Swedish Electric & Hybrid Vehicle Centre

ANNUAL REPORT

2015
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This year with SHC

The year 2015 has largely been influenced by two counterparts: a visionary outlook on coming research focus and a reflecting analysis of the past. All researchers and industrial engineers have been engaged in forming SHC’s future in terms of new challenging research fields and unresolved questions, while at the same time wrapping up ongoing research and the past four years of SHC as an organisation. Despite this heavy workload, everyone has contributed tremendously by delivering all reports and new research applications on time. A special thanks to Emilia who spent many summer days in her office finishing the final report for SHC’s second phase.

SHC Phase II was finished in June with a conference, a “Finale”. Since 2011, SHC researchers have performed 48 projects and seven pre-studies, while thirteen PhD students have graduated. Our nationally and scientifically broad community has welcomed nineteen new senior researchers and five new PhD students during this time.

The year took off by submitting the application for SHC Phase III to the Swedish Energy Agency, and the new phase began on 1st July. The industrial partners played an important part during the preparations, by prioritizing research topics as a base for new projects. A warm thank you to the thematic area researchers and engineers for being so committed in defining projects and applying for funding! We now look forward to starting our new projects. A few, e.g. a broadly collaborative fast charging project, have already started. We can see that the emphasis of the research questions have changed gradually; moving from the vehicle and its components towards charging and infrastructure.

An important new addition for SHC Phase III are thematic area researchers who will lead and coordinate the work of the thematic group along with the group leaders. They will conduct research within their themes, and familiarize themselves with the questions of the other themes, to increase synergies.

As we move on with the next four-year phase, I am happy to welcome Autoliv as a new partner in SHC. Bringing in questions and challenges from a supplier perspective is a very important step in SHC’s ambition to better serve the automotive industry in Sweden.

The interest for fuel cell technology is steadily increasing. The project Technology Watch of Fuel Cells that we run together with Energiforsk arranged a well-visited conference this winter. We were glad to see that many attendees were new for SHC and the project, and came from a variety of companies. The conference included a visit to the new hydrogen fuelling station at Arlanda where we had the chance to have a look inside the station.

The highlights of 2015 also include:

- Seven PhD students successfully defended their theses
- Magnus Karlström’s daily newsletter started a podcast with monthly broadcasts
- SHC representatives participated in a joint Nordic delegation at EVS28 in Seoul
- Patrik Johansson and team among the winners of an international energy storage innovation contest

Networking and collaboration are some of the strengths of SHC. I would like to thank our partners, the thematic area leaders and the Swedish Energy Agency for your joint efforts in making SHC an active and progressive Centre of Excellence. It is my hope that the initiatives we take now will make society, industry an environment benefit even more from our work in coming years.

Elna Holmberg
Director, Swedish Electric and Hybrid Vehicle Centre
The Swedish Electric & Hybrid Vehicle Centre (SHC) is a national excellence centre for research and development of hybrid and electric vehicles. It was established in 2007 by the Swedish Energy Agency in partnership with the Swedish automotive industry and academia. SHC unites Swedish competence in the field and is a base for cooperation between academia, industry and society.

SHC’s central task is to develop and optimize existing and future technology solutions such as energy supply, energy storage and propulsion for energy-efficient and eco-friendly electric and hybrid vehicle concepts. Our research activities concern the drivetrain with its components and control system as well as the infrastructure itself, communication between vehicles and the vehicle’s ability to utilize the infrastructure.

Our partners are automotive OEMs AB Volvo, Volvo Car Corporation and Scania AB, technology supplier Autoliv and technical universities Chalmers University of Technology, Lund University, KTH Royal Institute of Technology, Linköping University and Uppsala University.

Our research focus
Our research is conducted within four thematic areas - System studies and methodologies, Electrical machines and drives, Energy storage and Vehicle analysis. We also manage tech watch and initiate research within fuel cell technology. We aim to promote both deep, narrow technical studies and cross-discipline and cross-institution research when valuable.

SHC gives courses for doctoral students and runs a doctoral student network. Furthermore, we host a daily analysis of activities on the global arena. Our research and activities make us one of the stakeholders in national and international discussions within the electric and hybrid vehicle area.

A network centre
One of SHC’s primary functions is to stimulate and promote electric and hybrid vehicle related research at Swedish universities. The research financed through SHC spans over five different technical universities and over a range of different research disciplines, all of which are connected by their relevance for electric and hybrid vehicle technology. The advantage with the set-up is that it leads to genuine cooperation and knowledge-sharing between universities and industries within our thematic areas as well as within SHC as a whole.

SHC distributes its resources between all active research groups. An important part of the contribution to the research is by creating links, cooperation, knowledge transfer and highlighting shared interests, although the centre plays a minor role in the financing of projects.

Emphasising knowledge transfer
SHC regularly provides workshops and seminars on different research questions or other interesting topics connected to our research. The topics at some of these gatherings are very knowledge intensive, trying to reach into the fundamentals of a knowledge gap or an unexplored research question. Others, on the other hand, have a more general profile, allowing stakeholders to get the complete picture of all research projects in Sweden on a certain technology, application or system. Our workshops and seminars are open for our partners, while our bigger events welcome all interested colleagues. Every year we arrange a public conference where we address important topics and disseminate the results of the latest research. Our ambition is to strengthen the network function even further and to reach beyond our currently financed researchers and senior engineers in Swedish automotive industry.

Contribution to targets

The first of the tables below concerns the targets for SHC Phase II, while the second shows targets and their completion so far for SHC Phase III. The targets were re-defined for SHC Phase III and differ from the targets for SHC Phase II.

**SHC Phase II, January – June 2015**

|---------------------------|---------------------------------------------|
| To establish SHC as an internationally recognized Centre of Excellence and platform for research and development of hybrid-and electrical vehicles. | Some examples of international activities January – June 2015:  
  - Lars Nielsen visited and gave presentations at University of Michigan and Argonne National Laboratories.  
  - Mats Alaküla was invited speaker at Advanced E-Motor Conference, Frankfurt and International Conference on E-Mobility Charging Infrastructure, Berlin.  
  - Jonas Sjöberg was in the thesis committee for two PhD dissertations in control theory at INSA Lyon/Renault Trucks.  
  - Nikolce Murgovski and Mitra Pourabdollah made scholarly visits to TU Eindhoven in December 2014 – January 2015 where they also presented their research at seminars.  
  - Mitra Pourabdollah’s findings received media attention both on a national and an international level following her dissertation.  
  - Gabriel Oltean, PhD student at Uppsala University represented theme Energy storage with a poster at the AABC conference in Detroit. |

| To examine ten PhD students and employ at least eight new PhD students and five new senior researchers. | Five PhD students have graduated in January – June 2015:  
  - Mitra Pourabdollah, Chalmers  
  - Martin Sivertsson, Linköping University  
  - Daniel Wanner, KTH  
  - Peter Nyberg, Linköping University  
  - Henrik Lundgren, KTH |

Sixteen senior researchers were engaged previously during SHC Phase II:  
  - Juan Santiago, Uppsala University  
  - Mikael Alatalo, Chalmers  
  - Lars Lindgren, Lund University  
  - Henrik Ekström, KTH  
  - Anke Dierckx, Chalmers  
  - Jenny Jerrelind, KTH  
  - Lars Drugge, KTH |
1. **To employ at least eight new PhD students with external financing and at least eight senior researchers with parallel financing.**

   - Fernanda Marzano, Uppsala University
   - Tomas McKelvey, Chalmers
   - Hans Bångtsson, Lund University
   - Mikael Nybacka, KTH
   - Torbjörn Thiringer, Chalmers
   - Peter Göransson, KTH
   - Yujing Liu, Chalmers
   - Nikolce Murgovski, Chalmers
   - Lars Johannesson Mårdh, Viktoria Swedish ICT/Chalmers

   **During January – June 2015 three new senior researchers were engaged:**

   - Magnus Nilsson, Viktoria Swedish ICT
   - Eva Palmberg, Chalmers
   - Hans Bernhoff, Uppsala University

2. **To write at least three publications in international journals and conferences in each project.**

   **Objective completed for all long-term projects that have been on-going for some time. The greater part of the shorter projects that were carried out during spring 2015 have published or are currently working on publications of their results, or have conveyed them at conferences or seminars.**

3. **To create and manage a research platform/network with research education for SHCs PhD students. The platform should offer at least four PhD courses.**

   **The doctoral network has over 50 members and had two meetings in spring 2015, whereof one cross-thematic meeting with all SHC’s thematic areas.**

   **SHC did not arrange a PhD course this year, but two PhD courses managed by SHC researchers and promoted in SHC’s information channels were offered in spring 2015:**

   - Introduction to AC Machine Analysis (KTH, Oskar Wallmark)
   - High efficiency electrical machines (Chalmers, Yujing Liu)
SHC Phase III, July – December 2015
Since SHC Phase III has recently started and not yet gained enough pace, the target contribution for the latter half of 2015 is not as big as previous years.

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<td>Contribute to:</td>
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<tr>
<td>Cross-functional projects</td>
<td>• The associated project <em>Modelling and analysis of interaction between battery and voltage source converter in electric drivetrains</em> is carried out by themes Electrical machines and drives and Energy storage.</td>
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<td></td>
<td>• Theme Vehicle analysis and Technology watch of Fuel cells run a collaborative project called <em>Drivelinekonfigurationer för bränsleceller</em>.</td>
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<td>Benefits for the industry</td>
<td>• At present SHC has one industrial PhD; Rasmus Andersson at LTH/AB Volvo.</td>
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<td>• The project <em>Fast-Charging of Large Energy-optimised Li-ion Cells for Electrified Drivelines</em> involves VCC, AB Volvo and Scania along with Chalmers, KTH and Uppsala University.</td>
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<td>• The thematic areas have all had workshops and/or seminars where the industry partners have participated.</td>
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<tr>
<td>Scientific challenges</td>
<td>SHC has applied for financing for several research projects. However, due to the start-up phase of SHC III, no articles or conference contributions have been produced as yet.</td>
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<td>Dissemination of knowledge and research results</td>
<td>Some examples of dissemination of knowledge and results July – December 2015:</td>
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<td></td>
<td>• Anders Grauers gave a speech on cost analysis of charging systems for electric buses at the Nordic Electric Bus Initiatives conference.</td>
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<td>• Annika Stensson Trigell along with colleagues from KTH and Chalmers gave the academy's views on the Transport Administration’s report to the Government: <em>Analysis, Research and Innovation in the transport area</em>.</td>
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Dialogues and/or collaboration with
- CERC Combustion Engine Research Centre
- KTH Integrated Transport Research Lab
- Centre for ECO² Vehicle Design
- Viktoria Swedish ICT
- SAFER
- AstaZero
- KCK Centre for Catalysis.
- STand UP for Energy
- VTI - Swedish National Road and Transport Research Institute
- Chalmers Areas of Advance Energy, Transport and Material Science; Profile area Sustainable Vehicle Technologies
- Henrik Lundgren’s findings received media attention following his dissertation.
- Swedish television news *Rapport* made a feature of Verena Klass’ research.
- The results of Peter Nyberg’s doctoral research on drive cycles had attention from media as presenting solutions to the problems caused by standardized emission testing.
- Mats Alaküla and Hans Bångtsson gave a workshop on Cost analysis of electric road transport.
- Theme System studies and methodologies gave a workshop on Integrated hybrid powertrain control and exhaust after-treatment systems.
- Theme Energy storage gave a workshop on Charging infrastructure from a battery point of view.

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<th>Collaboration with other centres and internationalization</th>
<th>Dialogues and/or collaboration with</th>
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| Developing future competence | Out of the eight projects that currently run, four are PhD projects where the students are members of the doctoral student network. Several of our associated projects also engage PhD students. The doctoral network has more than 50 members and had one meeting during autumn 2015. |
SHC as a Swedish electromobility platform

This year’s activities have largely been influenced by the wrapping up of SHC’s second phase and the start of the third phase.

Spring 2015 was characterized by compiling reports of all activities and finalizing research projects. Some of those projects were presented at a conference that marked the end of SHC Phase II and highlighted some of its achievements.

The final program description for the third phase had been submitted by the beginning of 2015 after more than a year of gradual preparation. As the application for continuation was approved by the Swedish Energy Agency, SHC Phase III could start on 1st of July 2015. Since then, SHC’s members and staff have concentrated their efforts on developing SHC even further as an active forum for research, collaboration and technical discussion during SHC Phase III.

Expansion of SHC’s industrial base

SHC strives to engage new industrial partners such as suppliers to the automotive OEMs, and other organisations engaged in electromobility issues. One new partner, Autoliv Development, has joined SHC during 2015. Autoliv Development primarily takes part in the Energy storage theme, since one part of their business involves testing of batteries for electrical vehicles. In autumn, the theme had a meeting with the new partner at their research and tech centre in Vårgårda.

The partnership discussions with other industrial organisations continue in order to enlarge SHC’s industrial base.

Intensified activity in the thematic groups

The thematic activities were kept at a minimum level in several of the thematic groups during the finalization of SHC Phase II, as almost all engaged researchers were completing their research projects. Since then the thematic activities have intensified, particularly over the latter half of the year, through frequent thematic meetings, some of which have had a clear focus on special technical questions. By focusing on a specific topic and encouraging the researchers and engineers in the thematic groups to bring their colleagues, SHC aims for more knowledge intensive thematic meetings. One example of such an activity is theme System studies and methodologies’ workshop on integrated hybrid powertrain control and exhaust after-treatment systems this autumn, where we had the possibility to meet new colleagues from all vehicle manufacturers.

Some of the thematic groups have also changed character during this year. The portfolio of shorter senior projects that was initiated by the end of 2014 has led to many new researchers, previously in the outskirts of SHC, entering the scene. This has influenced not
only the research focus but also broadened the base of researchers in the groups, which naturally also has broadened the thematic areas.

Expanded research portfolio
To increase the breadth and quality of our common knowledge base we are now expanding our portfolio with externally funded projects defined by the thematic areas, in addition to projects funded by SHC. All themes have worked intensively on applications for external project funding, either in the end of the second or in the current phase. All applications have been jointly decided and supported by the thematic groups even though not all partners are engaged in all project proposals. A number of bilateral applications have also been submitted by SHC researchers or industry partners.

Cross thematic meeting
In March, all SHC’s thematic areas gathered at a two-day cross-thematic meeting in Hallsberg along with SHC’s doctoral network. The purpose was to learn about research carried out not only in the vicinity of senior SHC researchers, but also by all other research organisations in Sweden connected to SHC by the PhD network.

During these intense days the senior researchers, who are mostly engaged in their own thematic groups, were encouraged to listen to presentations from the other thematic areas at parallel sessions. Members from the doctoral student network introduced their work as did some of the researchers involved in the shorter projects initiated by the end of 2014. About 60 participants attended the meeting, and many new contacts were established due to the presence of “new” researchers in the short-term projects and the number of doctoral network members.

Thematic researchers – a new step towards realizing SHC’s full potential
The main objective for the centre, formulated by the board, is to aim for a dynamic, inclusive centre with critical mass that plays a noticeable role in the society. To realise this, the third phase of SHC entails some changes in the way the thematic groups are led and work.

To enable a more active role in the change towards fossil free vehicles and the realization of SHC’s potential as a competence hub, each thematic group will associate a thematic researcher. These young researchers will carry out research and play a central role in the daily operations along with the current staff, but also back up the thematic leaders as experts, aggregate the knowledge front and disseminate it to society.

The search for suitable projects and individuals has proceeded gradually during the year. The research challenge is essential for SHC and the thematic areas, but the researcher must also match the profile: an experienced researcher, interested in electromobility issues in society as well as in leadership, and with communication and administration talents.

By the end of this year each thematic area had one or two proposals for appropriate projects by researchers fitting the role of thematic researcher. The decisions will be taken at the first program council meeting in 2016.
Research advancements

The research portfolio in SHC has gone through a transformation since the centre started its first research projects, mainly in terms of PhD projects. As the greater part of these where finished during SHC’s second phase, the portfolio was extended with shorter projects, mostly carried out by senior researchers. Many of these researchers had not previously been engaged in SHC projects. Their involvement influenced not only the research portfolio but also gave new input into the thematic areas.

As SHC Phase II finished by end of June, the main part of our research projects was finalized by this time. Some of the projects financed outside of SHC and a handful of PhD projects continue during SHC Phase III. The PhD projects all involve PhD students who have come about halfway to the doctoral degree.

The research performed throughout SHC Phase II were shown at our yearly conference, this time named Finale of SHC II, where several of the biggest projects were presented along with some of the shorter ones started in 2014 (read a summary of the conference on page 23).

Industrial engagement in shaping the future project portfolio

By the end of SHC Phase II the industrial partners began a discussion on which research questions to bring into the thematic groups to form a project portfolio for SHC’s third phase. These discussions resulted in a list of prioritized topics that has been part of the base for the formulation of new projects in the thematic groups. Several of the industrial partners arrived at similar future technology challenges independently of each other.

Broadening the research platform with externally funded projects

During SHC’s first and second phase almost all projects were financed by SHC. Only a few had other financing sources and were formally associated to SHC. To support the industries and the universities in their ambition to build a substantial knowledge base and strengthen SHC as a broad platform for research, the thematic groups are now expanding their portfolio with externally funded projects, in addition to projects funded by SHC. The thematic groups have therefore worked intensely on building new research portfolios during the last year.

