October 2012, VINNOVA approved the support of Anders Ekberg's work as technical co-ordinator in the EU13 project "D-RAIL" with kSEK 400. This amount was paid by VINNOVA during Stage 7. 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 3 619, of which kSEK 3 330 are VINNOVA funds and the remaining amount is in-kind contributions from Abetong, Trafikverket och EBER Dynamics. CHARMEC's share of the VINNOVA funds is kSEK 1 865, of which kSEK 1 209 are assigned to Stage 7 and the remaining amount, kSEK 656, to Stage 8. At the end of Stage 7, kSEK 1 209 had been paid by VINNOVA.

In December 2010, the EU approved a project proposal from Chalmers/CHARMEC and our European partners providing kEUR 225 to the EU12 project "RIVAS". In September 2011, the EU approved a project proposal from Chalmers/CHARMEC and our European partners providing kEUR 250 to the EU13 project "D-RAIL". In 2013, the EU approved a project proposal from Chalmers/CHARMEC and our European partners providing kEUR 217 to the EU14 project "CAPACITY4RAIL". The EU funding does not formally belong to CHARMEC's budget.

Chalmers University supports CHARMEC financially. For Stage 7, the agreed amount was kSEK 750 from Chalmers centrally, kSEK 500 from Area of Advance Materials Science, kSEK 500 from Area of Advance Energy, kSEK 3 500 from the Department of Applied Mechanics centrally, kSEK 2 475 from its Division of Dynamics and kSEK 2 475 from its Division of Material and Computational Mechanics. The Department of Materials and Manufacturing Technology contributed kSEK 1 485. The Division of Technical Acoustics in the Department of Civil and Environmental Engineering contributed kSEK 495. Chalmers also agreed to contribute kSEK 3 000 during Stage 7 to the SD9 project "Multiobjective optimization of bogie system and vibration control" from a donation, see page 116.

Table 2. Budgeted and used cash and in-kind contributions (kSEK) during Stage 7, with the Industrial Interests Group (including Trafikverket) and Chalmers shown separately, for each programme area and for management and administration. CHARMEC's programme areas for Stage 7 are TS = Interaction of train and track, VB = Vibrations and noise, MU = Materials and maintenance, SD = Systems for monitoring and operation, EU = Parallel EU projects, and SP = Parallel special projects

	Cash		In-kind industry		In-kind Chalmers		Total	
Programme area	Budget	Used	Budget	Used	Budget	Used	Budget	Used
TS	10 652	11 091	2 190	1 212	–	–	12 842	12 303
VB	2 775	2 138	380	376	1 400	1 400	4 555	3 914
MU	19 803	20 338	4 410	3 382	6 225	6 225	30 438	29 945
SD	6 055	5 898	1 170	1 624	725	725	7 950	8 247
EU	4 277	6 391	–	97	800	800	5 077	7 288
SP	1 903	1 099	–	234	–	–	1 903	1 333
Management	4 250	4 068	–	–	450	450	4 700	4 518
Total	49 715	51 023	8 150	6 925	9 600	9 600	67 465	67 548

Note 1 Budget under "Cash" is as of 12 May 2016. These amounts have been transferred to the projects

Note 2 In-kind contributions from Chalmers include support from Area of Advance Transport and also Chalmers' support to EU projects

Note 3 The balance in cash to be transferred to CHARMEC's Stage 8 by 30 June 2015 is kSEK 53 950 – 49 715 = kSEK 4 235

FINANCIAL … (cont'd)

The following amounts in cash, totalling KSEK 29 734, due for CHARMEC's Stage 7 have been received as per agreements:

6 × KSEK 240	Abetong
6 × KSEK 400	Bombardier Transportation Sweden
6 × KSEK 192.5	Faiveley Transport Nordic
6 × KSEK 110	Green Cargo
6 × KSEK 30	Interfleet Technology
6 × KSEK 247.5	Lucchini Sweden
6 × KSEK 110	SJ
6 × KSEK 242.5	SL
6 × KSEK 25	SweMaint
6 × KSEK 2 500 + KSEK 2 704 = KSEK 17 704	Trafikverket
6 × KSEK 357.5	voestalpine Metal Engineering
3 × KSEK 100	ÅF Infrastructure

From UIC, KSEK 397 (KEUR 44) + KSEK 248 (KEUR 26) = KSEK 645 in cash have been received for projects SP25 and SP27. From VINNOVA, KSEK 400 + 1 209 = KSEK 1 609 in cash have been received for projects EU13 and SP26. From EU, KSEK 2 990 in cash have been received for projects EU12, EU13 and EU14 for Stage 7.

Finally, KSEK 750 + 500 + 500 + 3 500 + 2 475 + 2 475 + 1 485 + 495 + 3 000 = KSEK 15 180 have been received from Chalmers. The total 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 7, 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 originate from the Transport Area of Advance 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
Period	1997-04-01 – 2015-06-30 (– 2018-06-30)
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 3 900
Industrial interests in-kind budget and results, see pages 14–109	—

Anders Ekberg has devoted approximately half of his full-time position to the management and administration of the CHARMEC Competence Centre during Stage 7, 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 from Chalmers Applied Mechanics has assisted in financial issues. Bengt Åkesson, Professor Emeritus of Solid Mechanics and Director of CHARMEC until March 1997, has assisted in the quality assessment of research reports and administrative documents.

