Swedish Electric & Hybrid Vehicle Centre

ANNUAL REPORT

2016
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This year with SHC

The past year has been characterized by enthusiasm and continuous growth. The preparatory work in the beginning of SHC phase III, with applications and definitions of new projects, is now beginning to pay off. Almost ten postdoc and PhD projects and twenty new studies and smaller projects have been started in 2016. Several of these are financed by external funding, but SHC itself has also had two different calls this year which generated a large number of projects and studies.

We have welcomed four new thematic researchers to the thematic groups. The thematic researchers do not only perform excellent research in their fields of expertise, but also play a central role in the daily operations and in backing up the thematic leaders. One effect of their work is that the thematic activities have gained pace with a greater number of focused workshops and thematic meetings as well as outreaching seminars. This has attracted new people to the thematic areas and broadened our network.

Anders Nordelöf who has managed the doctoral student network for four years, left his position in the beginning of 2016. I would like to express my thanks to Anders for his commitment to the network, and welcome Fernanda Lodi Marzano who has succeeded him and done a great job in managing the network activities.

Our annual conference “Roads to the Future” took place in Göteborg in May. This time we had a look at e-mobility development worldwide. Key-note speakers Keith Hardy from Argonne National Laboratory, USA, and Anshuman Tripati from Nanyang Technological University, Singapore gave examples of the varying conditions for the development of sustainable technologies in different parts of the world.

Some other highlights from 2016:

- SHC arranged a seminar with Tom Turrentine, director of UC Davis Plug-In Hybrid & Electric Vehicle Research Center, together with Chalmers.
- Members from SHC joined a study visit to Japan and visited various companies, authorities and organizations of importance for Japan’s transition to electrified vehicles.
- Energy storage arranged “Next Generation Batteries”, a very successful workshop on the battery chemistries that may compete with lithium batteries in the future.
- The conference “Fuel Cell 2016” presented new research as well as international technology watch, and proved that we are experiencing a reborn interest in fuel cell technology.
- SHC had two cross-thematic meetings, one on battery management systems (arranged by Energy storage) and the other on electric road systems, which included a visit to the recently opened electric road in Sandviken.

Networking and collaboration are some of the strengths of SHC. A warm thank you to our partners, the thematic leaders and researchers and the Swedish Energy Agency for your efforts in making SHC a dynamic and inclusive Centre of Excellence.

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

SHC’s central task is to develop and optimize existing and future e-mobility solutions 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 CV AB, technology supplier Autoliv Development AB and technical universities Chalmers University of Technology, Lund University, KTH Royal Institute of Technology, Linköping University and Uppsala University.

Research focus
The Centre has this year included fuel cell technologies within its scope. Our research is now conducted within five thematic areas - System studies and methods, Electrical machines and drives, Energy storage, Vehicle analysis and Fuel cells. We promote both deep, narrow technical studies and cross-discipline and cross-institution research.

SHC gives courses for doctoral students and runs a doctoral student network. Furthermore, we host a daily analysis of activities on the global arena, distributed in the newsletter OmEV. Our research and activities make us a stakeholder in national and international e-mobility discussions.

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 conducted within SHC spans five technical universities and 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. Creating links and collaborations, promoting knowledge transfer and highlighting shared interests are important contributions to the research, 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 topics connected to our research. Some of these meetings are very knowledge intensive, reaching into the fundamentals of a knowledge gap or an unexplored research question. Others 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 questions and disseminate the results of the latest research. The ambition of SHC is to continuously strengthen the network function and increase the outreach.

SHC phase III runs until June 2019.
## Contribution to targets

### Objectives 2015 – 2019

**Contribute to:**

<table>
<thead>
<tr>
<th>Cross-functional projects</th>
<th>Status and contribution 2016</th>
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<tbody>
<tr>
<td>• Theme Vehicle analysis and Technology watch of Fuel cells run a collaborative project called “Drive line configurations for fuel cells”, finalized in 2016 with a planned continuation.</td>
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<tr>
<td>• “Cost-effective drivetrains for fuel cell powered Evs – CATARC” is run by Technology watch of Fuel cells and Electrical machines and drives (initiated in 2016).</td>
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<tr>
<td>• Collaboration between Energy storage and Electrical machines and drives in the associated project “Modelling and analysis of interaction between battery and voltage source converter in electric drivetrains” (funded by FFI), and also between this project and SHC project “Ultra compact integrated electric drives for tomorrow’s alternative drivetrains”.</td>
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### Benefits for the industry

<table>
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<tr>
<th>Benefits for the industry</th>
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<tr>
<td>• At present SHC has one industrial PhD; Rasmus Andersson at LTH/AB Volvo.</td>
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<tr>
<td>• The project “Fast-charging of large energy-optimised Li-ion cells for electrified drivelines” involves VCC, AB Volvo and Scania along with Chalmers, KTH and Uppsala University.</td>
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<tr>
<td>• The four new thematic research projects involve VCC, AB Volvo and Scania together with at least one of the academic partners.</td>
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<tr>
<td>• The greater part of the short projects started in May 2016 involve at least one industrial partner.</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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### Scientific challenges

SHC have started more than twenty new projects and studies in 2016 and several members also participate in associated projects.

### Dissemination of knowledge and research results

Some examples of how knowledge and results have been spread in 2016:

- Fuel Cell 2016
- Next Generation Batteries
- Roads to the Future
- Electro Mobility in Smart Cities (with Business Region Göteborg).
### Collaboration with other centres and internationalization

- Intense focus on electric buses in theme Vehicle analysis through a large number of presentations and seminars.
- Presentations on electric road systems by Electrical machines and drives, e.g. at IQPC, Berlin and Almedalsveckan.
- Thematic workshops on specific topics as well as open seminars at the universities.
- On the request from The Swedish Energy Agency for Chalmers University of Technology, SHC contributed with expertise concerning strategies for the conversion to a fossil fuel independent transport sector.

### Dialogues and/or collaboration with

- Argonne National Lab
- Centre for ECO² Vehicle Design
- CERC
- Chalmers Areas of Advance Transport
- China Automotive and Technology Research Centre
- IFPEN
- KCK
- KTH Integrated Transport Research Lab
- Oxford University
- UC Davis
- Université de Toulouse – LAPLACE
- Victoria Swedish ICT
- VTI

### Developing future competence

- Out of the projects that currently run, ten involve PhD students. The PhD students are members of the doctoral student network. The doctoral network has about sixty members, some of which work in associated projects, and had two meetings in 2016.
The awareness of e-mobility is growing, and steadily including and engaging new groups. Clear proof of this development is that SHC reaches a broader audience at events. For example, the workshop “Next Generation Batteries” attracted a wide range of participants, and the same can be said about the fuel cell conference that was arranged together with Energiforsk. At both events, we had the pleasure of seeing new faces and meeting representatives from organisations that haven’t previously been part of the SHC community. “Electro mobility in smart cities”, hosted by Business Region Göteborg, also welcomed a group for whom electrification is becoming a hot topic, and where there is great need for knowledge: municipalities, transportation authorities and public sector.