The first large project to get funding outside of SHC is the project Fast charging of large energy-optimized Li-ion cells for electric powertrains, an Energy storage project which was started this autumn. The project is a continuation of one of the theme’s projects from SHC Phase II. The application was written and managed by one of the researchers from Volvo GTT involved in the Energy storage theme and is now led by him. “By collaborating we get results that are greater than the sum of the parts”, said project leader Jens Groot, Volvo GTT in an article on SHC’s website as the project was launched. The project, which has a budget over 17 million SEK is financed by Batterifonden and by in-kind contributions from the partners.

The other thematic areas have all worked on project proposals, mostly aiming for the call Energieffektiva fordon but also for FFI.

Electrical machines and drives had intense discussions during summer regarding which research questions to focus on within their area of expertise. The outcome of the collaboration between the universities and industries was numerous brief drafts of research projects that combined and utilized the different competences across SHC’s partner universities.

Due to the limited resources in the calls, the drafts had to be prioritized. Of approximately fifteen joint project initiatives derived from the thematic roadmaps, eight projects were selected and submitted. Eventually SHC got two of those projects granted.

In addition to this ambitious work in all thematic groups, SHC also backed several bilateral projects through letters of support.

Doctoral degrees

The greater part of SHC’s doctoral research projects are now finished, as seven PhD students reached their doctoral degree this year. In System studies and methodologies Daniel Wanner, Mitra Pourabdollah, Peter Nyberg and Martin Sivertsson successfully defended their theses, as well as Ali Rabiei in Electrical machines and drives and Henrik Lundgren and Verena Klass in Energy storage. Several of the projects had attention from media and knowledge about the research
Research involving master students
Along with the work of senior researchers and PhD students, master students play an important part in some of SHC’s projects, contributing to the results and gaining experience for the future competence base.

*Automatic Conductive Charger Connections* runs at Lund University and KTH within Electrical machines and drives. This project is mainly a student project performed as two separate sub-projects at the different universities respectively. Both student groups have developed prototypes for automatic charging connection, which were demonstrated at the SHC conference in June.

Nikos Apostolopoulos, master student at KTH, contributed to the project *High-efficient, ultra compact integrated electric drives for tomorrow’s alternative drivetrains* by his master thesis study which was presented in December. The project scope is to combine a stacked polyphase bridge converter (SPB) and a permanent-magnet synchronous reluctance (PMSynRel) motor. Nikos’s contribution was a fully-functional SPB prototype with four submodules. “Nikos’ experience in electronics stemming from his internship at Tesla and his involvement with the KTH Formula E-Racing team has been extremely valuable for the members of our research group” said Oskar Wallmark, Nikos’ supervisor in an article on SHC’s website.

Thematic interaction in projects
SHC continuously encourages networking between the different thematic areas and between our partner universities and industries. Cross-functional work has been carried out this year in a collaborative project between Vehicle analysis and Technology watch of Fuel cells, as well as in the associated project *Modelling and analysis of interaction between battery and voltage source converter in electric drivetrains* which is performed by themes Electrical machines and drives and Energy storage.

Energy storage held a thematic meeting entitled *Charging infrastructure from a battery point of view* where Anders Grauers from Vehicle analysis, gave an invited presentation about his work on analysis of electrified bus systems.

Thematic seminars and workshops
The thematic areas have not only done a great effort in preparing new projects for SHC Phase III and communicating the results of projects that are now finished. They have also been active throughout the year in arranging project meetings, workshops and seminars with our partners.

System studies and methodologies arranged a seminar on energy management and hybrid powertrain dimensioning as part of the work in the project *Predictive control for complete vehicle energy management*. The project *Drive cycles* had a project workshop at Linköping University. Both these projects have presented results at public conferences as well (see Outreach). The theme also gave a partner workshop, which highlighted the problem of exhaust after-treatment system control presenting the topic from an academic and an industrial point of view. The discussions at this workshop were devoted to getting a common view and finding ways to proceed with possible collaborations.
Electrical machines and drives gave a seminar on Cost analysis of electric drive systems which was very well visited, with about 40 participants mainly from AB Volvo but also from academia, society and other industry representatives. Members from the doctoral student network were also present at this event, where the researchers from Lund University and AB Volvo presented the results of their study. The discussions were intense and deep, and concerned topics such as cost of construction of infrastructure, various types of electric roads and battery cost. The big difference in the cost of an isolated converter compared to an uninsulated was discussed as a topic to be investigated further.

Anders Graurers, Vehicle analysis, presented and discussed the results from the project Requirements on electric machines for about 20 engineers in the Electric propulsion group at Volvo Cars. The presentation and dialogue dealt with how to improve the requirements so that they allow more cost effective electric machines, and if requirements can be defined in a simple form which can be used to describe the effects of most types of transient overload.

For the thematic activities open for participants outside of SHC, see Outreach.

Technology watch of fuel cells
Fuel cells are getting more and more attention as an interesting propulsion technology. The relevance for and use of this technology in automotive applications is increasing internationally and several Swedish companies manufacture fuel cells, components and/or systems. It is therefore important for SHC to monitor, coordinate and disseminate information on the development of fuel cells.

SHC manages a project on fuel cell technology watch, financed by the Swedish Energy Agency and run in cooperation with Energiforsk. The project has its focus on automotive applications and the steering group consists of engineers from the vehicle industry. Since the extent of fuel cell research is relatively small in Sweden the project also partly involves non-automotive research and actors.

The second annual conference of the Fuel cell project was held at Arlanda in December and attracted about 70 participants ranging from academy and industry to producers, authorities and interest groups. Several new companies were present compared to last year’s conference – a sign that the interest in fuel cell technology is gaining pace.

The conference presented the results of the technology watch as well as gave a wider outlook. The presentations covered pre-studies and technology watches, reporting from IEA AFC annexes and technology watches within FFI fuel cell projects. A greatly appreciated feature at the conference was the demonstration of a fuel cell car from Hyundai during the concluding visit at the new hydrogen fuelling station at Arlanda.
This year has been a year of ending and starting. Several projects have finished their activities as the second phase of SHC ended and new activities have been initiated as the third phase started.

Professor Bo Egardt left his position as thematic area leader by the end of SHC Phase II in June this year. Jonas Fredriksson, associate professor at the Department of Signals and systems, Chalmers, has taken over the leadership of the theme and will guide the group during SHC’s third phase.

Four PhD students defended their theses in spring: Mitra Pourabdollah, Chalmers; Martin Sivertsson, LiU; Daniel Wanner, KTH and Peter Nyberg, LiU. A PhD project with Victor Judez at Chalmers is roughly halfway. Several of the projects received attention in media on international and/or national level. In addition, five short projects have run and was finished by the end of June.

Nikolce Murgovski and Mitra Pourabdollah, both from Chalmers, spent two months at TU Eindhoven in December-January 2014/15. Several papers on optimization of powertrains resulted from this collaboration.

Furthermore, researchers associated with SHC participated at several conferences during the year to present and discuss their research and results.

The theme has been active with meetings throughout the year, and also arranged workshops and seminars reaching out to a broader audience. A seminar on energy management and hybrid powertrain dimensioning was held at Scania, and a workshop on integrated hybrid powertrain control and exhaust after treatment took place at Chalmers.

During the start-up of SHC Phase III, the thematic group has worked intensely on identifying interesting research projects. Three industrially relevant areas for research have been identified; thermal modeling, dynamic simulation, performance analysis, control design, fault detection and isolation, and optimization. The research has its focus on methods and analysis related to hybrid and electric vehicles at a systems level.

**System studies and methodologies**

System studies and methodologies develops methods and algorithms, which are adopted and utilized in a hybrid vehicle setting by exploiting dynamic models, computational methods and simulation techniques. Main topics are mathematical modelling, dynamic simulation, performance analysis, control design, fault detection and isolation, and optimization. The research has its focus on methods and analysis related to hybrid and electric vehicles at a systems level.

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**Participants**

**Industrial members**
- Mikael Askerdal/Johan Lindberg, AB Volvo
- Mathias Björklund, Scania
- Sören Eriksson, Volvo Cars

**Senior researchers**
- Jonas Fredriksson, Chalmers, thematic area leader from July 2015
- Bo Egardt, Chalmers, thematic area leader until June 2015
- Annika Stensson Trigell, KTH
- Lars Eriksson, Linköping University
- Lars Nielsen, Linköping University

**PhD students**
- Daniel Wanner, KTH*
- Martin Sivertsson, Linköping University*
- Mitra Pourabdollah, Chalmers*
- Peter Nyberg, Linköping University*
- Victor Judez, Chalmers*

*PhD in 2015

**Associated projects**

**OCEAN – Operating Cycle Energy Management**
Main partners: AB Volvo, Chalmers
Duration: 2014-2016

**Life-long battery control**
Main partners: VCC, Chalmers
Duration: 2015-2018
Electrical machines and drives

Theme Electrical machines and drives is focusing its research on electrical energy conversion related technology specific to hybrid, plug-in hybrid and full electric vehicles, like charging systems, power electronic energy conversion systems, electrical machines and auxiliary systems.

On and off road transportation, either based on electric energy or supported by electric energy, require components and systems for supply and conversion of electric energy. Examples of off road transportation are mining and construction equipment vehicles. Examples of on road transportation are passenger cars, trucks and buses. All these systems are subject to development and refinement as electro mobility has become an emerging alternative to conventional forms of vehicle propulsion.

During 2015, theme Electrical machines and drives has concentrated on finalizing the projects of SHC Phase II and preparing the ground for the coming four-year period. The roadmap which was finished by the end of 2014 has two major directions as guidelines for new applications; I) Cost effective electrical drives and II) Charging Infrastructure. The group has held several intense meetings in order to map ongoing projects and define the need for new projects within these two directions. By the end of summer our efforts had resulted in a set of project applications with focus on electric machines, power electronics and charging systems.

The commitment among the area members has been apparent in the workshops and seminars arranged this year. Challenges with electric traction drives, inductive charging and cost analysis of electric drive systems are examples of thematic seminars within SHC. Furthermore, the thematic researchers have spread knowledge at conferences and other events in Sweden as well as internationally, such as the Advanced E-Motor Conference in Frankfurt or the International Conference on E-Mobility Charging Infrastructure in Berlin.

In the project High-efficient, ultra-compact integrated electric drives for tomorrow’s alternative drivetrains, PhD student Mojgan Nikouei Harnefors at KTH has initiated a collaboration with Eskilstuna Elektronikpartner AB to manufacture high-current converter submodules. This part of the research is funded by Vinnova. A very successful master thesis work was also made in this project by Nikos Apostolopoulos who built the converter prototype.

Ali Rabiei, PhD student at Chalmers and active in SHC, presented his doctoral thesis Efficiency analysis of drive train for an electrified vehicle in November. Ali has proposed various solutions to improve the energy efficiency in the electrical drivetrain of an electrified vehicle and quantified their benefits from an energy efficiency point of view.
An interest in the challenges of fast charging for Li-ion batteries has been the common focus for both industry and academia this year. As a result of this joint involvement, a new collaborative project, funded by Batterifonden, was started in autumn. The project aims to characterize the aging in large energy-optimized Li-ion cells caused by fast charging and will run for three years. Volvo GTT, Volvo Cars, Scania, Chalmers University of Technology, Uppsala University and KTH all contribute their expertise, and we look forward to close and intensive collaboration.

Two PhD students, both from KTH, have successfully defended their doctoral theses in 2015. Henrik Lundgren has studied thermal aspects of Li-ion batteries in vehicle applications, and collaborated with Scania on thermal management strategies for large-format commercial battery cells. Henrik’s research results were widely reported in media.

Verena Klass addressed the need for simple and cost-effective methods for state-of-health (SOH) estimation under electric vehicle operation in her doctoral thesis. Her research has resulted in a method that can estimate the SOH indicators capacity and resistance solely based on an input of on-board available signals such as current, voltage, and temperature. At the end of the year, Swedish television news show Rapport made a feature about Verena’s research. Henrik and Verena have now continued their careers at Etteplan and Scania respectively and we wish them the best of luck with their future engagements.

The Energy storage members participate in various activities with opportunity to spread knowledge about our research, such as seminars or conferences, on a national level as well as internationally. To mention a few, Henrik Ekström represented the theme in the joint delegation at EVS28 in Seoul and also presented Henrik Lundgren’s research at Nordbatt in Trondheim, while PhD student Gabriel Oltean from Uppsala University showed a poster about SHC and the work done within the Energy storage theme at the AABC conference in Detroit.

The thematic group meetings have gradually developed into gatherings with pronounced focus on various technical aspects of our research, where we invite members from the partner industries. As an example, one of our meetings addressing safety and battery crash testing was held at SHC’s new partner Autoliv. These intensified and deepened discussions facilitates the defining of concrete industry relevant topics and serve as a basis for identifying future projects and constellations.
Vehicle analysis

The Vehicle analysis theme analyses electric and hybrid vehicles based on outside perspectives, for example industrial, user or infrastructure perspectives. The research is based on analysis of what factors make electric and hybrid power trains attractive for different types of vehicles and how the powertrains should be designed to maximize the value-to-cost ratio. Changes in driving forces for electric and hybrid power trains are also watched, to understand which direction the development should take.

During this year theme Vehicle analysis has focused both on finalizing and presenting results from the remaining projects of SHC Phase II and on looking forward and generating ideas for new projects within as well as outside of SHC.

One example of a successfully finalized project is *Tekniköversikter inom Fordonsanalysområdet* where we have created a method to very quickly estimate the fuel savings potential for different types of hybrids in different driving cycles. The method uses drive cycle statistics rather than simulations, to estimate the fuel savings for different types of driving and provides clear insights into what properties of the driving cycle influence the fuel consumption most. As a result, it simplifies the overall discussion of pros and cons of different drivetrain concepts.

Tendencies in the vehicle industry and society in general indicate that we are at the beginning of a broad breakthrough for electric and hybrid vehicle technologies. This is true not only for research but also for products and services which are now increasingly being developed on commercial terms and becoming part of regular vehicle manufacturer portfolios. One of the effects of the growing interest for new technologies is an increasing need for knowledge and understanding of electrified buses and charging infrastructure that we have noted this year. As we define new projects, we intend to give even more attention to this interesting field, as can be seen in this autumn’s project proposals. Two proposals have been made for projects concerning electrified buses and charging, as well as several associated projects on related topics.

The growing interest in fuel cell technology has led to a collaboration with Viktoria Swedish ICT and Vätgas Sverige which started in the autumn. In this project we look for the best cost-benefit ratio for fuel cell power trains in different vehicles.

Our theme members have had several opportunities to spread knowledge about our research both inside and outside of SHC. “Requirements on electric machines” was the topic of a discussion led Anders Grauers and involving the Electric propulsion group at Volvo Cars, while the general public at Göteborg International Science Festival could listen to a presentation on how to take steps towards a smaller carbon footprint. Anders also represented the theme at EVS28 in Seoul.
### Theme 1: System studies and methodologies

- **Dimensioning plug-in hybrids using drive-cycle information**; Chalmers; Jonas Sjöberg
- **Drive cycles**; Linköping University; Lars Nielsen
- **Driver models and mission-based driving cycles**; Linköping University; Lars Nielsen
- **Evaluation of energy efficient cornering strategies using the KTH Research Concept Vehicle**; KTH; Jenny Jerrelind
- **Fault-tolerant over actuated HEVs**; KTH; Annika Stensson Trigell
- **Model for simulation of driving behavior during failures in electrified vehicles**; KTH; Lars Drugge
- **Optimal Energy Management of Electrified Powertrains**; Linköping University; Lars Nielsen
- **Predictive control for complete vehicle energy management + Extra financing for PhD project**; Chalmers; Bo Egardt
- **Safe and energy efficient vehicle designs**; KTH; Annika Stensson-Trigell
- **System level evaluation of diesel engine and emission after treatment systems for hybrid drivetrain applications in dynamic drive cycles**; Chalmers; Tomas McKelvey
- **Testing and evaluation of fault handling strategies in the research concept vehicle**; KTH; Mikael Nybacka

### Theme 2: Electrical machines and drives

- **A holistic approach to the integration of combustion engines and electric machinery in heavy hybrid electric vehicles**; KTH; Oskar Wallmark
- **A scalable model for life cycle inventory of electric automotive traction machines**; Chalmers; Anders Nordelöf
- **Automatic conductive charging connection**; Lund University; Mats Alakula; KTH; Mats Leksell
- **Compact rotor power transfer in wound rotor synchronous motor for high performance electric vehicles**; Chalmers; Yujing Liu
- **Cost analysis of electric drive system**; Lund University; Hans Bängtsson
- **EMC and safety studies on electric road systems**; Lund University; Lars Lindgren
- **Fault detection and increased reliability of a 3.3 kW on-board battery charger for PHEVs**; Chalmers; Saeid Haghbin
- **Flywheel energy storage**; Uppsala University; Hans Bernhoff
- **High-efficient ultra compact electric drives for tomorrow’s alternative drivetrains**; KTH; Oskar Wallmark
- **Hybrid drives for heavy vehicles**; AB Volvo (industrial project); Mats Alaküla
- **MEP-(Maximum efficiency point) control of PMSM, based on an equivalent circuit representation of electric machine instead of MTPA/MTPA (Maximum torque per ampere/voltage)**; Chalmers; Torbjörn Thiringer
**Modeling of resonant electric power conversion for wireless power transfer systems;** Chalmers; Tomas McKelvey

**Ultra Compact Cost Effective Fast Charger Stations;** Chalmers, Saeid Haghbin

**Wireless charging using a resonant auxiliary winding;** Chalmers; Mikael Alatalo

**Theme 3: Energy storage**

**Batteries – present and future challenges;** Uppsala University; Kristina Edström

**Fast charging of large energy-optimized Li-ion cells for electric powertrains;** AB Volvo, Jens Groot (project includes AB Volvo, Volvo Cars, Scania, Chalmers, KTH and Uppsala University)

**State-of-health estimation of lithium-ion batteries in electric vehicles: Battery system – Life model;** KTH; Göran Lindbergh,

**System identification methods for battery health estimation on-board electric vehicles;** KTH; Göran Lindbergh

**The Influence of Fast Charging on Li-ion Battery Ageing – Chalmers part;** Chalmers; Patrik Johansson

**The Influence of Fast Charging on Li-ion Battery Ageing – KTH part;** KTH; Göran Lindbergh

**The Influence of Fast Charging on Li-ion Battery Ageing – Uppsala part;** Uppsala University; Kristina Edström

**Thermal aspects of lithium-ion batteries in vehicle applications;** KTH; Göran Lindbergh

**Theme 4: Vehicle analysis**

**Tekniköversikter inom fordonstemat - Simplified fuel consumption models for hybrid powertrains and Method to estimate fuel consumption in different driving cycles;** Chalmers; Anders Grauers

**Tystgående citydistribution för nattleverans i Stockholm Stad;** KTH; Peter Georén
Collaboration with other organizations and knowledge of research activities outside SHC play an essential part in fulfilling the ambition to be the Swedish competence hub for electric and hybrid vehicles.