CHARMEC STAGE 8

The Principal Agreement for CHARMEC's Stage 8 (1 July 2015 – 30 June 2018) largely complies with VINNOVA's Principal Agreement for the Centre's Stage 4. As with Stages 5, 6 and 7, Trafikverket (earlier Banverket) has been included in the agreement for Stage 8 and partly holds the administrative role that was previously filled by VINNOVA. However, the financial agreements with Trafikverket are now 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 and 7.

The programme areas in Stage 8 are the same as those during Stage 7, see TS, VB, MU, SD, EU and SP on page 11. A new feature in Stage 8 is CHARMEC's involvement, 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 new situation will create new possibilities and challenges for CHARMEC and its partners.

President of Chalmers University of Technology, Stefan Bengtsson, signed the contracts for Stage 8 on 1 October 2015. Funding (KSEK) for Stage 8 (as of 8 February 2016) is shown in the adjoining table.

Former President of Chalmers University of Technology, Karin Markides, appointed the following Board members for CHARMEC's Stage 8 (decision dated 22 June 2015):

Ingemar Frej	Trafikverket (chair)
Rikard Bolmsvik	Abetong
Jakob Wingren	Bombardier Transportation
Fredrik Blennow	Faiveley Transport
Bengt Fors	Green Cargo
Martin Schilke	Interfleet Technology/SNC-Lavalin
Erik Kihlberg	Lucchini Sweden
Susanne Rymell	SJ
Robert Lagnebäck	SLL Trafikförvaltningen
Tilo Reuter	SweMaint
Björn Drakenberg	voestalpine Metal Engineering
Sebastian Stichel	The Royal Institute of Technology (KTH)
Per Lövsund	Chalmers

For a photo of the new Board, see page 9.

On 22 June 2015, Karin Markides also appointed Anders Ekberg as Director of CHARMEC for Stage 8.

	Cash	In-kind	Total
Industrial Interests Group	9 882	6 516	16 398
Trafikverket	16 500	–	16 500
Chalmers	14 476	3 000	17 476
Chalmers (donation)	1 350	–	1 350
Chalmers (AoA Transport)	–	2 000	2 000
Trafikverket (projects)	13 846	–	13 846
VINNOVA (projects)	656	–	656
EU (projects)*	9 691	–	9 691
From Stage 7	4 235	–	4 235
Total	70 636	11 516	82 152

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

CONCLUDING REMARKS

Stage 7 of the NUTEK/VINNOVA 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 been broadened. I believe that CHARMEC provides first rate research, is a knowledgeable dialogue partner, an important information hub and an expert network builder. As Railway Mechanics is key to the development of sustainable land transport both in Sweden and internationally, I look forward to Stage 8 with confidence. Our motto of "academic excellence combined with industrial relevance" will continue.

Gothenburg in June 2016

ANDERS EKBERG

CHARMEC RESEARCH 1995 – 2015 (Status as of May 2016)

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
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 Magnus Ekh
Ms Xin Li [1]

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

TS17 Optimization of materials in track switches
Prof Jens Nielsen / Prof Magnus Ekh
Mr Rostyslav Skrypnuk

TS18 Numerical simulations of train-track deterioration
Dr Björn Pålsson

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

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
Prof Wolfgang Kropp / Dr Astrid Pieringer
Mr Ivan Zenzerovic [1]

VB12 High-frequency wheel–rail interaction
Dr Astrid Pieringer / Prof Wolfgang Kropp

Departments involved at Chalmers:

Applied Mechanics
Civil and Environmental Engineering
Materials and Manufacturing Technology
Mathematical Sciences
Signals and Systems

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

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

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

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
Doc Anders Ekberg / Doc 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**
Doc Johan Ahlström / Prof Christer Persson
Mr Dimitrios Nikas

MU29 **Damage in wheel and rail materials**
Doc Johan Ahlström / Prof Christer Persson
Ms Casey Jessop

MU30 **Modelling of properties and damage in wheel and rail materials**
Doc Johan Ahlström

MU31 **Squats in rails and RCF** 5 **clusters on wheels**
Doc Elena Kabo / Prof Fredrik Larsson / Prof Anders Ekberg / Dr Peter Torstensson
Mr Robin Andersson 1

MU32 **Modelling of thermomechanically loaded rail and wheel steels**
Prof Magnus Ekh / Doc Johan Ahlström / Dr Tore Vernersson
Mr Ali Esmaeili

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

MU34 **Influence of anisotropy on deterioration of rail materials**
Prof Magnus Ekh / Doc Johan Ahlström / Dr Jim Brouzoulis
Mr Knut Andreas Meyer

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 and 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**
Prof Viktor Berbyuk / Prof Mikael Enelund
Mr Milad Mousavi [1]