Engaging new industrial partners and other organisations involved in e-mobility issues remains high on SHC’s agenda, in order to further develop our inclusive and dynamic platform. Throughout this year SHC has had fruitful dialogues with OEMs and suppliers as well as local authorities and institutes, and it is clear that the Centre is steadily spreading its network and reaching new groups.

Aiming to reach new research groups, we have initiated discussions on master thesis works with researchers at KTH who have not previously been involved with SHC.

The funding in the projects mainly comes from various programs initiated by the Swedish Energy Agency but to some extent also from Vinnova and Drive Sweden. The total funding of projects by the Centre’s own budget is about 20% of the total attracted budget.

One of the Centre’s objectives is that about half of the projects should be senior projects and half PhD projects. The Centre fulfils this ambition, and has a balance in the project portfolio between young and more experienced researchers.

Cross thematic interaction

Meeting across the thematic areas and learning from each other is one of the important functions of SHC. On a couple of occasions every year, we invite all thematic areas to a joint event. In March, Energy storage arranged an excellent cross-thematic meeting on Battery Management Systems at KTH, led by Matilda Klett, new thematic researcher and coordinator of theme Energy storage. Researchers from all the thematic groups shared their views and experiences, with Christian Fleischer from NEVS as invited external speaker. About fifty attendees came to the meeting, representing all SHC’s partners.

The set-up was round table discussions in small mixed groups – a very fruitful way of gaining insights into colleagues’ perspectives and understanding how their know-how could contribute to one’s own research.

The discussions during the meeting led to better understanding of batteries and their usage for many of the participants. It also resulted in a cross thematic pre-study between KTH, Chalmers and Volvo Cars. The study will investigate a simplified model for long-term battery prediction in the battery management system, suitable for on-board implementation.

SHC’s scope has broadened over the years along with the development of the transport society’s, and now includes the entire vehicle and related charging infrastructure. As an effect of this development, we are reaching a wider circle than ever before, both in the e-mobility community and in society at large. With electric roads being built for trial at several Swedish sites, our expertise is highly sought after. As far as electric roads are concerned, SHC is literally where the action is.

This autumn, we decided to embrace this knowledge and explore it further by keeping a cross-thematic meeting at Sandviken and visit the recently opened electric road. About thirty people, both senior researchers and doctoral students from the PhD network, gathered for the two-day meeting. Region Gävleborg introduced the project, followed by Christer Thorén, project manager of Hybrid Technology Development at Scania who explained Scania’s work with electrification and electric roads. The group then took a bus to the electric road for a tour of the premises and a look at one of the trucks. Anders Lewald from the Swedish Energy Agency, Johan Tollin from Vattenfall and representatives from the ElectriVillage project in
Mariestad were also invited speakers to the meeting, along with speakers from SHC.

Seminars and workshops for SHC partners
The thematic groups are steadily widening their networks, and increasing their influence in the academic and industrial world. They are active, knowledge intensive meeting points for a growing group of partner representatives and external colleagues.

The groups have also markedly increased the intensity of the thematic activities with a greater number of outreaching seminars as well as focused workshops and thematic meetings. This development is partly thanks to the enthusiastic work of the thematic researchers and the thematic leaders. A general feeling is that the workshops and seminars this year have attracted a wider range of participants from the partners, vitalizing the discussions with new perspectives and broadening the thematic areas.

The current focus of System studies and methods is to attract new participants and create new projects. To this end, the theme arranged three partner workshops:

"Multidisciplinary design optimization". A core group will continue the work that was outlined at this meeting.

"Platooning with hybrid vehicles” – resulting in several ideas for further research and the decision to start master thesis projects at AB Volvo.

"Integrated Hybrid Powertrain Control and Exhaust After-treatment Systems” – presenting key results of a pre-study as well as a discussion on potential future development.

Internationalization is on SHC’s agenda, and particularly visible in the activities of Electrical machines and drives. The theme arranged a workshop this summer called “Degradation and lifetime of traction electrical machines – modelling, testing and method” with invited speakers from Université de Toulouse – LAPLACE and DuPont, and external participants from SP, CEVT, University of Nottingham, University of Bristol and Oxford University. One outcome of this workshop was the forming of a collaborative network that aims to apply for EU funding.

New battery chemistries is one of the scopes for Energy storage, but the theme also concentrates on knowledge transfer between the design of the battery management system and processes within the battery. In autumn, the theme arranged a thematic workshop where all ongoing projects, both fully financed and associated to the thematic area, shared results from their activities, in order to increase communication between the projects.

Vehicle analysis has an intense focus on electrified public transport which has been manifested in different ways throughout the year. Since the theme has limited resources, Vehicle analysis has not arranged any partner activities as such. Instead, the theme has

Christer Thorén from Scania demonstrated one of the trucks that run on the electric road outside Sandviken.
contributed with a large number of outreaching activities such as courses, workshops, seminars and conference presentations, particularly in the field of electric city buses.

Besides the SHC partner activities, the themes have arranged open seminars and workshops. See Outreach for an account of these.

Thematic researchers as SHC ambassadors
SHC’s new thematic researchers are a welcome addition to the thematic groups. The search for candidates was initiated by the end of 2015, and in spring this year four researchers from four different universities were appointed. Francisco Márquez-Fernández represents Electrical machines and drives, Mikael Askerdal is thematic researcher for System studies and methods, while Energy storage has appointed two thematic researchers, Matilda Klett and Anti Liivat. The thematic researchers not only perform excellent research, but also play a central role in the daily operations by being SHC ambassadors at their universities and backing up the thematic leaders.

Knowledge base for electrified city buses
As electrified public transport is getting more common, the need for knowledge increases and spreads to new groups. Here SHC has an important function as a knowledge base. Being a fact-based, neutral party, our knowledge is of great weight.

Through targeted activities for different groups – from researchers and developers to public transportation authorities – theme Vehicle analysis has focused on spreading information and research results regarding the implementation of electric buses and the surrounding infrastructure. Anders Grauers, leader of Vehicle analysis, has been engaged in at least 13 such meetings, courses and workshops this year. For example a workshop on business models for electric buses, intended for bus operators and municipalities, a seminar on electrification of buses for Svensk Kollektivtrafik, and a course on the possibilities with electric buses, intended for developers and procurers of bus services. Anders also held a session on the implementation of electric buses in city traffic at the conference “Electro mobility in smart cities” in September. By this work, we have reached groups that generally is out of range for the academic world. There is a big interest in the research results, which are immediately put to use.

OmEV – global watch that reaches a wide group of followers
The newsletter OmEV reaches 1,360 subscribers in industry, academia and other companies and organisations. We are proud to host a global watch that has such a wide group of followers and such impact.