SHC is, by itself, a network centre that links five of the major universities in Sweden and the vehicle industry in the country together. Each of our partners collaborate with organisations, industries or universities relevant for their operation and research focus. Together, this probably covers almost all activities in Sweden. SHC therefore functions as a natural source for any researcher requesting information. As a centre however, SHC mainly focuses on collaboration with organisations that complement our knowledge, like combustion centres or fuel cell research activities or on strengthening our role in Sweden.

**Viktoria Swedish ICT**

Within Systems studies and tools, the Chalmers team has collaborated closely with researchers from the research institute Viktoria Swedish ICT, partly on the basis of shared personnel. The collaboration, which extends beyond SHC to Chalmers Energy Initiative and FFI projects, has an emphasis on using optimization and optimal control for energy management and for state-of-charge and temperature balancing of batteries. There is also a regular dialogue on management level on cooperation possibilities between Viktoria Swedish ICT and SHC.

SHC together with Viktoria Swedish ICT and Vätgas Sverige started a project in autumn 2015 which analyses powertrain configurations with fuel cells. In this project the recent development in fuel cell technology shall be put in a vehicle perspective to find which configurations of power trains are most interesting for fuel cell vehicles and in which niches these can be expected to find the best cost-benefit ratio.

**KTH Integrated Transport Research Lab (ITRL)**

ITRL, the Integrated Transport Research Lab is a research centre at KTH. It aims to coordinate and run a large, long-term and integrated research and demonstration projects within the challenge of sustainable transport solutions.

SHC collaborates with ITRL in several projects - using the centre’s Research Concept Vehicle (RCV) to conduct experiments. All of these projects focus on electric vehicles with active systems, especially steering and propulsion, and are based on results from previous SHC projects. In his doctoral project, Daniel Wanner made use of the RCV for fault handling strategies, and this work has been continued during the year within the framework of another SHC project. Thanks to funding from Vinnova, the researchers in two of the projects mentioned above had the opportunity to take the RCV to the test site Asta Zero.
in November, for additional tests on control strategies and fault handling.

The collaboration with ITRL enables an excellent platform for implementation and testing of research findings in a vehicle with enhanced possibilities for both actuation, measurements and control.

AstaZero
As mentioned above, the short-term projects Evaluation of energy efficient cornering strategies and Testing and evaluation of fault handling strategies which both make use of the KTH RCV, put their strategies to the test at AstaZero test track this autumn.

“We have created simulation models of the RCV in order to develop cornering strategies adapted to it”, explained Jenny Jerrelind who runs the cornering strategy project. “Now we wanted to try out those control strategies during real driving. We drove straight ahead, in large circles as well as in slalom to evaluate the energy consumption in curves and get an estimation of how much it can be reduced. AstaZero was a very nice test facility with professional and friendly staff.”

The researchers will now develop the physical platform and the control strategies further both for fault handling and for energy-efficient driving, and possibly perform additional tests further on.

Centre for ECO² Vehicle Design
The simulation results as well as the experimental validation of Evaluation of energy efficient cornering strategies are related to a PhD-project financed by the Centre for ECO² Vehicle Design, which focuses on developing a simulation environment to be able to simulate the rolling losses during driving. The results from the SHC project is valuable for this work. The PhD student involved in the ECO² project is also part of the SHC’s doctoral network, thereby an exchange of information between the SHC and the Centre for ECO² Vehicle Design is achieved.

Tunga Fordon
The collaboration with the heavy off-road vehicle network Tunga Fordon was continued this year with participation of SHC representatives in Tunga Fordon’s workshops. At one of the network’s seminars in Helsingborg, Mats Alaküla gave a presentation on energy efficiency of heavy off-road vehicles. A hybridized reach stacker – the first of its kind – presented at the seminar, was commented on by Anders Grauers in an article at SHC’s website as a sign that the use of hybrid and electric vehicle technologies is spreading.

Mats Jonasson, Jenny Jerrelind, Mikael Nybacka and Lars Drugge work in two different projects that have common ground in the measurements made with the research vehicle KTH RCV. In autumn they put their strategies to the test at AstaZero.
VTI - Swedish National Road and Transport Research Institute

Linköping University has a strategic cooperation agreement with VTI that concerns broad, long-term collaboration in education, research and innovation. Within this framework, an associated SHC project has been carried out in order to study barriers for the introduction of an electrified vehicle fleet. The project includes studies of driver behaviour by means of interviews and data logging, but also how the charging affects the electrical system at local and national levels, and the role that municipalities can take in the introduction of these vehicles.

Linköping University and VTI has also been collaborating in a short SHC project during spring 2015 with the objective to write an application on driver models and mission based driving cycles.
Outreach

Throughout 2015, SHC has reached out to society through various events and activities, ranging from news items and participation in events such as the International Science Festival, to public seminars and talks for the general public. However, during the latter half of this year we have mainly focussed our efforts on building a new project portfolio for SHC Phase III.

SHC conference “Finale of SHC II”

“We move into a higher gear for the finale of SHC Phase II” was the message for SHC’s annual conference which took place in Göteborg on the afternoon of 4 June. About 120 people gathered to hear SHC researchers introduce state of the art research from some of the projects conducted during SHC Phase II, and to mingle with friends and colleagues.

Following an introduction by Elna Holmberg, Anders Grauers, Chalmers, gave a presentation on the topic Why we don’t have optimal electric machines for vehicles, where he pointed out a need for dialogue between vehicle OEMs and EM suppliers to identify requirements with a good balance between electric machine cost and vehicle performance. Anders also stressed the need for new simple ways to define transient load. “This project is a good example of the benefits of the SHC network, with many important contributions from our project workshops”, he said.

Annika Stenson-Trigell, KTH, gave an overview of the four short projects using the KTH Research Concept Vehicle, followed by Ali Rabiei, Chalmers, who talked about energy efficient control of permanent magnet synchronous machines, and Yujing Liu, also from Chalmers, who presented the research of yet another of the short projects initiated in the end of 2014; Brushless wound rotor synchronous motor for torque boost and speed extension. As one of the project highlights Yujing mentioned how the technology developed in the project had been used in other SHC related research activities. As the last presentation before the coffee break, Lars Lindgren from Lund University talked about EMC and safety studies on electric road systems.

During the coffee break, master students from KTH and Lund University demonstrated automatic charger models created in the project Automatic Conductive Charger Connections which runs at Lund University and KTH. While tasting the SHC cakes, the attendees could also have a look at a poster exhibition presenting SHC’s thematic areas.

Following the break, Nikolce Murgovski and Magnus Nilsson from Chalmers presented a proposed control architecture suitable for energy management of platoons. They were followed by Peter Nyberg, Linköping University, who talked about his PhD work on methodologies for generation and transformation of...
driving cycles. Finally, Kristina Edström, Uppsala University together with Patrik Johansson, Chalmers and Göran Lindbergh, KTH introduced the collaborative research on ageing and Li-ion battery testing in relation to materials properties.

To conclude the conference and SHC Phase II in style, all our contributors and partners were invited to mingle and have some snacks and drinks before parting.

Public seminars and workshops

The thematic areas have conveyed their research results and initiated discussions by giving several public seminars and workshops during the year. These workshops have generally been well-attended and often given rise to interesting debates. Here follows some examples:

System studies and methodologies gave a seminar on *Energy management and hybrid powertrain dimensioning* at Scania. The speakers came from Chalmers, Linköping University, Viktoria Swedish ICT and Scania and gave many new insights in the field of sizing and energy management of hybrid powertrains. The seminar attracted about 30 participants coming from industry, academy and Government authorities. A seminar on the same topic was also held at DAF Trucks N.V in Eindhoven, as a result of Nikolce Murgovski doing a two-month scholar visit at Eindhoven University within the project *Predictive control for complete vehicle energy management*.

*Inductive charging of electric vehicles* was the theme for a very well attended workshop arranged by Electrical machines and drives. Some 50 participants from industry, academy, suppliers, research institutes and others with an interest in this technical area gathered at Chalmers to learn about technical aspects, user experience and ongoing European activities in the field of inductive power transfer. The speakers came from Viktoria Swedish ICT, Volvo AB and Chalmers University of Technology.

Furthermore, Electrical machines and drives introduced some possibilities for integration of power electronic, electrical machines and batteries at a seminar on *Modular converters and electrical machines for electric and hybrid vehicles*. The speakers were all theme area members from KTH, Chalmers and Uppsala University. As an add-on to the seminar, a presentation by Lars Hoffmann (SP) was given on “Safety related issues due to the introduction of high voltage in automotive industry”. The seminar gathered over 30 interested attendees. Besides academics, representatives from both the major automotive companies and smaller companies working in the field were among the participants.

A seminar on *Cost analysis of electric drive systems* was also very well visited, with about 40 participants mainly from AB Volvo but also from academia, society and other industry representatives. Members from the doctoral student network were also present at this event, where the researchers from Lund University and AB Volvo presented the results of their study. The discussions were intense and deep, and concerned topics such as cost of construction of infrastructure, various types of electric roads and battery cost. The big difference in the cost of an isolated converter compared to an un-insulated was discussed as a topic to be investigated further.

SHC researchers in interaction with society

Researchers from all SHC’s thematic areas have shared their knowledge and offered trade and industry, authorities and society in general their expertise in various ways during the year. Here we will just bring up a few examples:
Anders Grauers, theme Vehicle analysis, was among the speakers at Nordic Electric Bus Initiatives, where he gave a presentation on the theme “Method to analyse cost effectiveness of different charging systems for electric buses” for about 100 attendees from public transport authorities, municipalities, public transport operators, vehicle producers, energy companies and academia. Anders also presented and discussed the introduction of charging infrastructure and electric buses with representatives from Kollektivtrafikforum in Gothenburg/Partille/Möln达尔 and Västtrafik.

Oskar Wallmark, Electrical machines and drives, made his research accessible for a vast audience as his docent presentation Modular, integrated electric drives for automotive applications was made available on YouTube.

Annika Stensson Trigell, System studies and methodologies, represented the academy in expressing her views on the Transport Administration’s report to the Government, Analysis, Research and Innovation in the transport area, along with colleagues from KTH and Chalmers.

Göran Lindbergh, Energy storage, gave his views on the future development of fuel cells in an article in NyTeknik. Göran stressed the importance of the production technique and said that a 50 percent reduction of today’s fuel cell cost is realistic within five years.

In this year’s edition of the International Science Festival in Göteborg, Elna Holmberg tried out a new way of reaching the public. At the festival feature Vetenskapsrouletten, researchers ride the Ferris wheel at Liseberg to meet with random groups of visitors. Elna met with people from several different backgrounds and concluded that there is a great need for information about new vehicle technologies.”It was a lot of fun and time went immensely fast!”

Anders Grauers also participated in the festival, as part of a panel of experts who answered questions about how people can contribute to a reduction of emissions and climate change by individual, everyday actions.

Joint Nordic participation in EVS28

SHC and Volvo Construction Equipment were the Swedish delegates when fourteen enterprises from Denmark, Finland and Sweden joined forces to present their e-mobility solutions at the 28th Electric Vehicle Symposium (EVS28) in Seoul in the beginning of May. The participation was made possible by the support of the Swedish Energy Agency, Tekes – the Finnish Funding Agency for Innovation, and Nordic Energy Research.

Thanks to the Danish Embassy’s efforts and contacts, the group had the opportunity to visit both the “Environmental Ministry” Korea Environment Corporation and Hyundai Motors’ development office in Seoul. The highlight of this visit was a Q&A session with Sae Hoon Kim, responsible for the technology development of Hyundai’s fuel cell vehicles.

The SHC delegates, Elna Holmberg, Anders Grauers and Henrik Ekström, wrote reports from the conference, covering these visits as well as impressions from the conference itself. The reports were disseminated by Magnus Karlström’s newsletter and made available on SHC’s website. Elna Holmberg also wrote an article for SVEN (a magazine for Sveriges Fordonstekniska förening) where she presented Hyundai’s strategies for future vehicles.

Global watch of energy efficient vehicles

SHC hosts a project managed by Magnus Karlström, which summarises the international development of energy efficient vehicles in a daily newsletter, OMEV (Omvärldsanalys av Energi-effektiva Vägfordon). The project regularly delivers analyses of the development, distributed by email. In 2015, the readers have been able to follow a series of articles focusing on the plans of bus manufacture, and another that analysed TCO (total-cost-of ownership) studies for electric vehicles.

Oskar Wallmark reached a big audience when his docent lecture was made available on YouTube.
Furthermore, the newsletter has started a podcast. Three podcasts have been broadcasted so far, one on the development of batteries, one about noise, city planning and electric buses and one about the history of Swedish electric cars with a focus on the 1990’s. For the future, the OMEV team aim at publishing one podcast per month.

Since January 2015, Magnus Karlström and his fellow editors have distributed about 150 newsletters to approximately 1300 subscribers.

Media, newsletter and website

SHC’s monthly newsletter has above 400 subscribers, which makes it a useful tool for spreading information about activities and new research outside the “inner circle”. The newsletter gives an overview of the latest articles published on the website, informs about SHC events and events related to the area, announces the dates for upcoming dissertations and licentiate seminars and gives tips about calls and grants.

Webb articles highlighting activities and research within SHC have been published regularly during the year and been promoted by means of the newsletter and Twitter. This year, the news flow has contained articles about the collaborative SHC projects at KTH Research Lab, the new Fast Charging project, the plans for SHC Phase III and the reports from EVS28 to mention a few examples.

In connection to each dissertation, an article about the PhD student and her research has been published and also disseminated via the media channels of the concerned universities. The press releases for Mitra Pourabdollah’s and Henrik Lundgren’s dissertations were particularly successful and received plenty of media attention whereas Peter Nyberg’s work attracted interest as a consequence of the recent awareness of problems with standardized emission tests. Verena Klass’ research was also highlighted in media, by a news feature in SVT Rapport.

Student commitment in Shell Eco Marathon

The student competition Shell Eco Marathon was held in Ahoy Fair, Rotterdam, 21–24 May. The competition has the goal to drive as fuel efficient as possible, measured as km/l petrol or km/kWh depending on which type of fuel is used. Like previous years, SHC sponsored the teams from KTH and Chalmers.

This year there was only partial success for the two Chalmers teams. Both managed to complete their vehicles on time and enter the competition. However, both vehicles broke down before the finish line, and got no results.

“As a teacher I think that the project was a success”, said Sven B. Andersson, responsible for the Chalmers teams. “The students worked hard and took care of the problems as they appeared. The learning part was definitely there!”

KTH also participated with two cars. The urban concept car obtained a result of 96 km/l, which rendered a 7th position. The prototype team managed to get their hydrogen fuel cell car on the race track but due to functional problems they unfortunately did not get an official result.
Education

One of the goals of SHC is to contribute to future competence for academia and industry. Education and networking possibilities for the doctoral students involved in research projects and in SHC’s doctoral student network, as well as for engineers at the partner industries, form an important part of the centre’s activities.

The Doctoral Student Network
The Doctoral Student Network for Swedish hybrid vehicle research is an arena to collaborate and stimulate interaction with Swedish automotive industry for PhD students conducting research on electrification of road vehicle propulsion at different universities in Sweden. At the end of the year the network had 56 registered members.

Two main activities were arranged for the network members during 2015: a spring network meeting with a production factory visit in Gothenburg and a workshop meeting in autumn, at Chalmers. The network was also part of SHC’s cross-thematic meeting where several network members presented their work.

The spring meeting was a two-day event in Göteborg with focus on manufacturing, test and demonstration. The participants visited the Tuve truck factory belonging to Volvo Group Trucks Operations and were given a demonstration of the new ElectriCity indoor bus stop and charging facility in connection to Lindholmen Science Park. The second day also included a seminar with presentations on different aspects of test- and demonstration of electrified vehicles by speakers from Lindholmen Science Park, Viktoria Swedish ICT and AstaZero AB.