SD10 **Enhanced mechanical braking for modern trains**
Dr Tore Vernersson / Prof Roger Lundén
Mr Mandeep Singh Walia

EU15 **WRIST – Innovative Welding Processes for New Rail Infrastructures**
Prof Lennart Josefson / Dr Jim Brouzoulis

EU16 **In2Rail – Innovative Intelligent Rail**
Prof Anders Ekberg and co-workers

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 – Capacity for Rail**
Prof Anders Ekberg and co-workers

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**

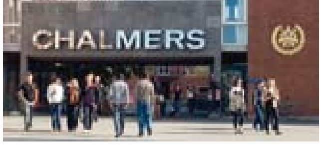
SP24 **Derailment risks in switches**

SP25 **Harmonized measurement sites for track forces**

SP26 **Holistic optimization of tracks**

SP27 **Optimized prestressed concrete sleeper – phase II**

All projects SP1-SP27 are reported on pages 97-109.



Departments and research groups / divisions / areas

APPLIED INFORMATION TECHNOLOGY
Cognition and Communication
Engineering Education Research
Informatics
Interaction Design
Language and Communication
Learning, Communication and IT

APPLIED MECHANICS
Combustion
Dynamics
Fluid Dynamics
Material and Computational Mechanics
Vehicle Engineering and Autonomous Systems
Vehicle Safety

ARCHITECTURE
Building Design
Theory and Method
Urban Design and Planning

BIOLOGY AND BIOLOGICAL ENGINEERING
Chemical Biology
Food and Nutritional Science
Industrial Biotechnology
System and Synthetic Biology

CHEMISTRY AND CHEMICAL ENGINEERING
Applied Chemistry
Chemical Engineering
Chemistry and Biochemistry
Energy and Materials

CIVIL AND ENVIRONMENTAL ENGINEERING
Applied Acoustics
Building Services Engineering
Building Technology
Construction Management
GeoEngineering
Structural Engineering
Water Environment Technology

COMPUTER SCIENCE AND ENGINEERING
Computer Engineering
Computing Science
Networks and Systems
Software Engineering
Software Technology

EARTH AND SPACE SCIENCE
Advanced Receiver Development
Global Environmental Measurements and Modelling
Optical Remote Sensing
Plasma Physics and Fusion Theory
Radar Remote Sensing
Radio Astronomy and Astrophysics
Space Geodesy and Geodynamics
Onsala Space Observatory
(National facility for radio astronomy)

ENERGY AND ENVIRONMENT
Electric Power Engineering
Energy Technology
Environmental Systems Analysis
Industrial Energy Systems & Technologies
Physical Resource Theory

MATERIALS AND MANUFACTURING TECHNOLOGY
Advanced Non-destructive Testing
High Voltage Engineering
Manufacturing Technology
Materials Technology
Polymeric Materials and Composites
Surface and Microstructure Engineering

MATHEMATICAL SCIENCES
Mathematics
Mathematical Statistics

MICROTECHNOLOGY AND NANOSCIENCE
Applied Quantum Physics
Electronics Material and Systems
Microwave Electronics
Nanofabrication
Photonics
Quantum Device Physics
Terahertz and Millimetre Wave Technology

PHYSICS
Biological Physics
Bionanophotonics
Chemical Physics
Condensed Matter Physics
Condensed Matter Theory
Eva Olsson Group
Materials Microstructure
Materials and Surface Theory
Subatomic and Plasma Physics
Theoretical Physics

PRODUCT AND PRODUCTION DEVELOPMENT
Design and Human Factors
Product Development
Production Systems

SHIPPING AND MARINE TECHNOLOGY
Cargo and Maritime Management
Marine Technology
Maritime Environment and Energy Systems
Maritime Humans Factors and Navigation

SIGNALS AND SYSTEMS
Antenna Systems
Automatic Control, Automation and Mechatronics
Communication Systems
Signal Processing and Biomedical Engineering

TECHNOLOGY MANAGEMENT AND ECONOMICS
Entrepreneurship and Strategy
Innovation and R&D Management
Science, Technology and Society
Service Management and Logistics
Supply and Operation Management

Areas of Advance

Built Environment
Energy
Information and Communication Technology
Life Science Engineering
Materials Sciences
Nanoscience and Nanotechnology
Production
Transport

Educational programmes

ENGINEERING FOUNDATION PROGRAMME
Engineering preparatory year

BSC ENG AND BSC
Building and Civil Engineering
Business Strategy and Entrepreneurship
Chemical Engineering
Computer Engineering
Economics and Manufacturing Technology
Electrical Engineering
Marine Engineering
Mechanical Engineering
Mechatronics Engineering
Nautical Science
Product Design Engineering
Shipping and Logistics

MSC ENG AND M ARCH
Architecture
Architecture and Engineering
Automation and Mechatronics Engineering
Bio Engineering
Chemical Engineering
Chemical Engineering with Physics
Civil Engineering
Computer Science and Engineering
Electrical Engineering
Engineering Mathematics
Engineering Physics
Industrial Engineering and Management
Industrial Design Engineering
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