The newsletter follows developments around the world in different e-mobility related areas, with initiated comments. The readers have been able to follow a series of articles focusing on the influence of Silicon Valley on the automotive industry, material constraints for battery production and the e-mobility development in Germany, mixed with reports from conferences and tips about events.

OmEV also runs a podcast with invited guests. The topics this year have ranged from battery standards to recharging infrastructure and electric bicycles and light electric vehicles. Magnus Karlström is chief editor and runs OmEV along with Helena Berg (Libergreen) and Martin Borgqvist (SP).

Else-Marie Malmek and Anders Grauers were guests in one of OmEV’s podcasts, where they talked about scenario planning and charging vehicles with Magnus Karlström.

International recognition
It is evident that SHC’s status as a Swedish platform for e-mobility is being recognised internationally and nationally, not only in the e-mobility community but in new contexts and by organizations outside our common sphere. At a Swedish state visit in Germany in October, Elna Holmberg was invited as a representative for Swedish expertise at a German-Swedish seminar on sustainable mobility. In the same role, Elna was interviewed for a study of the impact of “game changing technologies” on work in the manufacturing
industries across Europe between now and 2025. The study was performed by Faugert upon request by Eurofound, the European Foundation for the Improvement of Living and Working Conditions, and is a sign of how e-mobility is changing our society, and how this change brings up new questions and necessitates knowledge transfer to various new areas.
Research advancements

SHC phase III is gradually taking shape, but we are still in the start-up phase. To outline future research goals, the thematic roadmaps have been updated jointly by researchers and industrial engineers.

As the second half of 2015 was characterized by formulating projects and applying for funding, so this year has been marked by the starting up of new projects, both financed externally and through SHC’s own calls. Since the greater part of these projects started in the second half of the year, results in terms of publications or demonstrations cannot be expected yet, even for short studies. However, advancements can be seen in some of the projects initiated in 2016 or earlier. A few examples are given here below.

Project progress

Saeid Haghbin’s project on ultra-compact cost effective fast charging stations was initiated in 2015. The purpose is to demonstrate technological improvements in a 50 kW ultra-compact fast charger station, using SiC modules and monocrystalline magnetic materials. The first prototype for the dc/dc part is now constructed and under test. The next step is the construction of the whole setup. The researchers in this project work together with a team of researchers from Sharif University of Technology in Iran, and a PhD student from there will stay at Chalmers for 6 months to work with some part of the project. Collaboration is also established between the project and Chalmers Innovation office.

“Interdisciplinary post-doc cluster for future hybrid vehicles” is a collaborative project and continuation of the previous “System level evaluation of diesel engine and emission after treatment systems”. Three post-docs from different departments at Chalmers work together to develop a concept for a hybrid vehicle using a spark ignited engine and NOx-reducing emission after treatment system. The control part of the project is financed by SHC, while the other parts are funded by Centres of Excellence KCK and CERC.

Focusing on the control part, the results so far contribute to the theoretical part of the project. A less conservative advanced discrete-time gain-scheduled PID controller design technique has been developed for non-linear systems with input constraints. In the next step, these results will be implemented and validated on a detailed simulation model. Some of the results have been published in journals or in conference proceedings this year.

"Fast charging of large energy-optimised Li-ion cells for electrified drivelines”, that started in the end of 2015, aims to characterise the specific battery degradation due to fast-charging. The three industrial partners (AB Volvo, Volvo Cars and Scania) are very active in this big, collaborative project as they perform all ageing tests and participate in the modelling activities. The first results have been shared at SHC meetings and will be presented at AABC in Mainz in 2017.

Of the short studies that were funded in 2016 some have already been finalized:

The goal of the pre-study “48V mild hybrid electrically excited synchronous machine” was to design a research prototype machine according to ideas from Volvo Cars, to be used in another project, “Variable flux machine for electric vehicles”. This machine has been designed and is currently under manufacturing. The results of the pre-study led to a new application for a PhD project on integrated drives for electrified vehicles, which has been granted funding by The Swedish Energy Agency/ Energieffektiva vägfordon.

“Driveline configurations for fuel cells” studied different road vehicle driveline configurations with fuel cells to find the most promising type for road vehicles, mainly regarding total cost of ownership. The results show that fuel cell drive lines have a very different cost structure than battery electric drive lines, which makes both of them cost effective but in very different market segments. A follow-up project is planned for 2017, which will focus on analysing fuel cell drivelines for heavy trucks in more detail.
Doctoral projects

The move towards shorter senior projects and pre-studies has led to a reduced PhD portfolio. Most of the PhD projects from SHC phase II are finalized by now, while “Dimensioning plug-in hybrids using drive-cycle information” has stopped since the PhD student involved decided to leave his research position. However, three fully financed PhD projects are running: “Hybrid drives for heavy vehicles” (Rasmus Andersson, Lund University/AB Volvo), “High-efficient, ultra-compact integrated electric drives” (Mojgan Nikouei Harnefors, KTH) and the new thematic research project in System studies and methods, “Vehicle independent road resistance estimation” (Mikael Askerdal, Chalmers).

“Äldringsmekanismer och hur man förlänger livet på batterier i fordon och stationära applikationer” is a big, collaborative project financed by the Swedish Energy Agency. In this project, Chalmers, Volvo Cars, Uppsala University and ABB work on ageing prediction of Lithium batteries. PhD student Evelina Wikner from Chalmers participates with her doctoral research. Evelina is closely connected to SHC through her work and that of her supervisor Torbjörn Thiringer, and also through her engagement in the PhD network.

Mussa Shifa Abdilibari at KTH is also involved in two different projects in theme Energy storage and several PhD students from the doctoral network work in associated projects.

Faisal Altaf defended his thesis “On Modeling and Optimal Control of Modular Batteries: Thermal and State-of-Charge Balancing” at Chalmers this spring. Though not financed by SHC, Faisal has been an active member in SHC and in the doctoral student network.

Research involving master students

In some of our shorter projects master students are involved in collaboration with senior researchers, and given the opportunity to contribute to results and gain experience for a future competence base.

One of the applications that was granted funding this spring is a study that will run at Chalmers, KTH and Lund University, and be used by SHC’s researchers as part of the education. The goal is to model asynchronous machines and determine their performance as a reference for other types of traction machines. Some of this work is performed by master students in collaboration with SHC’s researchers.

In “Test bench for optimal design and control of energy buffers for minimizing energy consumption” master students develop a test bench, in collaboration with researchers at Integrated Transport Research Lab at KTH. The test bench consists of a hybrid vehicle and a “rolling road” facility, and will be used by researchers in Mechatronics at KTH. Data from tests with the Shell Eco Marathon car has been collected and will be used for calibrating the test bench later on. During autumn the test bench has been tested for the first time.

Cross-functional research

SHC continuously encourages networking between the different thematic areas and between our partner universities and industries. This year, we have seen cross-functional work in a number of projects:

Vehicle analysis and Technology watch of fuel cells have been collaborating in a project on driveline configurations for fuel cells, as described above. The project is now finalized and a continuation planned.