The autumn meeting was arranged in connection to an SHC workshop on electric road infrastructure held at Chalmers by theme area Electrical machines and drives, which was led by Hans Bångtsson and Mats Alaküla from Lund University. The workshop being scheduled for the afternoon, the PhD students met up in the morning to broaden the scope of the day by delving into related subjects in presentations by Chalmers researchers.

Education at our partner universities
Several of SHC’s senior researchers at our partner universities are involved in undergraduate and graduate-level courses with connection to our research topics. This year, two PhD courses were given by SHC researchers, one at Chalmers and one at KTH. These courses were not arranged by SHC, but were promoted through our channels and intended for PhD students.

Happy participants in the course High efficiency electrical machines, given by the Department of Energy and Environment, Chalmers.
and industrial engineers working in SHC’s field of interest:

*Introduction to AC Machine Analysis* was given at the Department of Electrical Energy Conversion KTH in April, and was managed and tutored by Oskar Wallmark. The aim of the course was to present an introduction to the theory of AC machine analysis at a somewhat more fundamental level than what is found in undergraduate/graduate-level courses.

At the Department of Energy and Environment, Chalmers, Yujing Liu gave a course on *High efficiency electrical machines*, with the objective of providing the latest knowledge and study results on loss analysis and efficiency measurements, as well as the state-of-art motor designs for high efficiency. The course included lectures by guest speakers from Lund University, AB Volvo and ABB, among whom were Mats Alaküla and Pär Ingelström, both active members of SHC.
Cost-efficiency of plug-in hybrids calculated a thousand times faster

Plug-in hybrids have low fuel consumption, but require more costly parts than cars with a regular combustion engine. During development, the optimal cost balance must be calculated, which has been extremely time consuming to date. Mitra Pourabdollah has developed a new method that dramatically reduces the time needed for these calculations.

A research team at the Department of Signals and Systems at Chalmers has developed a quick and simple method for engineers to calculate the lowest cost factoring in both manufacture and driving behavior. Researcher Mitra Pourabdollah describes the method in her PhD thesis:

“The operating cost of a plug-in hybrid depends on many different variables, such as the way you drive, how you charge the battery and how far you drive between charges,” she says. “Driving habits also affect what size battery you need. Component prices, different battery types and different driving habits combined result in a huge number of parameters that impact the overall cost.”

The new solution that Mitra Pourabdollah presents involves using a so-called convex optimization algorithm. The algorithm acts as a tool in which researchers enter the various parameters that can affect the cost of a plug-in hybrid, and see the results very quickly. The new method speeds up this part of the design process twentyfold. In extreme cases, calculations that would normally take a thousand hours can be completed in half an hour – almost two thousand times faster than previously.

“Dramatic time savings at this stage will allow more opportunities to consider other aspects of the design of the drivetrain and gain a broader perspective,” says Mitra Pourabdollah.

“Rapid feedback is essential for creative work,” says Anders Grauers, one of the supervisors of the project. “Even discounting the extreme cases, Mitra’s method means that you can get the results of your calculations on the same working day, a significant benefit for the creative process.”

Mitra Pourabdollah’s research colleagues Nikolce Murgovski and Lars Johannesson Mårdh originally came up with the idea of applying convex optimization to a complex vehicle model. They began by developing a method for plug-in hybrid buses. Following on from their work, Mitra Pourabdollah studied how the method could be applied to passenger cars. The basic algorithm is very flexible – and fun to work with.

“Finding a way to describe the various components that fit convex optimization is a bit like a game,” explains Mitra Pourabdollah. “The method has many other application areas as well, for example in active safety”.

Mitra Pourabdollah defended her thesis “Optimization of Plug-in Hybrid Electric Vehicles” in March 2015 at Chalmers. She was supervised by Bo Egardt and Anders Grauers.
Reduced fuel consumption for diesel-electric powertrains

A diesel-electric powertrain can give capacity to heavy vehicles which by far exceeds that of vehicles with conventional combustion engines. The technology, however, requires smart design of the control system. Martin Sivertsson studies how to exploit the full potential of diesel-electric drivelines.

A diesel-electric powertrain has no battery, but generates electrical energy via a generator run by the diesel engine. Hence, all electrical power must be produced exactly when it is needed. Furthermore, the engine has no mechanical connection to the wheels, which means that the rotational speed of the engine is a degree of freedom that must be controlled. Thus one can get maximum power even when the vehicle is stationary, a feature which is very valuable for heavy vehicles such as cranes and excavators. While the technology is common in ships and trains, relatively little research has so far been done on how it can be used for heavy vehicles.

In his thesis “Optimal Control of Electrified Powertrain” Martin Sivertsson presents two different strategies for the optimization of a diesel-electric powertrain, with respect to either response time or fuel consumption. The researchers have primarily studied how to perform a transient – a transition between two operating points in the driveline – in the best possible way. The results show that the time-optimal strategy can reduce the response time by 1-2%, while significantly reducing the fuel consumption at the same time.

“It is easy to determine the most effective operating point for the powertrain at constant output power”, explains Martin Sivertsson. “However, when the output power is changed, a different operating point will be the most effective. We have studied how to control this transition optimally. The slow dynamics of the diesel engine turbocharger as well as the choice to optimize for fuel or for time, are of great importance for how the powertrain should be controlled.”

The researchers aim to exploit the benefits of electrification in the smartest way possible. As a further part of the research they have added an energy storage to facilitate the transients, which improved the driveline response even more.

“With the extra degree of freedom from electrification, we can improve the performance more than can be done for a conventional combustion engine. It is important to make use of this opportunity in the best possible way”, says Martin Sivertsson. “For diesel-electric systems it is common to increase the idle speed to get good response, which is bad for fuel economy. With the smarter transient strategies which we propose, you can avoid such solutions and still get good response and reduced fuel consumption”.

Martin Sivertsson defended his thesis “Optimal Control of Electrified Powertrain” in June 2015 at Linköping University. He was supervised by Lars Nielsen and Lars Eriksson.
New methods for drive cycles

Researchers at Linköping University have developed new methods of generating and transforming drive cycles. The methods make it easier for car manufacturers to design the driveline to minimize emissions and fuel consumption. “A powerful and effective tool for vehicle development”, says Peter Nyberg, who presents the methods in his doctoral thesis.

A drive cycle simulates a vehicle’s speed at different times over a given route and is used by car manufacturers to measure fuel consumption and emission levels and optimize the control of the powertrain. The test values are used by vendors to state the fuel consumption, as well as for calculating the vehicle tax.

Peter Nyberg is a doctoral student in Vehicular Systems at Linköping University. His doctoral thesis presents methods for generating representative drive cycles – cycles that reflect real-world conditions – and transforming existing cycles to meet specific conditions. The methods can be combined to get test results that are easier to compare.

“The drive cycles used today are not always up to the mark”, says Peter Nyberg, “and for future vehicles, they will be outdated. The methods we have developed form a powerful and effective tool for vehicle development.”

In order to optimize the control of the powertrain in terms of robustness and sensitivity it is necessary to run several equivalent drive cycles on the same vehicle for comparison. Designing drive cycles with special conditions is a new step in vehicle technology and means that such comparisons can be made faster and yield more reliable results. Peter Nyberg explains:

“Previously, a drive cycle had to be scaled up in terms of time or speed, or repeated several times to make it more demanding for the vehicle to follow. With our methods, you can start with an existing cycle in a database and create new ones which have the same characteristics in the positions you want to study. If a number of such different but equivalent cycles give different test results, for example in terms of fuel consumption, we can make a much more efficient and reliable analysis of the causes than has been possible before.”

The possibility to change details of a drive cycle opens for more elaborate studies of different vehicle types, such as studies of hybrid electric vehicles’ dependence on braking energy or customization of drive cycles for concept cars that cannot follow standard drive cycles. As our driving behavior changes due to changes in the infrastructure and the vehicle fleet, the automotive industry will see an increasing need for new drive cycles.

Peter Nyberg defended his thesis “Evaluation, Generation and Transformation of Driving Cycles” in June 2015 at Linköping University. He was supervised by Lars Nielsen and Erik Frisk.
Reduced risk of accidents for electric vehicles

The increasing amount of complex components and subsystems in electrified road vehicles can increase the risk for faults to occur during operation. Daniel Wanner’s research makes it easier for the driver to stay in control of the vehicle in critical situations.

Electrified chassis and powertrain systems open up for a variety of features for added safety and convenience in electrified road vehicles. However, the technology increases the risk of technical faults in novel systems such as the electric powertrain. At the same time, faults can still occur in systems like the brake system or in the event of a puncture. The fault does not necessarily have to be serious, but can still lead to unexpected behavior in the car, forcing the driver to compensate by means of speed and steering. If the car deviates from its planned route, it may drive off the road or collide with oncoming traffic.

KTH researcher Daniel Wanner has studied faults in electric powertrains of cars using electric wheel hub motors. As an example, he demonstrates that a technical fault on one of the rear wheels can cause a sudden braking behavior, thus getting the car off course. In such a case, a car without a control strategy will move about 1.3 meters sideways on the road while the driver tries to get the car back on course, according to studies on driver reactions made by Daniel Wanner and his colleagues.

In his doctoral thesis Daniel Wanner presents a solution to the problem – a so-called fault-tolerant control strategy that allows the car to retain its course even during a fault. In tests, the researchers found that lateral movement, yaw rate and steering is reduced by up to 90 per cent if the vehicle is equipped with such a strategy, compared to a car without a fault-tolerant control strategy.

“This solution has the potential to really improve road safety”, says Daniel Wanner. “At best, the control strategy can compensate for the fault so that the driver doesn’t need to act at all.”

Solid preparatory work with a number of studies formed the basis for the results Daniel Wanner presents. Among other things, he has developed a method for the classification of faults based on how difficult it is for the driver to control them. The method can be used in the automotive industry early on in the product development process to decide which faults should be taken into consideration.

Moreover, the researchers have conducted an experimental study in a driving simulator and a modified electric vehicle to investigate how drivers behave during a fault on one of the rear wheels at different speeds and manoeuvres. These studies formed the basis for EU legislation recommendations and have been conducted within the project EVERSAFE with participants from Sweden and Germany.

Daniel Wanner defended his thesis “Controlling over-actuated road vehicles during failure conditions” in June 2015 at KTH. He was supervised by Annika Stensson Trigell and Lars Drugge.
Battery health estimated while driving

Verena Klass has developed a method to estimate the health of Li-ion batteries while driving, using the battery log data. The research utilizes data from the automotive industry and breaks new ground in battery health estimation.

The research results make it possible to estimate the battery’s health indicators – capacity and internal resistance – while driving, using available data such as current, voltage and temperature. The estimates are easy to compare with measured values obtained in standard lab tests but require no additional equipment or knowledge in addition to battery log data.

“As long as the battery is not taken out of the car for a lab test, we know very little about its state of health”, says Verena Klass who has conducted the research as a PhD student in electrochemistry at KTH Royal Institute of Technology. “Since electric vehicle batteries are subject to great stress, they are often oversized, as a safety measure. With continuous health status updates, the use of the battery could be adapted for greater safety and efficiency.”

The method is based on a self-learning algorithm of the type used by search engines such as Google to rank search results. However, it has not been applied to battery health estimation before.

By examining large amounts of battery data from the automotive industry, Verena Klass could develop data-driven models for typical driving events. The battery models were tested virtually, a procedure which provides the same results as real-life battery tests in a lab. The next step was to verify the calculated health indicators using the measured resistance and capacity values. The method was tested on a full electric car, a plug-in hybrid and a hybrid truck.

“The idea is that the method should work for all types of vehicles and for any battery”, explains Verena Klass. “I do not even know the electrolytes of the batteries I study, but I can nevertheless estimate their internal resistance.”

The method is still on research level, but Verena Klass can think of several future applications.

“A method that does not require lab tests may be interesting for the second hand market when the use of electric vehicles increases. An app could for example calculate whether a used Li-ion battery is suitable for further use in a car or as backup power for domestic purposes”, concludes Verena Klass.

Verena Klass defended her thesis “Battery Health Estimation in Electric Vehicles” in October 2015 at KTH. She was supervised by Göran Lindbergh and Mårten Behm.
Effective cooling of electric car batteries

High temperature is one of the biggest security risks for lithium-ion batteries in electric and hybrid vehicles. Temperature conditions also have great impact on the aging of the battery. Henrik Lundgren has together with Scania created a model that makes the development of cooling concepts for these batteries more effective.

Temperature is one of the factors that most influence safety, lifetime and performance of lithium-ion (Li-ion) batteries, and is a major obstacle on the road to market success for electric and hybrid vehicles. The problems grow with battery size, causing a great need of knowledge about the thermal processes among vehicle manufacturers.

“The temperature influences the mass transport, i.e. the ions’ way through the electrolyte of the battery”, explains KTH researcher Henrik Lundgren. “The lower the temperature, the slower the mass transport. At higher temperature, the process is faster but also the side reactions, which leads to faster aging and greater risk of faults.”

“Henrik’s research is a step forward in our work with thermal modelling”
Pontus Svens, Scania

Henrik Lundgren has investigated how Li-ion batteries are affected by different temperature conditions and has developed new tools for analysing temperature effects. In cooperation with Scania, he has developed a thermal model to study the cooling of large Li-ion batteries. The model allows the battery researchers to perform tests faster than before and reduces the need for measurements through simulations to just a few. Thus, problem areas can be found at an early stage.

“Having a well-functioning process to test and evaluate new battery system is essential”, says Pontus Svens, development engineer of energy storage at Scania. “Henrik’s research is a step forward in our work with thermal modelling. It has given us the confidence to use this type of thermal model to test large battery cells.”

The results reached by using the model shows that significant differences in cooling only can be achieved inside the battery itself - something that requires very close cooperation between battery manufacturers and automotive industry. Such a development is hardly realistic according to Henrik Lundgren, which makes it even more urgent for vehicle manufacturers themselves to conduct effective studies.

Scania can now build on Henrik Lundgren’s model to examine different cooling concepts and perform further tests as part of a wider study on thermal modelling of large batteries.

Henrik Lundgren defended his thesis “Thermal Aspects and Electrolyte Mass Transport in Lithium-ion Batteries” in June 2015 at KTH. He was supervised by Göran Lindbergh and Mårten Behm.
Project reports

Since most of SHC’s projects were finalized by summer 2015, summaries are presented here (with a few exceptions for running projects). The final reports are available on the website: www.hybridfordonscentrum.se/en/forskning/.

The projects of each theme are presented in alphabetic order.

System studies and methodologies

Dimensioning plug-in hybrids using drive-cycle information/Drive cycles

**Participants:**

*Part a (Drive cycles)*: Prof. Lars Nielsen (project leader)  
Peter Nyberg (PhD student)  
Erik Frisk; Linköping University

*Part b (Dimensioning plug-in hybrids using drive-cycle information)*: Prof. Jonas Sjöberg (supervisor)  
Anders Grauers (supervisor)  
Victor Judez (PhD student); Chalmers

**Reference group:**

Sören Eriksson, Volvo Cars  
Mathias Björkman, Scania  
Sixten Berglund, AB Volvo

**Total cash support from SHC:**

*Part a*: 2025 kSEK,  
*Part b*: 1013 kSEK

**Duration:**

2013–2015

The objective of this project has been to obtain representative driving cycles sufficiently close to data from real-world driving.

A driving cycle is a representation of vehicle speed versus time. In the automotive industry driving cycles have been used to evaluate vehicles both in the development phase of new vehicles and in gas emission tests. Using fixed driving cycles there is a risk that the vehicle is optimized for a certain driving cycle. If the driving cycle is not representative for real-world driving there is a considerable risk that it will be a sub-optimal solution for real-world driving.

One case of use of driving cycles is the sizing of powertrain components. For hybrid electric vehicles the energy consumption, emissions and economic viability of the vehicle strongly depends both on the component sizing and on the use of the vehicle in real-world driving. Therefore driving cycles that correctly describe the use of the vehicle are of great importance for the sizing process.

The generation of representative driving cycles (part a of the project) is solved by a two-step-method where the first step is generation of candidate driving cycles using a Markov chains where the transition probabilities are estimated from real-world driving data. As a second step these candidate driving cycles are transformed to target statistical measures that can for example be that of real-world driving. The transformation of the
driving cycles where formulated as an nonlinear programming problem and was solved by standard optimization techniques.

On the application side, driving cycles are used to sizing the battery and range extender of a Range Extender Vehicle (part b of the project). The objective is determining which driving cycles characteristics most influence the sizing of battery and range extender for Range Extender Vehicles. Additionally we investigate the robustness of the battery size and range extender sizing towards changes in the driving and economical parameters. The problem of finding an optimal battery size is formulated as an optimization problem, in which the Total Cost of Ownership of the vehicle is minimized. In the case of the range extender sizing both performance requirements and control strategies are considered when determining the optimal sizing.

The combination of the two driving methods yields a stochastic and general to generate driving cycles with certain properties that can be used during several stages during the vehicle development process of vehicles.


### Driver models and mission-based driving cycles

**Participants:**
- Sogol Kharrazi, VTI
- Lars Nielsen, Erik Frisk, Linköping University

**Reference group:**
- 

**Total cash support from SHC:**
- 200 kSEK

**Duration:**
- 2015

This project is a collaboration between Linköping University and the Swedish National Road and Transport Research Institute. The aim is to prepare an application on the topic of “driver models and mission based driving cycles”.

In recent years, various studies have been undertaken to develop methodologies for generation of representative driving cycles that reflect the real world driving conditions. There are different factors that affect the real world driving patterns, such as vehicle type, driver and traffic condition; thus, for a comprehensive assessment of powertrains, there is a need for driving cycle generation methodology which takes into account all these factors. This need will be addressed in the prospective application which will be focused on defining representative driving missions (including e.g. road types, obstacles and traffic conditions) and generating the speed profiles for the defined driving missions using driver models.

The existing literature in the field of stochastic generation of driving cycles has been reviewed, as well as the existing knowledge in the field of driver behaviour modelling in microscopic traffic simulation. Some of the identified areas for further research are generation of a driving mission with similar statistical properties as naturalistic driving data, identification of the key parameters of the driver behaviour models for generation of driving cycles and estimation of the driver model parameters.
Evaluation of energy efficient cornering strategies using the KTH Research Concept Vehicle

Participants:
Jenny Jerrelind, Lars Drugge; KTH

Reference group:
Annika Stensson Trigell, KTH,
Mats Jonasson, Volvo Cars,
Leo Laine, AB Volvo,
Markus Agebro, Scania

Total cash support from SHC:
325 kSEK

Duration:
2014–2015

Reducing vehicle energy consumption is a key issue for the vehicle manufacturers as well as for the consumers and an important aspect for our environment. The introduction of more advanced drive systems will allow vehicles to be implemented with multiple electrical actuators enabling over-actuation. These actuators open up for new and cost-efficient solutions for motion control, which makes it possible to develop vehicle control strategies for enhanced energy efficiency without compromising comfort and safety.

The aim with this project is to study and develop energy-efficient cornering strategies for electrified vehicles with different degrees of active control of the propulsion and steering, as well as evaluate these strategies by using the KTH Research Concept Vehicle (KTH RCV). The research work is based on the preliminary findings in the now finished SHC-project “Generic vehicle motion modelling and control for enhanced driving dynamics and energy management”.

A simulation environment for development and evaluation of energy efficient cornering strategies using over actuation have been developed. Simulations for different types of manoeuvres (double lane change, single lane change and steady-state cornering) and parameter settings have been performed and analysed. It is found that it is possible to improve the energy efficiency in the order of 1-5 % during cornering with the developed cornering strategies. Simplified cornering strategies are now prepared for implementation in the KTH RCV to experimentally evaluate their energy efficiency.
Fault-tolerant over actuated HEVs

Participants:
Annika Stensson Trigell (project leader),
Daniel Wanner (PhD student),
Lars Drugge (co-advisor),
Oskar Wallmark, Mats Leksell (co-advisor),
Mattias Tidlund; KTH

Reference group:
Mats Jonasson, Volvo Cars
Leo Laine, AB Volvo

Total cash support from SHC:
4500 kSEK

Duration:
2009–2015

The challenges of the trends in chassis and driveline electrification in combination with the continuing growth of individual road transport have led to the research objectives of this project. The goals of this research are to characterize the influence of different failure modes on the dynamic behaviour of vehicles and the associated driver-vehicle interaction as well as developing fault-tolerant control strategies for compensation of these failure modes.

The central research question is formulated as follows: To what extent influence different failure modes the dynamic behaviour of vehicles and driver reactions, and how can severe failure modes be prevented by exploiting over-actuation through fault-tolerant control strategies?

Since particular focus is on HEV concepts where propulsion power is obtained from in-wheel motors at each wheel an important initial task was to present an electromagnetic design of a light in-wheel motor to fulfil the required specifications. As a result from the motor design procedure, various transient models have been obtained which accurately predicts the behaviour of the motor during various types of electrical faults and control methods. These transient models, and simplified versions of them, have been used in various vehicle simulations to predict vehicle behaviour for different vehicle control strategies during failure modes. A method to assess possible risks of failures has been proposed and evaluated. Possible consequences on the dynamic behaviour of the vehicle caused by the identified faults have been analysed, and solutions on to how to compensate for the occur-ring faults have been developed. As an example, if the propulsion power suddenly vanishes from one wheel of a vehicle, the remaining
vehicle, can, if properly controlled, maintain vehicle stability and thereby guaranteeing passenger safety. Also the effect of including drivers in the loop has been studied.

The project was made in collaboration with Volvo Cars, AB Volvo and BAE Systems Hägglunds. Daniel Wanner defended his thesis *Controlling over-actuated road vehicles during failure conditions*” in June 2015.

Model of simulation of driving behaviour during failures in electrified vehicles

*Participants:*
Lars Drugge, KTH

*Reference group:*
Annika Stensson Trigell, KTH
Mats Jonasson, Volvo Cars
Malte Rothhämel, Scania

*Total cash support from SHC:*
210 kSEK

*Duration:*
2014–2015

The aim of this project has been to design a failure sensitive driver model using parameters derived from experiments in a moving-base driving simulator performed within the ERA-NET Electromobility+ project EVERSAFE, where the subjects were exposed to sudden failures in one of the rear wheels that required adequate corrective measures to maintain the vehicle control and regain the planned trajectory.

A driver model has been developed that can represent the driving behaviour during failures in electrified vehicles. The model is based on measurements of human responses when exposed to different failure conditions influencing vehicle directional stability. The developed driver model is building on the findings in the finalised SHC-project “Fault-tolerant over-actuated hybrid electric vehicles”, which had the aim to analyse the impact of failure modes and find suitable fault-tolerant control strategies in electrified vehicles, in order to gain knowledge of driver-vehicle interaction during a failure.

The developed driver model has been used in a simulation environment to evaluate the influence of failures in electrified vehicles. The results show that the proposed failure-sensitive driver model is capable of maintaining the vehicle control and regaining the planned trajectory similarly to the way in which humans achieved this during a rear wheel hub motor failure. Furthermore the model has been used to analyse the influence of fault-tolerant vehicle dynamic control strategies on the driver-vehicle interaction using the Research Concept Vehicle (RCV) at KTH. Finally, the modelling and evaluation of the driver model have been documented in a scientific publication accepted for publication in the proceedings of FAST-zero’15.
Optimal Energy Management of Electrified Powertrains

Participants:
Prof. Lars Nielsen (project leader)
Martin Sivertsson (PhD student)
Lars Eriksson, Linköping University (supervisor)

Reference group:
Bo Egardt, Chalmers
Sören Eriksson, Volvo Cars
Mathias Björkman, Scania
Lars Nielsen, Linköping University

Total cash support from SHC:
675 kSEK

Duration:
2014–2015

The main objective of this project was to study optimal energy management of electrified powertrains. The level of hybridization has a strong impact on the nature of the models and methods suitable to solve the problem. In the project modeling for optimal control as well as optimal control studies are central parts.

Adding more than one motor to the powertrain increases the complexity of the powertrain since more degrees of freedom (DoF) have been introduced. This freedom increases the demand for intelligent control in order to benefit from the electrification. Optimal control is an interesting path both to study how to best exploit the DoFs, or to control the powertrain in real-time. The size of the additional energy storage, e.g. battery, influences the nature of the optimal control methods used and which level of detail that needs to be modeled.

In hybrid electric vehicles (HEV) the size of the energy storage reduces the impact of poor transient control, since the battery can compensate for the slower dynamics of the combustion engine. For HEVs the problem instead is how and when to use the battery to ensure good fuel economy. A map-based equivalent consumption minimization strategy controller using feedback control from the battery state of charge is designed and tested in a real vehicle with good results, even when the controller is started with poor initial values. In a plug-in HEV (PHEV) the battery is even larger, enabling all-electric drive. Thus it is desirable to make use of the energy in the battery.

Several contributions to hybrid vehicle technology have been made in this project. For industry producing off-highway and heavy duty machinery, the main source of power, even in the presence of electrification/hybridization is the diesel engine. How to control the diesel engine in electrified powertrains, with and without energy storage, has received very little attention. In this project both a methodology for how to approach the problems have been developed, and results have been presented showing how to exploit the DoFs. Further a model has been made freely available for the academia and industry to conduct their own studies, and an optimal control benchmark has been suggested, aimed at assisting in the development of new optimal control tools.

For passenger cars, and especially plug-in hybrid electric vehicles, the main contribution is a control methodology showing how close to optimal performance can be achieved using only information available in a GPS.

The project has shown the benefits of electrification and hybridization also for the off-highway industry, both developing a methodology for how to solve the problems, and...
showing what the benefits are of different levels of electrification. These topics have received very little attention from the research community. A further novelty is showing both academia and industry that complex optimal control problems of the size seen in the project, can be solved using numerical optimal control, advancing the use of these methods. The energy management controller suggested for a plug-in hybrid electric vehicle is shown to be the best performing controller in the IFP PHEV benchmark, showing a methodology to implement close to optimal energy management using a minimum of future knowledge.

Martin Sivertsson defended his thesis *Optimal control of electrified powertrains* in June 2015 at Linköping University.

Predictive control for complete vehicle energy management

*Participants:*
Bo Egardt, Chalmers

*Reference group:*
Bo Egardt, Sébastien Gros, Chalmers
Mikael Askerdal, AB Volvo
Anders Lasson, Volvo Cars
Mathias Björkman, Scania

*Total cash support from SHC:*
1180 kSEK

*Duration:*
2014–2015

The purpose of this (half-year long) project is primarily to bridge the gap between Chalmers’ successful and finished projects in energy management during Phase 2 of SHC and a planned continuation project during Phase 3. The latter has been prepared in a pre-study and approved by the steering group, but funding of a continuation project has not yet been decided.

Part of the results of this project is based on a model predictive control architecture that divides the energy management problem into three layers that operate with different update frequencies and prediction horizons. The top layer plans the kinetic and electric energy in a convex optimization problem, the medium layer plans the gear and powertrain mode in a dynamic program, whereas the lowest control layer tracks available references in real time. Both the top and the medium control layers employ predictive road information, while the top control layer also incorporates information about the surrounding vehicles and traffic flows.

Research results for a predictive cruise controller that safely keeps distance to surrounding vehicles are presented where it is also shown that predictive information of the movement pattern of surrounding vehicles can be incorporated into the convex optimization in order to minimize energy losses.

When a platoon with multiple vehicles is formed, limited information from the top control layer can be shared between the vehicles to minimize energy losses of the entire platoon. By modelling the air drag with affine (linearized) relations, it is possible to optimize the energy management in a centralized convex program, or by applying algorithms from distributed optimization, without sharing sensitive information. It is
shown that optimized energy management can be achieved by sharing only the optimal time trajectories (as a function of distance) from each individual vehicle. Neither of the vehicles needs to reveal any other details about the energy-management strategy.

Another part of the results is based on adapting a model predictive control to complex powertrain configurations. A method for applying convex modelling and optimization of electrically supercharged internal combustion engine vehicles has been presented, as well as model predictive control of a hybrid electric powertrain with an electrified waste heat recovery. Finally, a survey of optimization strategies for system-level design in hybrid electric vehicles has been prepared.

A minor part of this project has supported the final stage of Mitra Pourabdollah’s PhD project at Chalmers. Mitra defended her thesis *Optimization of Plug-in Hybrid Electric Vehicles* in April 2015. The report can be found in Chalmers Publication Library.

Safe and energy efficient vehicle designs

**Participants:**
Annika Stensson Trigell, KTH
Mats Jonasson, Volvo Cars

**Reference group:**
Annika Stensson Trigell (KTH)
Oskar Wallmark (KTH)
Leo Laine (AB Volvo)
Malte Rothhämel (Scania)

**Total cash support from SHC:**
320 kSEK

**Duration:**
2014–2015

The project aims to design a functional architecture in electric vehicles in order to get higher energy efficiency and keep a high level of safety.

A control architecture has been developed and tested for the KTH Research Concept Vehicle (RCV). The architecture is tailor-made for over-actuated vehicles and admits a systematic approach for controlling the motion of the car body and the vehicle’s actuators, and thereby the developed architecture contributes to controlling vehicles in a safe and energy efficient manner.

The aim with the proposed architecture is to:
- Control actuators efficiently, e.g. admit low energy consumption
- Provide an inherent protection for faults
- Separate the task of controlling the motion of the car body and controlling the actuators – and hence facilitate the integration of vehicle dynamics functions
- Verify previous research in a real car

The developed architecture comprises of:
1. A Driver Interpreter (DI), which uses sensors from steering wheel and pedals, to interpret how the driver wants to move the car body. The DI outputs desired longitudinal force and lateral force defined at the vehicle’s centre of gravity (CoG). DI also outputs a desired yaw torque, defined around a vertical axis in CoG, to be able to provide rotation of the car body.
2. A Force Allocator (FA), which includes logic to distribute desired forces to each wheel, meeting the demands from the DI. The distribution can be done in infinitely many ways, but the FA has here been implemented to find the solution, which gives the smallest norm of forces, by the use of Penrose Moore pseudo inverse. The FA however admits other allocation logic to be implemented.

3. An Actuator Coordinator (AC), which here is implemented to convert desired wheel forces to four steering angles and four wheel torques. The conversion to steering angles is here implemented by an inverse of a tyre model.

The proposed control architecture was programmed in Simulink and implemented into the RCV. Tests performed at Arlanda test track shows that the proposed control architecture works as intended.

System level evaluation of diesel engine and emission after treatment systems for hybrid drivetrain applications in dynamic drive cycles

Participants:
Tomas McKelvey, Jonas Sjöblom, Chalmers

Reference group:
-

Total cash support from SHC:
300 kSEK

Duration:
2014–2015

Modern, efficient combustion powertrains includes, besides the combustion engine, an exhaust after treatment system (EATS) to limit the emissions. In a hybrid vehicle application the combustion powertrain is complemented with e.g. an electric motor/generator and some electric energy storage capability. To obtain an efficient vehicle that minimizes fuel costs and obey legislative emission limits an overall control system is required. The efficiency of the EATS is highly dependent on the temperature in the catalysts. In the traditional, non-electrically heated catalysts the temperature can only indirectly be influenced through the control of the combustion engine. In transient work cycles, where the combustion engine is operating at various loads, the after treatment system temperature and efficiency to reduce emissions will vary significantly. In hybrid applications, where engine shut-off is employed, the situation is further pronounced. Efficient/optimal system level control strategies that explicitly accounts for the temperature effects are non-trivial for transient work cycles.

In this project dynamic drive cycles have been tested and evaluated using a hybrid drivetrain in a test rig. Studies have been made of conventional ICE operation and a strategy when the electric machine have briefly been evaluated to analyse the influence of emissions, by supporting the ICE. The strategy have only been using small amounts of energy during these tests. Load has been shifted from the combustion engine to the electrical motor. Good results have been made, Engine Out emissions peaks with NO was reduced from 2000 PPM to 500 PPM during cold start conditions and small torque split during transient operation.
The development of new electrified driveline configurations with wheel hub motors can reduce the commonly known trade-off between the objectives vehicle handling, comfort and energy efficiency. Vehicles with these types of electrified drivelines are often over-actuated; i.e. more actuators than needed to control the degrees of freedom of the vehicle are available. The implementation of novel control concepts into such over-actuated vehicles enables to switch dynamically between these main objectives depending on the driving situation. Besides the increase of the degrees of freedom on how to control these over-actuated vehicles, it also increases the number of possible failure modes during operation.

In this work, fault handling strategy for one possible failure mode (negative torque on one rear wheel) in such a new electric driveline is analysed in an experimental vehicle, the KTH Research Concept Vehicle (RCV). The chosen control method is based on the control allocation principle and employs the pseudo-inverse method, which can be performed in real-time. The electric driveline of the RCV incorporates a wheel hub motor in each of the four wheels, which is individually controlled by a power electronic converter. Another fault handling strategy has also been studied for the failure mode above and a failure mode of one disengaged steering actuator.

The strategy here was to control the steering angles on the wheels only as well as a combined approach with both torque control and steering angle control. The project have through validation of past simulations results and further tests shown that over-actuation can be used to effectively mitigate failure conditions by using torque control and steering control seems to also show promising results.

The project has collaborated with ITRL – Integrated Transport Research Lab that owns and manages the RCV.
To realize major improvements in terms of energy efficiency of the propulsion system in heavy hybrids, a truly holistic approach is needed. This is a long-term goal of the HOLICE project established within the Scania and KTH strategic collaboration platform (ASP). The project received funding from SHC for the period 2014-10-01 to 2015-03-31 with Oskar Wallmark (KTH/Dept. Electrical energy conversion) as project leader.

In this project a general survey of today’s state of the art was first carried out. As a key outcome a list of potential ideas for realizing improvements in heavy hybrid-electric drivetrains has been identified. Several of these proposals identify possible potentials for improvement through unconventional use of electrification to mitigate limitations of the combustion engine. Most of these proposals must be considered as high-risk nature, and a selection of the proposals will be identified for further analysis in the form of master theses project works, representing more detailed pre-studies of the proposals.