The associated project “Modelling and analysis of interaction between battery and voltage source converter in electric drivetrains” is performed by themes Electrical machines and drives and Energy storage.

One of the international PhD collaborative studies that was financed in 2016 is run by Technology watch of Fuel cells and Electrical machines and drives. This project is currently being initiated and will gain speed in 2017.

New projects initiated

With the aim to develop and strengthen SHC with new perspectives, a call for shorter projects was made before summer. As a result, twelve new projects and studies were started, the majority of which are conducted in collaboration with one or several of SHC’s industrial...
partners. Common for many of these projects is that they have the possibility of leading to new, bigger projects.

Last year’s applications in the thematic groups have led to three externally funded projects, one in Energy storage and two in Electrical machines and drives, being added to our research portfolio. These projects are all financed by FFI/Energieffektiva vägfordon. Furthermore, Technology watch of fuel cells is financing a new project in Vehicle analysis in collaboration with Viktoria Swedish ICT.

As mentioned before, the strategic work of the thematic researchers is a valuable addition in the thematic groups. The researchers have done pre-studies in close dialogue with SHC’s industrial partners, to ensure that the longer projects address topics prioritized by the industry. The pre-studies being finalized, the longer projects have now taken shape:

- “Efficient and safe battery operation – aspects of expansion and utilization” (Matilda Klett, KTH)
- “Power conversion challenges with an all-electric land transport system” (Francisco Márquez-Fernández, Lund University)
- “High energy density battery materials – understanding their endurance with the help of modelling” (Anti Liivat, Uppsala University)
- “Vehicle independent road resistance estimation” (Mikael Askerdal, Chalmers)

The thematic researchers contribute experiences and connections from previous work places. In Matilda Klett’s project, the work related to silicon-containing electrodes and performance of Si-containing cells has so far been carried out in collaboration with personnel at Argonne National Laboratory, USA. Francisco Márquez-Fernández’ project collaborates with the Energy and Power Group at the University of Oxford in modelling the grid impact of high power charging systems.

Funding of PhD projects with international collaboration

One of SHC’s objectives is to develop long term international cooperation with research Centres similar to SHC. The Centres should be suitable as strategic collaboration partners and promote SHC’s development as well as our international reputation. Pursuing this goal, SHC funded three projects in autumn to finance PhD students in strategic collaborations. The three selected international collaboration Centres are UC Davis in USA, IFPEN in France and CATARC in China. The projects will start in 2017.

Technology watch of fuel cells

The interest in fuel cells for automotive applications is growing steadily and several Swedish companies manufacture fuel cells, components or systems. At the third annual conference by Technology watch of fuel cells it was clear that the technology is on its way to becoming a branch in Swedish industry. Given this development, it is of high importance for SHC and the Swedish Energy Agency to continue the technology watch project together with Energiforsk, that in its first phase was financed until 2016-12-31.

By the end of 2016 it was decided that Technology watch of fuel cells will run for another period, from January 2017 until June 2019. The project will now have the status of a fifth thematic area within SHC, with a broader thematic group to complete the steering group. Bertil Wahlund at Energiforsk will continue as project manager, with the addition in the thematic group of an academy representative as thematic leader.

Besides watching and analysing the global development, the project will carry out R&D studies and spread information on fuel cell research and development. Focus for the coming years will be broader and include stationary applications as well as transport applications.
System studies and methods

System studies and methods develops methods and algorithms, which are adopted and utilized in a hybrid and electric vehicle setting by exploiting dynamic models, computational methods and simulation techniques.

Our main topics are mathematical modelling, dynamic simulation, performance analysis, control design, fault detection and isolation, and optimization. The research is focused on methods and analysis related to hybrid and electric vehicles on a systems level.

This has been a vitalizing year with activities, new projects and new people joining us. The theme has been discussing research co-operations that focus on new and relevant topics by arranging a series of workshops on subjects such as platooning and optimization, to which we have invited interesting speakers who previously haven’t taken part in the Centre. The workshops have been relatively small, but have generated fruitful discussions and been well appreciated. A general experience is that the meetings this year have attracted “new” people related to the topics, and also to the thematic group. Thus, the theme has been broadened and complemented by fresh competence.

We have started five new studies, based on last year’s intense work on defining projects. These include a pre-study for “Vehicle independent road resistance estimation”, a PhD project conducted by the newly appointed thematic researcher Mikael Askerdal. Mikael splits his time between Volvo Group where he is energy management specialist, and Chalmers where the thematic project is just starting up. Some of our current projects collaborate with other Centres, such as Centre for ECO2 Vehicle Design, Competence Centre for Catalysis (KCK) and Combustion Engine Research Centre (CERC).

Spreading research results to a broader audience, several researchers from System studies and methods gave presentations at Reglermöte in Göteborg and also at the IFAC AAC conference in Norrköping and its pre-conference tutorials at Linköping University.

In connection to Faisal Altaf’s dissertation, System studies and methods and Energy storage gave an open seminar at Chalmers with Prof. Hosam Fathy, Penn State University, entitled “Power that does not get old before it’s sold. A Few Perspectives on Battery Health Monitoring and Control”. The seminar was very appreciated and attracted about thirty participants both from SHC’s partners and from external organizations.

The apparent movement towards multi-disciplinary optimization and overall solutions has influenced the topics of the workshops this year and has crystallized as a common topic. System studies and methods has initiated work, and also arranged a dedicated workshop in this field. We look forward to a continuation by defining further collaborations and projects in the coming year.
Electrical machines and drives

Electrical machines and drives is a competence base for technology related to electric energy transfer and conversion between the electric utility grid and the wheels of electric vehicles, including both traction and auxiliary loads.

Looking at global trends, we see a movement towards a higher degree of electrification. Along with this comes an increased development of related technologies for energy supply, with standardization of static conductive charging for light vehicles and a growing supply of inductive charging systems as a result. Taking this development into account, the research focus of Electrical machines and drives has been reviewed and broadened this year, mainly towards the power interaction between vehicles and grid. Moreover, new emphasis is directed at modular concepts of both machines and converters, condition monitoring and manufacturing processes.

2016 has been a year of fruitful collaborations. Besides the well-established collaboration with SHC’s industrial partners, the theme has broadened its engagement by initiating projects with a number of other companies and organizations. For example, a new project on SiC converter for high speed slot-less machines has been started with Atlas Copco, and a project on electrical machines for high production, involving CEVT and AAM is awaiting funding approval. Furthermore, we have spread knowledge about electric road systems and charging infrastructure together with Mariestads kommun, for example at Almedalsveckan.

We are happy to welcome Francisco Márquez-Fernández back to the theme as our new thematic researcher. Fran will explore the challenges associated to electric power transfer to and from vehicles, including not only charging technology on-board, but also off-board equipment and power grid impact of charging stations. The project includes collaboration with the Energy and Power Group at the University of Oxford.

With the growing number of electric drives in vehicles there is a need for condition monitoring and lifetime estimation techniques for the relevant components already from the design stage. A short project on condition monitoring has been financed this year, and the theme also organized a very successful workshop with several new international collaborators participating. One pleasing result of the workshop was the forming of a collaborative network, that aims to apply for EU funding in the near future.

Although none of the theme’s current projects deals with EMC, this topic is regarded as highly significant and represents an interesting area for possible project applications in the coming year.
Energy storage

Energy storage has the primary function of deepening the understanding of battery packs, cells, materials, and performance limiting processes, and make this knowledge useful for electrical and hybrid vehicle system development. The focus lies on energy storage using lithium-ion battery technology. Nevertheless, the theme maintains an openness for major technological breakthroughs in battery development that may change this picture.

The interest in fast charging is steadily growing and the joint effort of Energy storage in this field continues since last year. The big, collaborative project on fast charging of large energy-optimized Li-ion cells is gaining pace and the first results have been shared at SHC meetings.

With the maturing of commercial Li-ion technology for vehicles, the battery management system is also of central interest for theme Energy storage. From a battery research perspective, part of the challenge is the meeting point between the physical/chemical based concepts of batteries with the electrical and control engineering side of the energy management system. This has opened up for a new, short Energy storage study involving Chalmers and Volvo Cars. In all, five new projects started in 2016, four of which are fully financed by SHC.

The theme has welcomed two thematic area researchers: Matilda Klett (KTH) and Anti Liivat (Uppsala University). Their roles comprise research work and coordination in the organization. Both Matilda and Anti started out with pre-studies that are now developing into full thematic research projects.

Open seminars and workshops mixed with thematic meetings have proven a fruitful concept. Among the highlights this year are a well-visited cross-thematic meeting on Battery Management Systems and the workshop “Next Generation Batteries”. The latter turned out to be a very successful event with some hundred participants, attracting not only SHC’s partners but several other organizations. Both Swedish and international researchers presented their work with different battery chemistries during this day. Energy storage research results have also been spread at external conferences, e.g. at the Swedish Energy Agency’s battery conference in Göteborg, the 18th International Meeting on Li Batteries in Chicago and the 67th International Society of Electrochemistry Meeting in The Hague.

Outlining the agenda for coming years, Energy storage has proposed a revised roadmap where we maintain focus on deepening our understanding of the performance limiting processes within Li-ion battery materials, electrodes, cells, and packs and on making this knowledge useful in hybrid and electric vehicle management systems. We see a shift towards high-energy cell designs that is likely to influence the management in power demanding situations and applications.
Vehicle analysis

Theme Vehicle analysis 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 watched, to understand which direction the development is taking.

The introduction of electric city buses is now really taking off – a development which is clearly reflected in the high demand for knowledge from public transportation authorities, manufacturers and operators that we are now experiencing. The topic has greatly influenced the activities of Vehicle analysis during the past year. There is a big interest in the results of the theme’s studies and projects, and the results are immediately put to use.

To meet the great need for knowledge, we have held several workshops and seminars directed at those engaged in the development, deployment or procurement of bus services, and also given presentations at a wide range of events for industry, academia, public transport authorities and politicians. The fact that we are reaching public transportation authorities is particularly gratifying and proof that the importance of our research is becoming evident to a steadily growing group of actors.

Vehicle analysis’ research on electric public transportation is well branched, which is clear in the cooperation and dialogue that we have with partners outside of SHC, for example Viktoria Swedish ICT, Lindholmen Science Park, Västragötalandsregionen, Skånetrafiken and Business Region Göteborg. We have also presented the results of our studies for delegations from Singapore Land Transport Agency and Norwegian public transport authorities.

Widening the perspectives of the research area, the theme is planning a PhD project on charging behaviour and infrastructure in collaboration with UC Davis.

As is the case with electric buses, fuel cell technology is becoming increasingly popular. The project on cost-benefit ratios for fuel cells that we have run with Viktoria Swedish ICT was finalized this year, and the results presented at the conference “Fuel Cell 2016”. A follow-up project is planned for 2017, which will focus on analysing fuel cell drivelines for heavy trucks in more detail.

The technology for electric vehicles has matured and is now a natural part of the industry’s development. Therefore, uncertainty about electrified vehicles is shifting from the powertrains and their components, to what role electrified vehicles will play in the future transport system. To help finding likely development trends, Vehicle analysis will continue to extend the research to system challenges, such as the role of public charging infrastructure as an enabler for cost effective electric vehicles.
SHC projects 2016

The list only includes projects that have been running in 2016. Projects that have received financing but not yet taken off are not listed.

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<th>System studies and methods</th>
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<td>Project responsible at SHC: Lars Drugge, KTH</td>
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<td>Project responsible at SHC: Jonas Fredriksson, Chalmers</td>
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<td>Interdisciplinary post-doc cluster for future hybrid vehicles</td>
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<td>Project responsible at SHC: Tomas McKelvey, Chalmers</td>
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<tr>
<td>Modelling of hybrid powertrains and exhaust after treatment systems</td>
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<tr>
<td>Project responsible at SHC: Lars Eriksson, Linköping University</td>
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<tr>
<td>Test bench for optimal design and control of energy buffers for minimizing energy consumption</td>
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<td>Project responsible at SHC: Mikael Hellgren, KTH</td>
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<tr>
<td>Vehicle independent road resistance estimation</td>
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<td>Project responsible at SHC: Jonas Fredriksson, Chalmers</td>
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<tr>
<th>Electrical machines and drives</th>
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<td>48V mild hybrid electrically excited synchronous machine</td>
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<td>Project responsible at SHC: Yujing Liu, Chalmers</td>
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<td>Field intensified PM machine for an HEV application</td>
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<td>Project responsible at SHC: Torbjörn Thiringer, Chalmers</td>
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<td>Project responsible at SHC: Mats Alaküla, Lund University</td>
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<td>Project responsible at SHC: Oskar Wallmark, KTH</td>
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<td>Hybrid drives for heavy vehicles</td>
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<td>Project responsible at SHC: Mats Alaküla, Lund University</td>
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<tr>
<td>Investigation of state-of-the-art of additive manufacturing of electric machine components for EV/HEV applications</td>
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<tr>
<td>Project responsible at SHC: Oskar Wallmark, KTH</td>
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<tr>
<td>Multi physical modelling of a hybrid cooling circuit and its attached components for an electrified vehicle</td>
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<tr>
<td>Project responsible at SHC: Torbjörn Thiringer, Chalmers</td>
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<td>Power conversion challenges with an all-electric land transport system</td>
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<tr>
<td>Project responsible at SHC: Francisco Márquez-Fernández, Lund University</td>
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<tr>
<td>Pre-study Power conversion challenges with an all-electric land transport system</td>
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<tr>
<td>Project responsible at SHC: Francisco Márquez-Fernández, Lund University</td>
</tr>
</tbody>
</table>
Thermo-mechanical fatigue of electric machine windings
*Project responsible at SHC*: Oskar Wallmark, KTH