The key results so far are a mapping of different research initiatives and funding bodies with focus on hybrid electric drivetrains and combustion engines and a list of suggestions suitable for coming pre-studies in the form of master thesis project works. Additionally, one of the suggestions for a coming pre-study, comprising of a novel hybrid driveline configuration, has been experimentally implemented as a small scale hybrid electric vehicle built by approximately 20 students at KTH and competing in the 2015 Shell Eco marathon competition which was held in Rotterdam (see Figure 1). Also, a waste-heat recovery system was installed in the vehicle.
A scalable model for life cycle inventory of electric automotive traction machines

**Participants:**
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**Reference group:**
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Maria Wallenius Henriksson, AB Volvo/VGTT
Axel Edh, Volvo Cars

**Total cash support from SHC:**
530 kSEK

**Duration:**
2014–2015

This project has the aim to establish a scalable life cycle inventory (LCI) for an electric permanent magnet synchronous motor (PMSM) intended for electric vehicle propulsion. Life cycle assessment is a frequently used tool when assessing the environmental impact of electric powertrains in vehicles. However, within the research field there is a lack of new and relevant inventory data for powertrain components, which can be scaled and adapted to match different powertrain requirements.

The purpose of the work here described is to establish a general scalable inventory for a PMSM intended for electric vehicle propulsion, including new manufacturing data.

The project started in March 2015 and finished in June 2015. The project then continued with funding from Chalmers Energy Area of Advance. The SHC project was initiated to establish a first version of the scalable PMSM LCI.

A generic and scalable LCI model of a PMSM intended for automotive traction applications has been established as a result of the SHC part of the project. The model takes into account that active and passive parts of the machine scale differently when power requirements are altered. Two different reference geometries, where the radius is fixed and length is scaled up and down, have been analysed with ANSYS Maxwell, a design software and support tool for electric motor development. Maximum speed (revolutions per minute) and internal parameters such as number of poles, magnetic flux density, winding fill factor are held fixed in the design. Complex design issues have not been in focus and data precision has been balanced based on relevance from an LCA perspective. For example, the permanent magnet composition has focused on the content of the main constituents and a representative modelling of the rare earth metal content, whereas plausible minor alloys of the magnet like copper and aluminium have been
disregarded, as these substances are included in much larger quantities in other subparts such as windings and housing.

In the model file the user specifies the maximum power value and receives data for the material configuration and weight. Options are available for calculation of the inventory with or without shaft, with or without one, or both, endplates including bearings on each side, and with or without housing. This allows for large flexibility in the inventory analysis if the motor under study is mounted alone or integrated with other powertrain parts such as a transmission or inverter.

Some manufacturing data has also been investigated within the scope of the SHC project and a new dataset for the making of electrical steel from hot rod coiled steel has been collected from Surahammars Bruk AB. It constitutes the foundation for the making of both the stator and rotor steel laminations. However, collection or adaption of data for manufacturing of magnets, motor laminations, housing and complete assembly remains for the second part of the project. The second phase will also include a validation of the model with industry data, and a more thorough description of how to use the model from the perspective of an LCA practitioner.

Automatic conductive charging connection

**Participants:**
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**Reference group:**
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Johan Lindström, Scania
Pär Ingelström, AB Volvo

**Total cash support from SHC:**
LTH: 100 kSEK; KTH: 75 kSEK

**Duration:**
2014–2015

This project is mainly a student project performed as two separate sub-projects at LTH and KTH. The projects are summarized separately below.

In today’s society transportation in different forms have a big influence on the environment. To decrease the dependency on fossil fuels a lot of effort has been put on lowering fuel consumption and making the vehicles run on electricity. Both hybrid- and fully electric vehicles are becoming more popular. One of the big problems to solve is the power storage and charging of the vehicles. Batteries are heavy, and take up a lot of space. However, if the vehicles could be charged more often the amount of batteries could be reduced to a reasonable level. Transportation vehicles normally have several stops on their route at which point they could be charged by an automated charging station.

**LTH part:**
This report covers the development of a possible solution to the above mentioned problems and describes an automatic charging station for powers up to 200 kW that not only is completely automated but also would make the charging faster than it is today.

The solution is a robot arm with six degrees of freedom, where the arm is placed on a rail. The conductor is cylindrical for easier localization and connection, with another
shape the conductor would need to be rotated before fitting with its counterpart, this step is now unnecessary. The work presented here is the implementation of the conceptual design in a working prototype.

The developed connector consists of a male and a female part. These are not bound to be connected with a certain angle of rotation in relation to each other. The female part is passive, meaning the male part is the one to induce a pressure over the phases. This pressure is achieved through having three segments which are pressed outwards by means of a pneumatic mechanism. There are five phases (3 active, ground and protective earth) located on top of each other, where the male phases contain knobs on the surface to ensure good contact. The male part consists of isolating material separating the 5 phases and also empty space in the middle where cables can go down and connect to the phases.

**KTH part:**
In this sub-project a novel approach to the automatic connection problem has been analysed. It consists of a retractable ring on the ground side, and a hook and slot on the vehicle side. The hook grabs the ring and slides it up into the slot where the electrical connection will be done.

A mechanical model of the system has been built that shows the concept of the system. 3-D printing has been used to visualise the insertable electrical connector.

The conceptual idea is still in a development phase and the work will continue to see how it can be further developed. It is foreseen that a successful implementation of a cheap and reliable automatic charging connection can be very important for a larger introduction of electrically drive distribution trucks.
Compact rotor power transfer in wound rotor synchronous motor (WR-SM) for high performance electric vehicles

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**Reference group:**
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Anders Grauers, SHC
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Martin West, AB Volvo

**Total cash support from SHC:**
1300 kSEK

**Duration:**
2014–2015

Electric and hybrid vehicles requires high performance electric motors with high peak torque, wide speed range, high efficiency, and low-cost for mass production. The commonly used permanent magnet (PM) motors and induction motors have unsatisfactory performance under field weakening and are expensive in material purchase (rare earth magnets) or mass production. A wound rotor synchronous motor (WR-SM), due to its independent and controllable rotor excitation, can deliver any desired torque at any speed with high efficiency. However, the brushes and slip rings for rotor excitation need maintenance and may influence operating reliability. The purpose of this project is to find a compact concept to transfer power into the rotor windings and verify the concept experimentally together with a wound rotor synchronous motor (WR-SM).

The project starts with the idea of a high frequency rotating exciter. The size of exciter decreases with the increase of its frequency. The power needed in the rotor winding is not more than a few percent of the motor power. The high frequency exciter of small size can be integrated into the rotor for a compact design.

The technical results of the project is a new high performance traction motor which has:

- Peak torque can be boosted up to 300%
- Wide area with high efficiency (down to 5% of peak load)
- New control possibility
- Very high efficiency rotor power transfer (5% higher than the state of art 2014)
- Compact and low-cost solution for rotating transformer (peak power 2.7kW, weight 0.4kg)

The academic results include innovative design of rotor power transfer and system testing of the brushless WR-SM.

The results show the great potential for this motor concept to be used in high performance electric and hybrid vehicles. The study in this project is far from comprehensive due to the project resources and time. Deeper and wider study in different aspects about this concept is recommended by industry.
This project provides a holistic perspective on the costs of different variants of a full electric road transport system. To do this, a selection of the dominating types of vehicles and a finite set of charging solutions are studied. Four different vehicle types are studied:

- Cars
- Long Haul Trucks (& Coach Buses)
- Distribution Trucks
- City Buses

The study is made with Sweden as example.

Each vehicle type has unique specifications of electric traction power, electric driving range / battery size and charging power/charging time requirements. Electric Road Systems (ERS) are assumed to be present along all National and European roads.

The modelling is made with two different scenarios; I) The Over Head (OH) scenario, representing what is currently possible with existing technology; and II) The Road Bound (RB) scenario, representing what is “around the corner” in terms of charging technology.

In both scenarios, all vehicle types have an on board charger providing a full battery charge in 8 hours used for night time charging.

The results presented in the report (see www.hybridfordonscentrum.se/en/forskning) are based on a lot of assumptions and input data which can and should be discussed. The output data may for the same reason not be an exact description of the cost to set up any of the different scenarios studied. However, the trends and main results are indisputable:

1. The societal cost of any of the OH-Scenarios are at least 3 times higher than the cost of the RB-Scenarios. The total national annual cost of vehicles and Infra structure spans from 25 000 M$/year with Road Bound ERS to 96 000 M$/year with Over Head based ERS.
2. The battery cost is the by far the dominating part of the cost. That is why technologies that support small batteries benefit. In particular, cars benefit significantly from Road Bound ERS; both in terms of reduced battery needs and eliminated need for High power Charging Stations.
3. AC High Power Charging may not affect the vehicle cost much, if Integrated Charging is applied, but has a significant impact on the static infrastructure cost.

Based on the results from this report, it is recommended that:
1. The development of Road Bound ERS is strongly supported. Compared to Over Head ERS there is no big cost difference on the ERS Infra Structure itself, but Road Bound ERS presents a cost reduction of at least 59,000 M$/year on the vehicles (mainly on the Car batteries) and another 1,000 M$/year for the static charging infrastructure needed for the full electric road transport system. Compare to the Swedish Gross National Product 2014 = 480,000 M$.

2. The development of Automatic AC Charging capabilities for both Buses and Distribution trucks is encouraged. The application of such solutions will reduce the cost for Distribution Trucks (mainly on the batteries) with more than 700 M$/year while increasing the cost for the static Charging Infrastructure for these vehicles with about 8 M$/year.

There are more conclusions to be drawn, and the reader is encouraged study the report and consider the implications of the results presented.

EMC and safety studies on Electric Road Systems

Participants:
Richard Sebestyen, AB Volvo (project leader)
Mats Alaküla, Lars Lindgren, Lund University

Reference group:
Richard Sebestyen, AB Volvo
Håkan Gustavsson, Scania

Total cash support from SHC:
2000 kSEK

Duration:
2013–2015

This project has analysed the electromagnetic emissions from an Electric Road System (ERS) with a new measurement method. The measurement result indicates that it should be possible to fulfil current standards. The project also suggested Electromagnetic Compatibility standardization (EMC) of conductive ERS, as current standards are not fully relevant to ERS. In addition to potential EMC problems, the risk with short circuits through tires in some ERS-solutions has been investigated and was found to be less of a problem than expected.

Electric Road Systems are systems that supply energy from the electric grid to electric vehicles while they are driving. ERS can reduce the needed battery size in electric vehicles and reduce the fuel consumption in hybrid vehicles, but can also generate radio interference, i.e. EMC problems.

In this project an overview of EMC standards for road vehicles, trolley busses and trains and how they relate to ERS is made. A small scale test rig for testing the behaviour of sliding contacts in an ERS context is built and used to determine the generated EMI. A full scale electromagnetic physical model of an ERS with a car is built and the electromagnetic propagation is measured in this model. The results from the small scale test rig and the full scale electromagnetic physical model are combined to an emission spectra that has been compared against EMC standards.

In addition to the EMC related activities the probability and effects of short circuits through tires is investigated. The general structure of different types of tires is
investigated by contacting the tire manufacturer Bridgestone. The probability of short circuits is evaluated by measuring the insulation e.g. between screws puncturing the tire. A capacitor discharge rig has been built and used to test what happens if a short circuit through a tire happens. The capacitor discharge circuit consisted mainly of a 600 V capacitor bank of 10 mF with reverse polarity protection diodes, a 70 μH current limiting inductor and a mechanical switch.

Since these systems are new, very few studies on these subjects have previously been published. The development of ERS technology is very much about “breaking new grounds” and all challenges addressed as well as results achieved in this project are unique.

Fault detection and increased reliability of a 3.3 kW on-board battery charger for PHEVs

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Reference group:
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Total cash support from SHC:
700 kSEK

Duration:
2014–2015

Reliability is an important performance index of a modern power electronics converter. The failure modes and effect analysis (FMEA) is one the most used techniques to evaluate or possibly improve the reliability of a power electronic system. This is one of the key challenges in electronics converters for vehicle industry. The project aim is to increase the reliability of a 3.3 kW on-board vehicle battery charger. However, the techniques can be utilized in other electronic converters like traction inverters and DC/DC converters.

For a 3.3 kW vehicle battery charger an FMEA is provided to evaluate and quantify the reliability for important fault scenarios. In addition, the cause of failures and recommended actions are also provided. After the fault detection, appropriate changes in software are provided to be able to continue the charger operation but probably with a reduced functionality. For example reduced charging power to a pre-determined level is necessary in many fault cases.

In addition to the fault detection and changes in operation, some design changes in electronic hardware are suggested to increase the reliability. For example providing a bypass current flow path by adding an extra diode to the charger circuit is suggested. Computer simulations have been performed to verify the theoretical analysis, fault detection algorithms and provided solutions for increased reliability. Hardware development to verify the analytical and simulation results is in process.
The project was performed in collaboration with ePower (Kongsberg Automotive) as one of the leading on-board charger producers. The idea was to use the project results to enhance the product performance.

Flywheel energy storage – a white paper

Participants:
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Johan Lundin, Uppsala University
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Johan Abrahamsson, Uppsala University

Reference group:

Total cash support from SHC:
150 kSEK

Duration:
2015

At the Institution for Science and Technology in Uppsala new types of rotating energy storage are being developed. The idea is to make kinetic energy storage with electrical interfaces which can handle both high power and still have a given energy density. These flywheels differ from traditional flywheels since they aim for comparably high energy densities.

There is a need to understand why the flywheel energy storage research is needed, and if there is any international interest and within the research and technical community for the technology. Another important aspect is the potential for future developments. We have seen a need to make a comparison between different types of high-power energy storage in different contexts (end applications), to help decision makers understand the niche for flywheels.

The state of the flywheel energy storage industry and research has been investigated, specifically for hybrid and electric vehicles within the SHC area. The overall aim was to do a literature study to increase the understanding on the flywheel niches. The research at Uppsala University was also described and put in context with international research, leading manufacturers and relevant patents.

Flywheels were found to be used in large scale settings in a variety of systems already (both within the SHC area and outside), some of which are:

- A manufacturer will supply 500 power buffers in London buses. Early results indicate a 45% fuel saving for a 17 ton bus.
- Another manufacturer reports 35% fuel savings for SUVs in the US FTP drive cycle, and 18% fuel savings.
- Another manufacturer holds 30% of the frequency regulation market in northeastern USA with only 10% of the power. The dominance is mostly due to a great ability to follow the control signals and cycle.

A literature study in flywheel was written, and it has the following results:

- Accurate description of state-of-the-art in flywheels,
- Discussed commercial potential, and future research potential
- Explained flywheel in the context of other energy storage
• Summarized relevant research in the field (26 research groups)
• Summarized manufacturers in the field (27 companies)

All of this is important to increase the understanding of the need for flywheel energy storage, and the niches they excel in.

High-efficient, ultra-compact integrated electric drives for tomorrow’s alternative drivetrains

Participants:
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Sonja Lundmark, Chalmers
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Partners:
Outside SHC, Eskilstuna Elektronikpartner AB (EEPAB) is participating (funded by 50% from EEPAB and 50% from Vinnova) in the project building a full-scale converter prototype.

Funding
Total cash support from SHC: 1575 kSEK
Vinnova funding (2015–2016): 300 kSEK

Duration:
2013-2018

By utilizing a number of low-voltage, series-connected, three-phase converter submodules, a very compact integrated electric drive, comprising of an electric machine and the associated power electronic converter, can potentially be formed. Besides reducing space requirements, a compact, integrated electric drive reduces cabling costs and minimizes EMI emissions making it very attractive in automotive applications.

In this project, the above described converter topology when applied in an automotive application is investigated. Both specific converter and electric machine design aspects are being considered. Until now, two experimental converter prototypes have been built on which key control and modulation properties have been demonstrated. Additionally, design considerations for the corresponding electric machine have been proposed and are currently used to develop a prototype electric machine using specifications from Volvo Cars Corporation (in-kind contribution within SHC). During spring 2015, a collaboration with the Swedish company Eskilstuna Elektronikpartner AB has been established aiming at manufacturing full-scale converter submodule prototypes during late 2015 or early 2016.

The project, which has been carried out between August 2013 and today, represents approximately the first half of PhD student Mojgan Nikouei Harnefors’ studies towards
fulfilling the PhD degree. The overall goal of the PhD project is to demonstrate the feasibility of the proposed converter topology in automotive applications using experimental evaluation data built and designed using specifications from the Swedish automotive industry. In this way, the project contributes with important information to the member companies within SHC to be used when selecting future technology pathways.

The overall goal is to extensively evaluate key aspects of the proposed integrated electric drive technology with automotive applications in mind. The concept has several potential advantages including reduced system costs, reduced amount of cabling as well as weight and EMI reductions; all of them contributing towards possibilities for significant cost reductions for the Swedish automotive industry.

Key results until now:
- Two converter topology prototypes have been finalized. The first, utilizing two converter submodules and the second, four converter submodules (see Figure 1-2).

Figure 1: Photograph of a converter submodule prototype (one out of four) used to evaluate control and modulation aspects of the converter topology.

Figure 2: A converter prototype comprising of four, series connected submodules.

- A general algorithm for stabilizing the capacitor voltages on each submodule has been proposed (presented in [1] with an extended journal submission [2]).
- Converter operation with four submodules and a permanent-magnet motor load has been successfully demonstrated [3].
- In the project’s framework, a collaboration with Eskilstuna Elektronikpartner AB was recently established enabled by additional funding from Vinnova (within the ‘Smartare elektroniksystem’ national research agenda) in order to manufacture low-cost, high-current converter submodules.
A machine design scheme incorporating potentials/limitations of the converter topology has been proposed [4] and has been used to determine a suitable machine design given certain specifications from Volvo Car Corporation (representing an in-kind contribution). At present, the machine prototype is being manufactured.

Figure 3: Drawing of the machine prototype presently under manufacturing.

An analytical method for predicting the resulting battery current ripple with phase-shifted modulation carriers has been proposed and evaluated experimentally [5].

During 2016, experimental evaluation of the full-scale modular converter prototype (presently being designed) and corresponding prototype machine (presently being manufactured) are planned. The associated results will be used in coming publications and guide the research activities for the final phases of the PhD project. The work carried out and being planned also represents key material for a coming application within a EU Horizon 2020 research call.

An international collaboration is planned to be initiated during 2016 with work on an EU Horizon research application targeting a future extension of this research.

Publications and conferences 2015
Hybrid Drives for Heavy Vehicles

The main purpose with the project is to build knowledge in electric machine design and to learn how to use important tools useful in an EM design process. One such tool is a Matlab and FEMM based design tool developed at the department of Industrial Electrical Engineering and Automation (IEA) at Lund Institute of Technology (LTH). Throughout the project, this design tool is further developed and verified against measurements to increase the capabilities of the tool. The purpose is also to gain a basic knowledge in the adjacent areas such as electric machine control with field weakening algorithms and torque control. Also the mechanical interface towards the rest of the drive train is included. Basic knowledge in mechanical power transfer through gear trains is needed to understand the other components in a powertrain.

The results related to machine control and field weakening are implemented in the test rig when the prototype machine is verified. The ambition with this project is to focus on the machine design related aspects of the work.

The main results of the project can be divided in two:

I) Obtained knowledge and skills in electrical machine design. The main contribution is the parameterization and optimization of the magnetic, mechanical and thermal design. Lots of effort is also put in the analysis of deviations between expected and measured properties.

II) Building of four traction machine prototypes designed according to the requirements for propulsion of a hybrid electric heavy commercial road vehicle.

Automotive electric traction applications sets very different demands on electric drives than industrial applications do. This is a challenge for both the automotive industry, that is lacking design and operation experience, and for the drives manufacturing industry, that is lacking application experience. This project is unique in the sense that it builds a bridge between the automotive application and the electric traction machine design and production, in particular with the application owner. The consequence is a stronger understanding of the specific traction application requirements that eventually leads to better buyer/supplier relationships and lower cost for the vehicle end customer.

The licentiate thesis that gives a detailed description of the electric machine design work was presented and defended in November 2014. The project is undertaken as an Industrial PhD work and is funded by AB Volvo, which has also funded the prototype building and experimental evaluation.
MEP-(Maximum efficiency point) control of PMSM, based on an equivalent circuit representation of electric machine instead of MTPA/MTPA (Maximum torque per ampere/voltage)

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Lars Johansson, Volvo Cars
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Oskar Wallmark, KTH
Sebastian Hall, Lund University

Total cash support from SHC:
865 kSEK

Duration:
2014-2015

Today, for controlling a Permanent Magnet Synchronous Machine (PMSM) either a constant control angle for the current is used or it is obtained from a circuit based modelling of PMSM in order to get the Maximum Torque Per Ampere (MTPA) trajectory. This, however, does not necessarily produce the maximum torque per ampere for the entire operating region of the machine since the circuit based model is simple and may not accurately present the torque production in the machine.

The aim of the project is to create knowledge about the applicability of the equivalent circuit of electric machines for efficiency calculations. The main goal is to obtain a PMSM control strategy that maximizes the efficiency considering the equivalent inductances and magnet factors with dependency on the operating point and temperature.

The developed algorithm has shown to improve the torque capacity of the machine at very low speeds up to 6% compared to an ordinary control strategy, however the energy benefit is shown to be less significant and is limited to 0.2% depending on the drive cycle.

The work gives the possibility to reduce the losses in the electrical machine without adding any extra hardware, only slight software modifications are needed. The reduced losses lead to longer driving range, and less need for cooling. The large reduction of losses at full current gives the possibility of actually slightly increasing the maximum torque of the electric machine.
Modeling of resonant electric power conversion for wireless power transfer systems

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Johan Winges, Chalmers  
Yinan Yu; Chalmers

**Reference group:**
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**Total cash support from SHC:**
300 kSEK

**Duration:**
2015

Wireless power transfer (WPT) is important for charging the battery in hybrid vehicles with an electric motor. The design and optimization of WPT-systems is non-trivial and one particular challenge is the modeling of non-linear components that are featured in power inverters and rectifiers. In this project, we develop and test models for these non-linear components in the setting of a WPT-system and, in particular, we focus on techniques that can be used for gradient-based optimization of the WPT-system.

First, we have implemented and simulated accurate models of the circuit in SPICE and performed successful comparisons with measurements to validate this model. We have demonstrated that the Rectifier-Compensated Fundamental Mode Approximation Analysis (RCFMA) can be a useful technique to incorporate the rectifiers in frequency-domain analysis of WPT-systems. However, we find that Modal Analysis (MA) is a more attractive approach and we have successfully implemented and tested this approach for simple rectifier circuits. In the context of the WPT-systems of interest in this project, it is also demonstrated that the magnetically coupled resonant circuits require a more sophisticated version of MA that accounts for the entire system and we have derived such a formulation, which is currently implemented and tested.

The Modal Analysis (MA) is based on a set of different time-domain solutions that is used to form combined trajectories (based on time-continuity of appropriate currents and voltages) that occur after transients in the system have vanished. The MA leads to a set of non-linear equations and their solution correspond to the times when the diodes in the rectifier are switched on and off. This approach is known to be accurate for systems with high coupling-coefficient. In this project, we have extended this technique for low coupling-coefficient systems that require highly resonant circuits with possibly different resonance frequencies. Tests of MA for simple circuits are successful and we currently implement and test MA for the complete WPT-system.
Ultra Compact Cost Effective Fast Charger Stations

Participants:
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Torbjörn Thiringer, Chalmers (Scientific Advisor)
Robert Karlsson, Chalmers (Engineering Advisor)

Reference group:
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Lars Kvarnsjö, Vaccume Schmeltz
Niklas Carlsson, Göteborg Energy
Per Norberg, Vattenfall
Roger Bedell, Opbrid
Hector Zelaya, ABB
Johan Felt, Saab Aero

Partners:
Elteknik (Chalmers), Göteborg Energy, Vattenfall, Vaccume Schmeltz, and Saab Aero.

Financing:
The total project budget is SEK 4.875 million, the main part of which is financed by Energimyndighetens (90%).

Duration:
2015-2018

A fast charger station can charge the vehicle battery in 5-10 minutes but they are very expensive and massive. The cost of these chargers is in the range of half a million SEK. Recent advancements in the device developments and design tools enables one to have a higher power density (power divided by volume or mass) chargers that is equivalent to a smaller size and weight. Semiconductors based on Silicon Carbide (SiC), magnetic materials based on Nanocrystallin and modern design tools like FEM simulators are examples of these advancements. In the new designs the power density can be as high as 1 kW/Liter which is a considerable reduction in the charger volume, mass and in the long run consequently on the price.

The aim of this project is to design, simulate, implement and verify an ultra-compact cost effective fast charger station with a power level of 50 kW. The purpose is to demonstrate the latest technological improvements in device and materials by implementation of a 50 kW ultra-compact fast charger station by using SiC modules and monocrystalline magnetic materials. The implemented charger has a performance index slightly above the state of the art that is mainly due to using new device and materials.

So far, the charger specification and the design of DC/DC stage is finished. The next step is to implement the DC/DC stage of the charger.

The reference group and industry partners provide support and feedback from different aspects: for example grid issues are the expertise of Göteborg Energy and Vattenfall, the charger is the area which ABB and Opbrid are working with, and the compactness and reliability is the interest of Saab Aero.
Wireless charging using a resonant auxiliary winding

Participants:
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Reference group:
Robert Eriksson, Volvo Cars
Mats Josefsson, Volvo Cars
Sten Bergman, Elforsk

Total cash support from SHC:
1800 kSEK

Duration:
2014–2015

Inductive power transfer for charging of electric vehicles is rising as a viable solution for charging of electric vehicles. There is a potential for fully automatic charging of the vehicle without messing with cables, which is the case with conductive chargers. The handling is also safe without risk of injuries due to high voltage.

The inductive power transfer takes place between two coils of which one is buried in the ground and the other one is placed under the car. The distance between the coils can be relatively large which means that the leakage factor is rather high. There is also a need for reactive power in the form of capacitors, which will be used for compensating for the big air gap, which can be as high as 15–20 cm. In order to manage the power transfer a resonant circuitry is used at relatively high frequency.

This project has investigated different types of inductive power transfer coils and also the possibility of adding an extra winding to the system. The extra winding is connected to a capacitor and by means of resonance or near resonance the reactive power that is needed comes from this extra winding.

The best type of the investigated coils is the so called DD-coil which has low leakage field and can be used with larger air gaps compared to a circular coil. The bar type which has been used in a student project has been tested and works fine, but the leakage flux is higher compared to the DD-coil and it will be harder to shield the passenger compartment from to high flux density. A DD-coil with the size of 400 * 400 * 20 mm can handle the power of 6 kW. A work done by Qualcomm indicates that the size may be lowered by 40 %.

The extra coil and capacitor works well and make the system more tolerant to misalignment. The total number of turns and the amount of copper will however increase compared to a two coil solution.

Methods for analysing the system has been developed in the project. The methods includes FEM-analysis and simulations and to some extent laboratory work. It should be possible for skilled staff to follow the workflow. Next step could be to develop a working system out of specifications from VCC.

The technology has a potential to make it easier to use electro mobility. The plug-in cars that will soon come to the market have small batteries and the need for easy and convenient charging will be high in these vehicles.
Energy storage

Batteries – present and future challenges

In order to find long-term battery solutions for electric vehicles, both the present and future challenges have to be reviewed. In two complementary reports, this project sheds light on both aspects by identifying the gaps between the battery packs and vehicle requirements, and reviewing research trends of emerging battery technologies in the 2025 perspective.

The first part of the project relates to the current regulations for batteries and the ongoing discussion for the development of future regulations and how this will influence the present available battery cells and the vehicle requirements. The gap analysis is based on legislation, scientific publications and vehicle requirements, both heavy-duty vehicle and passenger car requirements. On-going research trends are identified to analyse if the gaps can be closed in the near future. The title for the part is: “White spots on the future battery map induced by the development of vehicle regulation”.

The main identified issues are the on-going discussions about the risks with electrolyte leakage and whether the organic solvents used in the battery cells could be harmful for battery users in any way. Toxicology shows typical solvents such as EC, DMC and EMC to be harmful even at low amounts. Beside the discussion about toxicity, the worry about thermal propagation is a main concern where relevant test methodology is lacking. The outburst of fire and explosions are as serious issues as the worry for toxicological effects. The report suggests future research directions towards solid state batteries or at least the use of gel type electrolytes to diminish the risk for electrolyte leakage.

The second part of the project; “Emerging Battery Technologies towards 2025”, reviews research trends to identify how these technologies may fit to different vehicles and vehicle requirements in terms of performance, weight, volume, and cost. The main question answered is whether there are any potential post-Li technologies to replace the Li-ion technology in electric vehicle applications by 2025. Overall, this study indicates that until 2025, any huge improvements in the performance of automotive batteries are highly unlikely as there are no game-changing technologies approaching the consumer market today.

Read the reports at www.hybridfordonscentrum.se/en/forskning.

Participants:
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Reference group:
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Johan Lindström, Scania
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Total cash support from SHC:
100 kSEK

Duration:
2014–2015
Fast charging of large energy-optimized Li-ion cells for electric powertrains

**Participants:**
Jens Groot, Volvo GTT (coordinator/project leader)
Pontus Svens, Scania CV AB
Annika Ahlberg-Tidblad, Scania CV AB
Henrik Markusson, Theresa Granerus, Volvo Cars
Patrik Johansson, Chalmers
Kristina Edström, Uppsala University
Göran Lindbergh, KTH

**Reference group and/or Steering group**
TBD

**Partners:**
Chalmers, KTH, Uppsala University, AB Volvo,
Scania CV AB, Volvo Cars

**Financing:**
The total project budget is 17.3 MSEK, of which 0 SEK is funded by SHC. Batterifonden supports the project with 13.3 MSEK. Academic partners are fully funded and industrial partners receive 50% funding.

**Duration:**
2015-2018

Despite rapid development of automotive batteries the cycle life is still an issue, especially when fast-charging is used. This is especially the case for large-format energy-optimised cells developed for EVs and heavy-duty PHEVs. The aim of this project is to:

1. Quantify and characterise Li-ion battery ageing as a function of load conditions, cell design and cell chemistry.
2. Develop ageing models for the most important ageing mechanisms and incorporate these into physical first-principles models for large-format energy-optimised cells.
3. Identify suitable battery types and establish recommendations for cycle life optimisation while fast-charging.

An improvement in the overall energy efficiency of vehicles is needed in order to reduce the CO2-emissions from the road transport sector. Both light-duty and heavy-duty hybrid electric vehicles (HEVs) and Plug-in HEVs (PHEVs) have recently been introduced on the market. However, despite rapid development Li-ion batteries are still comparably expensive. Moreover, the battery lifetime is shorter than the vehicle lifetime and the ageing is difficult to forecast. Also, the aging rate is strongly depending on the load conditions. One of the strongest ageing factors is the use of fast-charging, which in combination with the choice if cell chemistry and temperature may reduce the battery cycle life drastically. Unfortunately, fast-charging is also identified as a key feature for many PHEVs and EVs, especially for heavy-duty vehicles. The battery degradation associated to fast-charging has thereby a direct negative impact on the competitiveness of current EVs and PHEVs. Although a lot of research has been made within the field of battery cycle life, surprisingly few projects have studied the combination of large-format energy-optimised cells, fast-charging and ageing.
The overall target of this project is to characterise the specific battery degradation due to fast-charging. This is accomplished through several sub-targets:

A. Characterisation of ageing during fast-charging by laboratory testing of cells and material analysis of severely degraded battery cells

B. Model development (physical, first-principles) and model parameterisation for large-format, commercially available Li-ion cells with different design (prismatic, cylindrical, pouch). The models shall include cell performance and distribution of temperature, current and ageing.

C. Identification of cell types (chemistry and physical design) especially suitable for fast-charging

D. Provide recommendations for charging strategies for optimisation of cycle life

E. Give three post-docs academic merits and publish scientific papers

The project is in the starting phase. So far, a test matrix for the first cycle life test phase has been determined and tests of energy-optimised commercially available Li-ion cells have been started. The next step includes the initiation of further cycle life tests at AB Volvo and initiation of modelling activities.

The project is formed by a broad cooperation between all parties within the Swedish Electric & Hybrid Vehicle Centre Theme 3 to ensure high technical and scientific level. Three post-docs and research efforts by senior researchers from industry is included as well as cycle life testing and cooperation with other national R&D projects. The project is directly based on previously run collaboration projects and will, directly and indirectly, collaborate with other national research projects funded by STEM/Batterifonden/FFI and SHC. Through the participation in EU-funded research we indirectly collaborate on an international level.

Publications and conferences 2015
State-of-health estimation of lithium-ion batteries in electric vehicles: Battery system – Life model

This project addresses the need for simple and cost-effective methods for estimating the state-of-health (SOH) of batteries under electric vehicle operation.

Within the scope of this project, such a method has been developed. The method can estimate the SOH indicators capacity and resistance solely based on an input of on-board available signals such as current, voltage, and temperature. The concept is based on data-driven battery models and virtual tests in correspondence to standard performance tests as established in laboratory testing. The method has been applied for battery data collected in field tests and has also been validated under controlled conditions in laboratory. The method has been shown to work for EV, HEV, and PHEV battery data i.e. a variety of different batteries, operating conditions, and usage patterns.

The demonstration of this simple SOH estimation method represents a contribution to hybrid vehicle technology. The implementation of this kind of methods in tomorrow’s hybrid vehicles will be an important factor for their broad commercial success as a suitable SOH estimation method will not only ensure safe and reliable HEV operation, it even contributes to cost-effectiveness as the battery can be utilized in an optimized way and the method itself only relies on simple resources.

Apart from the PhD student (Verena Klass) and the supervisors (Mårten Behm, Göran Lindbergh) at Applied Electrochemistry at KTH, Pontus Svens (Scania) has been involved in one of the studies within the scope of this project. The research in the project has been dependent on battery data from industry, which has been delivered by ETC Battery and FuelCells AB, Volvo Car Corporation, and Scania AB.

Verena Klass defended her thesis *Battery health estimation in electric vehicles* in October 2015 at KTH.
The state-of-health (SOH) of automotive batteries is an essential parameter that preferably should be monitored during the operation of traction batteries in order to enable optimized battery utilization. Accessing the battery SOH on-board is not a trivial question as conventional standard tests established in laboratory testing for determination of degrading battery properties such as capacity and resistance are not accessible during constant battery operation. A way to avoid this problem is the usage of a battery model that captures the essential battery behavior, and that is solely based on battery data generated on-board the vehicle during normal operation.

The original project idea has been to use the previously developed SOH estimation approach (SHC project State-of-health estimation of lithium-ion batteries in electric vehicles: Battery system – Life model) and exchange the battery model used there with a model derived using system identification techniques. These system identification activities have been based on a battery data set that has been produced in the laboratory in the recent SHC project previously mentioned.