Traction system parameter identification and condition monitoring via modulation spectra response
*Project responsible at SHC*: Avo Reinap, Lund University

Ultra-compact cost-efficient fast charging stations
*Project responsible at SHC*: Saeid Haghbin, Chalmers

Traction induction machine modelling conducted in student projects
*Project responsible at SHC*: Torbjörn Thiringer, Chalmers

Variable flux machine for electric vehicles
*Project responsible at SHC*: Yujing Liu, Chalmers

**Energy storage**

Efficient and safe battery operation – Aspects of expansion and utilization
*Project responsible at SHC*: Matilda Klett, KTH

Electrochemical modelling for prediction of long-term battery power
*Project responsible at SHC*: Torsten Wik, Chalmers

Electrochemical study of durability aspects in large vehicle batteries
*Project responsible at SHC*: Rakel Wreland, KTH

Fast-charging of large energy-optimized Li-ion cells for electrified drivelines
*Project responsible at SHC*: Jens Groot, AB Volvo

High temperature lithium batteries: From fundamental science to vehicle integration
*Project responsible at SHC*: Patrik Johansson, Chalmers

Pre-study Efficient and safe battery operation – Aspects of pressure and utilization
*Project responsible at SHC*: Matilda Klett, KTH

Pre-study High energy density battery materials – understanding their endurance with the help of modelling
*Project responsible at SHC*: Anti Liivat, Uppsala University

Åldringsmekanismer och hur man förlänger livet på batterier i fordon och stationära applikationer
*Project responsible at SHC*: Torbjörn Thiringer, Chalmers

**Vehicle analysis**

Energy transfer solutions for electrified bus systems (2015-2016)
*Project responsible at SHC*: Anders Grauers, Chalmers

Energy transfer solutions for electrified bus systems (2016-2017)
*Project responsible at SHC*: Anders Grauers, Chalmers

Decision support for implementing electric buses in public transport
*Project responsible at SHC*: Anders Grauers, Chalmers

Driveline configurations for fuel cells
*Project responsible at SHC*: Anders Grauers, Chalmers

Effects of the automated transport system – SEVS for AD
*Project responsible at SHC*: Anders Grauers, Chalmers

**Technology watch of fuel cells**
<table>
<thead>
<tr>
<th>Project</th>
<th>Title</th>
<th>Project responsible at SHC</th>
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<tbody>
<tr>
<td>Bränslecellsdrift av tunga truckar – Potential inom processindustrin</td>
<td>Elna Holmberg, SHC</td>
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<td>Bränslecellsdrivna lastcyklar – En förstudie</td>
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<td>När passar bränsleceller bäst? – en studie av elektrifierade drivlinor</td>
<td>Anders Grauers, Chalmers</td>
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</tr>
<tr>
<td>Technology review – Solid Oxide Fuel Cell</td>
<td>Elna Holmberg, SHC</td>
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Collaboration with external partners

Collaboration with other organizations and knowledge of research activities outside SHC play an essential part in being a Swedish e-mobility hub.

SHC is in 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 covers a large part of all research activities within hybrid and electric vehicles in Sweden.

As a Centre however, SHC mainly focuses on collaboration with organisations that complement our knowledge, and on strengthening our role in Sweden.

Below are a few examples of Centres and organizations with which SHC have collaborated through dialogue and research activities in 2016.

Lindholmen Science Park
Lindholmen Science Park has been managing an electrified bus project in which Anders Grauers has been very much involved. In collaboration with Lindholmen Science Park, theme Vehicle analysis arranged a half-day course for those working with development, use or procurement of bus services and with a need/wish to learn more about electric buses. The course taught how electric charging buses function, their advantages, limitations and costs, with explanations based on concrete examples. The course was followed by a seminar on the same day, focusing on the introduction of electric buses.

Viktoria Swedish ICT
Vehicle analysis collaborates with Viktoria Swedish ICT in a project which puts the recent development in fuel cell technology in a vehicle perspective to find which configurations of power trains are the most interesting for fuel cell vehicles. The project was finalized in 2016 and a continuation is planned.

In a strategic collaboration on electric road systems, SHC works with Viktoria Swedish ICT and VTI. The aim of this collaboration is to build a joint knowledge base around ERS in order to strengthen the Swedish and Nordic research and innovation resources. There is also a regular dialogue on management level regarding cooperation possibilities between Viktoria Swedish ICT and SHC.

CERC – Combustion Engine Research Centre and KCK – Centre for Catalysis
Three excellence Centres at Chalmers (SHC, CERC and KCK) receive funding from Chalmers Area of Advance Transport for an interdisciplinary post-doc cluster for future hybrid vehicles. This multidepartment project develops a concept for a hybrid vehicle using a spark ignited engine and emission after treatment system. The focus around a common concept promotes new interactions between the departments (Signals and systems, Applied mechanics and Chemical and biological engineering) and further enhance connections between the Centres.

Centre for ECO² Vehicle Design
The project “Energy efficient driving using electric wheel corner functionalities” that was initiated this summer has established collaboration with the Centre for ECO² Vehicle Design at KTH. It is expected that it will be a fruitful collaboration with the ECO²-project “Innovative lightweight vehicle concept with wheel corner modules”, where an extended brush tyre model has been developed for rolling resistance studies within vehicle dynamics simulations.

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, that was finished this year, 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.
Outreach

The year has offered a great number of new projects and events for SHC’s partners, but also various public activities, ranging from news articles and events such as Almedalsveckan and the International Science Festival, to public seminars and talks.

Open conferences, seminars and workshops
The Centre has arranged several public events on various aspects of e-mobility in 2016. Some of these have had the scale and setup of conferences while others have been on narrower subjects for a smaller audience, suitable for fruitful discussions.

Global aspects on e-mobility at Roads to the Future
“Roads to the Future” is SHC’s centrally organized, public conference. This time, we took a step back for an overview of the e-mobility progress worldwide.

Close to 200 participants gathered to hear about how e-mobility is developing worldwide. Key-note speakers Keith Hardy from Argonne National Laboratory, USA, and Anshuman Tripati from Nanyang Technological University, Singapore gave examples of the varying conditions for the development of sustainable technologies in different parts of the world. Though working under different conditions, Hardy and Tripati agreed in their views regarding the implementation of sustainable mobility – public awareness and education is essential in order to change habits.

NEVS, Volvo GTT, Volvo Cars and Scania also contributed with how the companies work internationally with e-mobility. The academic perspective was provided by SHC’s thematic leaders Göran Lindbergh and Mats Alakula.

To conclude the conference, all speakers gathered for a panel discussion led by Anders Grauers and Elna Holmberg.