This is the first study on SOH estimation with system identification methods from real-life battery data. The main results concern using the linear models to derive a map describing the characteristics of the battery (in terms of model parameters) for given state-of-charge (SOC) and temperature. This allows the computation of one SOH indicator (resistance) directly, avoiding the implementation of a virtual test. In a second step, the possibility to compute further of SOH indicators (resistance and capacity) will be investigated and compared with previous methods.

The battery data analysis performed in order to identify a suitable battery model has contributed with a deeper understanding of battery behaviour e.g. the frequency content of the different measurable battery signals and the linearity/nonlinearity of the relationships in-between the signals.

System identification methods are supposed to be suitable for on-board estimation with simple model architectures and fast computation times. The automotive industry should be highly interested in this kind of methods as to their potential contribution to managing the battery in electric vehicles in a safe, reliable, and cost-effective way.

A unique benefit from this project is the cooperation between two different research groups creating synergies between the expertise in batteries and system identification.
The Influence of Fast Charging on Li-ion Battery Ageing
– Chalmers part

Participants:
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Reference group:
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Kristina Edström, Torbjörn Gustafsson, Uppsala University
Göran Lindbergh, KTH
Patrik Johansson, Chalmers
Theresa Granérus, Henrik Markusson, Volvo Cars
Annika Ahlberg-Tidblad, Pontus Svens, Scania

Total cash support from SHC:
1250 kSEK

Duration:
2014–2015

The project is part of a larger project involving all partners in SHC Theme 3. It has addressed the challenges related to fast charging of Li-ion batteries for vehicles and how fast charging will influence battery ageing via analysis of materials changes at the very detailed level. New knowledge has come about from attacking the jointly formulated research questions for academia and industry within SHC on how fast charging of batteries influence battery cell behaviour, and on the novel cell chemistries foreseen as the nearest future batteries.

In this subproject at Chalmers the focus was the proper development of advanced tests of systems during operation, in situ, that ultimately can lead to better tools for monitoring commercial batteries, but also lay the foundation for the batteries of the future. A commercial test cell has been implemented for our in situ set-up, using charge and discharge rates relevant for industry and using materials from a partner university (UU). Hereby we can now monitor changes in the anode material as a function of charging conditions in a time-resolved manner. In house developed cells for special studies have also been developed within the project.

The development of proper analysis tools examining the consequences of fast charging is a rather unique task/accomplishment. Very few academic groups have this competence we now have acquired. For the electric and hybrid vehicle technology and industry the new detailed knowledge can, after extension, hopefully be implemented into charging patterns etc. to save life-length for the energy storage.
The Influence of Fast Charging on Li-ion Battery Ageing – KTH part

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Theresa Granérus, Henrik Markusson, Volvo Cars
Annika Ahlberg-Tidblad, Pontus Svens, Scania

Total cash support from SHC:
1500 kSEK

Duration:
2014–2015

The project is part of a larger project involving all partners in SHC Theme 3. The purpose was to find out what a battery cell is subjected to in terms of temperature, electric potential and current etc., on a local scale, during fast charging in an EV or PHEV.

The activities at KTH focused on the three following areas:

- Capacity fade modeling due to SEI formation and lithium plating in the negative electrode
- Modeling temperature distribution during fast charging in a large battery in a hybrid vehicle load cycle
- Experimental work on small scale model batteries

As one of the main contributions from the project, a validated model for temperature distribution of a large scale battery when used in a hybrid drive cycle up to 8C was developed. The modelling approach can be used as a general framework to investigate temperature distributions in large scale batteries when subject to different load cycles. Since, for instance, large internal temperature differences in a battery during fast charging may be a cause for accelerated ageing, these models be a design tool to avoid operational conditions were this may occur.

Another important contribution is validated model for capacity loss due to SEI formation, valid for currents up to 1C was also developed. Since the model can be directly plugged into more advanced battery models, the model can form a foundation for future fast charging ageing models. Possibly, such models can be used to optimize battery charging strategies with the aim to prolong battery lifetime.

The work contributes to a deeper understanding of ageing processes in lithium ion batteries, and the models developed may be used by battery integrators to optimize charging protocols and battery cooling systems.
The Influence of Fast Charging on Li-ion Battery Ageing  
– Uppsala University part

The project is part of a larger project involving all partners in SHC Theme 3. This particular project has focused on showing how graphite reacts to fast charging by studying graphite electrodes at different temperatures and at different rates. An important aspect of this work has been to combine the graphite with electrolyte formulations that can lead to as fast charging as possible and prevent lithium plating on the graphite surface. Surface treatment to create a better route for the lithium ions to enter the graphite even at high charging rates is also a part of the project.

We report studies of Li-ion battery cells which we have made ourselves as model systems for studying fast charging. The work is built to cover the whole chain from battery cell components to tests of cells in vehicles. The graphite electrodes made at UU have been used to fast charging by Chalmers as well, in their effort to develop a method to study electrodes exposed.

The studies aim to see the limit of what a graphite electrode can handle. Therefore we have cycled batteries with a rate of 5-10C and studied the electrochemical response as well as the surface chemistries. It is clear that how the graphite is pre-cycled before assembled into a full battery cell is important for how well the battery can function. We have also made a matrix of studies where the graphite is cycled at different temperatures and allowed to rest for different time periods to study if there is any self-healing in the system. This is important for a cell used in real life since it will give information if it would be OK to sometimes use fast charging without influencing battery life time. The preliminary results are promising.

The second part of our study is to influence the graphite surface by coatings to prevent lithium plating. Here we have used the common method of carbon coating but instead of coating particles we have coated the electrode surface. The risk here is to also block the important pores in the electrode. However, the results we have are promising and will be followed up in a new Battery Fund project.

The third part of the project is to build on the pre-study on fast charging to write a review article on this topic, since there is a lack of collected information about fast charging.
Lithium-ion batteries are a key technology for the electrification of vehicles. The performance, safety, and ageing of lithium-ion batteries are highly affected by temperature. In high-power applications, such as hybrid electric vehicles, the electrolyte, a component of a battery, has been found to limit the performance.

This project has been studying temperature and electrolyte related aspects in lithium-ion batteries. More specifically, one part of the project has been studying the mass-transport phenomena of present and future lithium-ion battery electrolytes and how they depend on temperature. Another sub-project evaluated a flame-retardant electrolyte additive in high-power applications, for which it was found to be unsuitable. Lastly, one sub-project has together with Scania been studying a large-format commercial battery cell with a thermal management system in plug-in hybrid electric vehicle applications using both experiments and modelling. Different thermal management strategies were evaluated with the model but were found to only have a minor impact on the temperature of the active components within the battery.

The mass transport characterizations contribute to hybrid vehicle technology by providing input to models, which can be used to optimize a certain battery cell, module or pack thermal or electrochemical design. The evaluation of the additive provided very direct suggestions to the battery manufacturers of hybrid vehicle batteries, as it was found that it was not suitable for the demanding load cycles used in hybrid and plug-in hybrid electric vehicles. The collaboration project with Scania and their large-format battery contributed to hybrid vehicle technology in a more direct way, as it answered engineering questions relevant to their product design, e.g. “How do we cool our battery most efficiently?”, “How hot will the battery get and how large temperature gradients will develop given a specific usage scenario?”, “Would it improve the thermal management systems performance if we changed the surface that is being cooled?”.

This project is an important step to the successful integration of lithium-ion batteries in hybrid vehicles, and has been a forum for knowledge transfer and collaboration between the academy (KTH) and the industry (Scania).

Henrik Lundgren defended his thesis *Thermal aspects and electrolyte mass transport in Lithium-ion batteries* in June 2015.

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**Participants:**
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Henrik Lundgren (PhD student)
Mårten Behm (advisor), KTH

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Kristina Edström, Torbjörn Gustafsson, UU
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**Total cash support from SHC:**
4500 kSEK

**Duration:**
2010–2015
Vehicle analysis

Tekniköversikter inom fordonsanalystemat

Participants:
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Reference group:
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Sören Eriksson, Fredrik Ekström, Volvo Cars

Total cash support from SHC:
450 kSEK

Duration:
2014–2015

As the benefit of a hybrid powertrain, in terms of fuel use, depends strongly on how the vehicle is used, there is a need to have methods which can calculate the fuel use for a given usage pattern. Typically this is done by simulating the powertrain in a long series of driving cycles which shall represent the total use of the vehicle. However, as the simulation model for a powertrain is complicated and the driving cycles are very long it is difficult to make simple and rough estimates of fuel consumption based on this type of analysis. An easy way to estimate the potential of different solutions is vital for being able to understand which powertrain type is suitable for which vehicle.

In this project a method to quickly estimate the savings from only a few statistical measures of a driving cycle is developed and tested on one powertrain. The method translates the driving cycle into a power-duration plot from which it can be calculated how much energy the powertrain is using in different operating modes and how long it operates in them. This can be easily calculated, without needing a model of the powertrain. These measures are then used in a very simple fuel consumption model, to estimate the fuel consumption of a specific vehicle driven according to the analysed driving cycle.

For each driving cycle it will be very easy to test powertrains with different degree of hybridization, and thus a suitable powertrain can be found quickly.

The method is excluding some phenomena which can increase the fuel consumption, and is therefore mainly capable of estimating a lower bound on the fuel consumption. This means that it should mainly be used to find interesting candidates, and to eliminate solutions which are definitely not cost effective, before doing a detailed analysis of a small number of candidates using the traditional detailed models.

Due to its simplicity and the possibility to analyse a driving cycle from only a few measures this method is a tool which can help powertrain engineers to better understand how the potential to hybridized vehicles change for different driving cycles. This will be important for making better and quicker decisions about which powertrain to develop or which versions of powertrains to offer to different customers.
Tystgående citydistribution för nattleverans i Stockholm stad

This study has been focused on one of the critical enablers for night time delivery in cities, also called Off-peak or Off-hour delivery, which is noise related to the transport as such. Noise generated by a transport, may be divided in two main categories, one related to the movement and operation of the vehicle in itself and one to the handling of the goods at the site of delivery. Both has to be considered and controlled in order for an Off-peak delivery scheme to be set up, operated and in the end tolerated by people living in the city. At the same time, the overall transport efficiency must be carefully controlled in order to provide a balanced solution.

In this study the most critical sources of noise, from both categories, have been reviewed and possible modifications have been identified for later implementation in a parallel activity.

It is a well-known fact that the power train, is one of the most critical components with respect to noise under city driving conditions. Hybrid solutions, with electric-diesel/gas configurations, offer a potential solution to the problem of noise generated while driving. However, the optimal configuration from a total energy point of view is not obvious as energy for auxiliary systems, such as cooling and brake systems, also need to be balanced.

The report (available at www.hybridfordonscentrum.se/en/forskning/) gives a brief overview of the most important noise sources. This serves as the pre-cursory to a series of planned modifications of some of the trucks that will be involved in the Off-peak delivery study that is currently on-going in Stockholm. The report then gives a brief qualitative overview of the functional requirements and possible modifications to an existing truck that then would meet those and be eligible for Off-peak delivery service.

The work within this pre-study has been conducted as a series of workshops and is based on preliminary experience from the Off-Peak research project, financed by FFI and hosted by KTH-ITRL. The pre-study is a preparation to a larger research effort aiming at identifying sources and improvements on the trucks involved in the field test of Off-Peak project.

Participants:
Peter Göransson, KTH
Ragnar Glav, Scania.
Peter Georén, KTH

Reference group

Total cash support from SHC:
180 kSEK

Duration:
2015
Operations and Finance

The duration of SHC Phase II was prolonged by three months until the end of June 2015. The reasons for the extended phase were the long lead times at the universities when recruiting competence and the long time required to build up qualitative cooperation within the centre, with external partners as well as with other centres of excellence. The third, four year long, phase of SHC started 1st of July 2015.

Board and management
The initial six months of the new phase have, from a board perspective, been dominated by a review of the cooperation agreement between the partners. In the middle of December all partners agreed on the contract. During these both criticising and supporting discussions, the overall quality of the agreement has been improved, the awareness of the legal implications have been actualised and a slight modification of the content is done. The Swedish Energy Agency has now also become a partner in SHC and not only takes part as financing agency.

An important change in the set-up of SHC and the cooperation agreement is the mandate of the steering group consisting of the partner representatives. The group, previously acting as the board for SHC, now no longer has the same mandate as in SHC Phase II. The group is called “Program council” during this third phase and has only a recommending role when it comes to budget and program content. The final decisions in SHC are instead taken by the President of Chalmers University.

The board for SHC Phase II completed three meetings during spring and the Program council for SHC Phase III have met four times during autumn, mainly for discussions on the agreement.

SHC has two new members in the Program council. Fredrik Lagergren is replaced by Jan Wikander, Dean of the School of industrial engineering and management, KTH, and Klas Niste is replaced by Robert Eriksson. Robert Eriksson has been involved in SHC issues for many years as a member of theme Electrical machines and drives and later on also as a member of the management team.

Finance
The research budget for each partner university is shown in figure 1. As can be seen in the figure Chalmers has received the main part of the project funding. The main reason for the uneven distribution is Chalmers’ high engagement in the smaller studies offered in the end of 2014 and beginning of 2015. All other years of the second phase, KTH has received the largest share of the funding from SHC.

Since the partners did not approve of the main cooperation agreement until December 2015, the research funding shown in the figure all rise from projects during the first half-year. When all partners have signed the agreement and the projects are formally decided the picture will look slightly different.

The total cash spending during the last half of 2015 is 2,059,141 sek. It covers the administration, research communication and research management, mostly carried out in the thematic groups.

The partners’ in-kind contribution is shown in figure 2 on the following page. One university, Linköping University, which has only a minor contribution to the in-kind during 2015 has contributed substantially the other years.

It should be noted that the financial data presented in the two figures in this chapter are not
representative for the yearly outcome in SHC. A better picture of the total received funding at the different universities as well as in-kind contribution is given in the final report for SHC Phase II.

**Figure 2. Planned and actual in-kind contribution.**

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**SHC Board/Program council**
Nils-Gunnar Vågstedt, Scania, (Chairman of the Board)
Anders Axelsson, Lund University
Dan Paulsson, AB Volvo
Eva Pålsgård, Uppsala University
Fredrik Larssen-Jan Wikander, KTH
Hans-Olof Dahlberg, Energiinmyndigheten
Klas Niste/Robert Eriksson, Volvo Cars
Maria Grahn, Chalmers
Peter Värbrand, Linköping University

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leader of Theme Vehicle analysis
Bo Egardt/Jonas Fredriksson, Chalmers,
leader of Theme System studies and methodologies
Elna Holmberg, SHC, Manager
Göran Lindbergh, KTH,
leader of Theme Energy storage
Mats Alaküla, Lund University,
leader of Theme Electrical machines and drives

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Keith Hardy, Argonne National Laboratory, USA

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Johan Lindeström, Scania
Jonas Fredriksson, Chalmers,
leader of Theme System studies and methodologies
Lars Nielsen, Linköping University
Mats Alaküla, Lund University,
leader of Theme Electrical machines and drives
Pär Ingelström, AB Volvo
Robert Eriksson, Volvo Cars
Torbjörn Gustafsson, Uppsala University

**Staff**
Elna Holmberg, Director
Anders Grauers, Hybrid vehicle specialist
Anders Nordelöf, Manager of the doctoral student network
Emilia Lundgren, Communications officer
Maria Odéus Forsberg, Controller
Publications & conference contributions

This list contains publications actually published in 2015. Publications lists for ongoing projects are given in the project reports on previous pages. Complete lists of publications for the finished projects can be found in the reports on the website: www.hybridfordonscentrum.se/en/forskning/

System studies and methodologies


PhD theses


Conference contributions


Failure handling strategy in an experimental research vehicle, D. Wanner, M. Nybacka, O. Wallmark, L. Drugge and A. Stensson Trigell, IAVSD, Graz, August 17-21, 2015.

Fault handling strategy in an electric vehicle with four wheel hub motors, D. Wanner, M. Nybacka, O. Wallmark, L. Drugge and A. Stensson Trigell, 24th International Symposium on Dynamics of Vehicles on Road and Tracks, August, 2015.


Electrical machines and drives


Coils for wireless charging of vehicles using a resonant auxiliary winding, Mikael Alatalo, Chalmers University of Technology, 2015.

Investigations on an inductive power transfer coupler with two or three windings, Eva Palmberg, Chalmers University of Technology, 2015.


Doctoral theses

Master theses


Conference contributions


Energy storage


PhD Theses


Vehicle analysis


*Requirements on electric machines for road vehicles*, Karthik Upendra, Anders Grauers, Chalmers University of Technology, 2015.

*Synergy and conflicts between waste heat recovery system and hybrid electric vehicle*, Karthik Upendra, Anders Grauers, Chalmers University of Technology, 2015.
The **Swedish Electric & Hybrid Vehicle Centre** (SHC) is a national centre of excellence for hybrid and electric vehicle technology. We unify Sweden’s competence and serve as a strategic base for interaction between academia, industry and society.

SHC’s driving force is to explore hybrid and electric propulsion systems, find the best technical solutions and analyse the subsystems. We carry out industry relevant research in the field and conduct studies of different hybrid and electric vehicle technologies to assess their potential. Through education, research and development, we provide strategic knowledge and competence and facilitate cooperation between industry and academia. Our activities make us one of the stakeholders in national and international discussions within the electric and hybrid vehicle area.