Next generation batteries
While lithium-ion batteries still dominate the electric vehicle industry, other chemistries are emerging, often known as Next Generation Batteries (NGB). The interest from industry and academia for these chemistries is growing steadily, as was clearly seen at the workshop “Next Generation Batteries”, arranged by SHC Energy storage and Chalmers.

About a hundred participants attended the event to learn more about tomorrow’s vehicle batteries. Both Swedish and international researchers presented their work with different battery chemistries during the day, among them Rosa Palacin from ICMAB-CSIC, Barcelona, Robert Dominko from NIC, Ljubljana and Anna Teyssot from Renault.

Fuel Cell 2016
The third annual conference arranged by Technology watch of fuel cells was held in Stockholm in November. This time, the conference not only presented the results of international technology watch and the works of the annexes, but also new research, including an SHC project performed in collaboration with Viktoria Swedish ICT. Furthermore, leading developers such as...
PowerCell, Sandvik and Plansee gave presentations to a broad audience. The day included a study visit to MyFC, manufacturer of a fuel cell charger for small electronic devices.

The conference was proof that the interest in fuel cells is steadily increasing and that the technology is on its way to becoming a branch in Swedish industry. Magnus Karlström commented in an interview on SHC’s website: “PowerCell presented elaborate plans at the conference. Several small entrepreneurs were also present. Most likely, they consider how fuel cells can be used in their products. It is a sign that the technology is closer to the market now than before.”

**Getting to Zero – seminar with Tom Turrentine**
The UC Davis Plug-In Hybrid & Electric Vehicle Research Center is the hub of collaboration and research on plug-in hybrid and electric vehicles for the State of California, and has many similarities with SHC. When the Centre director Tom Turrentine visited Chalmers, SHC took the opportunity to arrange a seminar which was very well visited by industry and academy. “I am convinced that people will prefer electric cars, as have already been seen in several studies. They simply like the feeling”, said Tom Turrentine in an interview made by Chalmers Area of Advance Energy.

**Collaboration with Business Region Göteborg on e-mobility in cities**
On two occasions, SHC have collaborated with Business Region Göteborg in spreading knowledge on implementation of e-mobility in cities: 'Kan man ladda elbilen hos dig?’ Municipalities, property owners, hotel owners and system suppliers were invited to this seminar with the opportunity to meet industry players, and learn about solutions for convenient charging in cities.

”Electro mobility in smart cities”, an international conference in Göteborg, with seminars, study visits and matchmaking. SHC provided speakers and arranged a session on implementation of electric buses in city traffic.

**Autonomous transport systems - the good, the bad and the unknown**
SHC had an active part in this full-day seminar arranged by Chalmers Area of Advance Transport, not only by suggesting knowledgeable and experienced speakers, but also by contributing with expertise. In a session moderated by Elna Holmberg, Anders Grauers gave a presentation on long term effects of autonomous vehicles and Mats Alaküla talked about auto-charging of electric vehicles.

**Energirelaterad fordonsforskning**
SHC researchers showed several posters at The Swedish Energy Agency’s conference “Energirelaterad fordonsforskning”. Verena Klass and Matilda Klett contributed with research presentations in a session chaired by Elna Holmberg.
SHC researchers in interaction with society

While conferences and workshops, though open to a general public, chiefly attracts those already familiar with e-mobility questions, news media and popular events are channels where knowledge can be spread to an ever broader audience. Below are some examples of how SHC’s members have reached out to society this year:

News articles


Mats Alaküla: “Elvägar – för mer än bara lastbilar” (Elektroniktidningen 2016-11-02); “Premiär för ny svensk elväg” (NyTeknik 2016-07-06); “Tanka med sol, vind och vatten” (SvD 2016-05-05) and “Elprofessorn är säker på sin sak” (Mariestadstidningen 2016-07-12).

Anders Grauers: “Därför blir elektrifierade och hybridiserade tunga arbetsfordon allt vanligare” (web article for supplier Compotech, 2016-05-31) and “Miljöfordon – framtidens transportmedel” (Inrikes #9 2016).


Almedalsveckan

KTH and Chalmers arranged a session at Almedalsveckan called “Förarlöst – men inte utan styrning” where a panel lead by the former Minister for Communications discussed innovation and research, funding and future. Elna Holmberg and Lars Nielsen were two of the invited experts.

Mats Alaküla was also present in Almedalen, introducing ElectriVillage, a project conducted by Mariestads kommun in collaboration with Lund University.

The International Science Festival

Does a truck have to be over 10 meters long and smell of diesel? Elna Holmberg set out to answer this question at “Vetenskapsrouletten” during the International Science Festival in Göteborg. Jonas Fredriksson, leader of System studies and tools also participated by introducing school children to control and programming at the lab at Chalmers.

Study visit to Japan

A group of researchers, companies and public authorities went to Japan in late September, to study how the country works with the transition to an electrified vehicle fleet. SHC’s director Elna Holmberg was one of the participants.

The programme for the five day tour included visits to various companies, authorities and organizations of importance for Japan’s transition to electrified vehicles. Among others, the group visited Nissan and Toyota, CHAdemo, Japan’s Ministry of Economy, Trade and Industry and the Association for the Promotion of Electric Vehicles. At the Swedish Embassy in Tokyo the visiting Swedes presented themselves and their activities to their hosts.

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 Energieffektiva Vägfordon). The project regularly delivers analyses, distributed by email to about 1,360 subscribers.

Magnus Karlström and his fellow editors distributed about 140 newsletters in 2016. The readers have been able to follow a series of articles focusing on the influence of Silicon Valley on the automotive industry, material constraints for battery production and the e-mobility development in Germany, mixed with reports from conferences and tips about events.

The podcast that OmEV introduced last year has continued with seven new podcasts broadcasted in 2016. The topics have ranged from the standards of batteries to recharging infrastructure and electric bicycles and light electric vehicles.

Communication

Communication at SHC include both information to and between our partners, and spreading knowledge outside the organization. Marketing and administrating events, writing news articles, managing newsletter and website and producing graphic material are some of the tasks of the communications officer.

The number of subscribers to SHC’s monthly newsletter is steadily growing, reaching about 600 by the end of the year. 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.

Articles highlighting activities and research within SHC have been published regularly during the year and been promoted by means of the newsletter and Twitter. 38 articles were posted on SHC’s website in 2016, ranging from short news paragraphs to in-depth articles. This year, the news flow has contained presentations of the thematic areas expectations and plans for SHC phase III, interviews with Anshuman Tripati and Keith Hardy at the time of “Roads to the Future”, interviews with the new thematic researchers and a follow-up on SHC’s alumni and their roles in the industry, to mention a few examples. Networking with communications officers in other organizations is important when spreading these news in other channels than SHC’s own.

With increased activity in the thematic groups follows an increased amount of communication support. Over twenty different events have received support such as marketing, website, graphic material and articles this year.

As SHC expands, the website is in need of a makeover to match the Centre’s profile. A considerable effort has been made in planning new functions for the website and a new visual identity for SHC. This work will continue in 2017.
Education

One of the goals of SHC is to contribute to future competence for academia and industry. Graduate education, PhD courses and networking possibilities for doctoral students as well as for engineers at the partner industries, form an important part of the Centre’s mission. This year, the thematic groups have been planning a PhD summer school for 2017, “Components and systems for Electromobility”, with contributions from all thematic areas.

Education at our partner universities

SHC’s senior researchers have central roles in the teaching on Bachelor’s, Master’s and Doctoral level at their universities, and some have also given guest lectures at other universities during the year.

SHC researchers collaborate with master students in a project on asynchronous motors at Chalmers, KTH and Lund University, and also one at KTH where the students develop a test bench. Through the test bench project at KTH, senior researchers also collaborate with students in the Shell Eco Marathon work. Moreover, System studies and methods are planning three master student projects in platooning, in cooperation with AB Volvo. Of these, one is already initiated and the remaining two are planned for 2017.

Doctoral network

SHC’s doctoral network welcomes all doctoral students from Swedish universities whose research is related to electric and hybrid vehicles and the surrounding infrastructure. The network members are invited to SHC’s events and PhD courses, and to recurring network activities. At the end of the year the network had 64 registered members.

After managing the doctoral student network and organizing its activities for four years, Anders Nordelöf resigned by the end of 2015 to fully focus on his research. New manager of the network is Fernanda Lodi Marzano, researcher in Energy storage at Uppsala University.

Two major activities have been arranged for the network in 2016: a spring meeting in connection to the SHC conference “Roads to the Future” and an autumn meeting including a visit to Scania. The network members were also invited to SHC’s cross-thematic meetings.

The theme of the spring meeting was “Electrification of public transportation” and was held at Chalmers. The morning session included a presentation on environment, trends and technologies by Volvo Buses and an introduction to the regional perspective for development of public transportation, policies to promote electric vehicles in Göteborg and a presentation of the project “ELMOB”. The afternoon session was dedicated to impact and entrepreneurship in relation to research.

When the network gathered at Scania’s site in Södertälje, the aim was to learn more about how Scania works with electrification, and what skills will be in demand in coming years. A group of about thirty doctoral students was received at Scania, for presentations of electric and hybrid technology, technology trends from the company’s perspective and a tour of the site. During the two-day meeting the group also had opportunity to network with each other, talk about their own research and do some “speed dating” to find new research contacts.
In an article on SHC’s website, doctoral student Maria Taljegård explained that the network is an important platform for meeting doctoral students in the same research area and getting to know those who work at other universities. “On this occasion I go to know two or three doctoral students that I may have further exchange with concerning my research”, she said.
The third phase of the Centre lasts from 1 July 2015 to 31 June 2019. Since the first half-year of the phase was affected by negotiations on the cooperation agreement, 2016 has been the first year with full activity. All thematic areas have started projects with thematic researchers, who also take part in the operation of the Centre. A number of other research projects, from longer PhD projects to shorter studies are initiated as well as knowledge transfer activities and workshops on new research issues.

In the end of 2016 the Centre included 45 ongoing research projects and studies with a total budget of over 70 million Swedish kronor. The three thematic areas with the largest number of projects are Electrical machines and drives, with 19 projects, System studies and methods with 11 projects and Energy storage with 10 projects.

The increased activity is also reflected in the outcome of SHC’s budget. Just over 26 million of the Centre’s own core project budget was allocated in research projects. The remaining project budget is about 12 million. As mentioned earlier, the total budget for projects tied to the Centre’s activities is about five times as large as the core budget.

Distribution of funding

The number of projects is growing steadily in pace with the development and reputation of the Centre. By the end of 2016 the Centre included 45 research projects and studies with a total budget of over 70 million Swedish kronor. The three thematic areas with the largest number of projects are Electrical machines and drives, with 19 projects, System studies and methods with 11 projects and Energy storage with 10 projects.

The size of projects vary rather much between the themes. Both Electrical machines and drives and Energy storage have large externally funded projects while System studies and methods has rather small projects (figure 1). Theme Energy storage is therefore the second largest theme from a budget perspective.

The funding in the projects mainly comes from various programs initiated by the Swedish Energy Agency but to some extent also from Vinnova and Drive Sweden (figure 2).
The total funding of projects by the Centre’s own budget is about 20% of the total attracted budget.

When only projects with funding from the Centre is studied, as in figure 3, it is clearly shown that theme Energy storage has received less funding that the other two areas. Theme Vehicle analysis has up to now no funding at all from the Centre. However, this data changes with the elapsed time of the phase of the Centre.

One of the Centre’s objectives is that about half of the projects should be senior projects and half PhD projects. Figure 4 shows the distribution of funding in PhD projects, projects with senior researchers and studies. As can be seen in the figure, the Centre fulfils its ambition to have a balance in the project portfolio between young and more experienced researchers. The figure showing only projects financed within the Centre is similar, with the exception that the studies take a larger part of the total project budget.

The distribution of the total cash project budget for projects running during 2016 is shown in figure 5. It includes both projects financed by SHC’s own budget and projects with external funding. The reason for KTH dominating the funding from the Centre is that KTH is the only university with a PhD student. All other remaining projects funded by SHC are shorter studies. If the same diagram is made to show all projects decided, but not yet started, during 2016, the picture looks different (figure 6). The difference mainly originates from Chalmers now having two new PhD students who will start during 2017.
Note that the cooperation projects also include projects that have partners outside SHC.

Centre finance
All universities have reported the outcome of their research projects funded by the Centre (table 1). The activity level in the research projects during 2016 looks low at first sight but the funding is distributed evenly over all project’s duration and does not take into account the planned activity level. The majority of the projects continue during 2017 or beyond, and the more intensive periods of research projects are often not in the early phases. It is often very difficult to predict the time required to recruit a student or plan resources with high precision. Lund University is involved in several projects but the outcome of these is not yet included in the table.

Table 1. Outcome in research projects funded by SHC 2015-2016.

<table>
<thead>
<tr>
<th>Outcome in research projects</th>
<th>2015-2016, 1 July 2015 -31 December 2016</th>
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<tbody>
<tr>
<td></td>
<td>Outcome in project (SEK)</td>
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<tr>
<td>SUM CHALMERS</td>
<td>657 385</td>
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<tr>
<td>SUM KTH</td>
<td>2 152 070</td>
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<tr>
<td>SUM LINKÖPING</td>
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<tr>
<td>SUM LUND</td>
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<td>SUM UPPSALA</td>
<td>592 389</td>
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<tr>
<td>SUM ACADEMY</td>
<td>3 724 818</td>
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<tr>
<td>PLAN ACADEMY</td>
<td>5 284 000</td>
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There is no other evidence that the activity level in the Centre or in the thematic areas are low. On the contrary, the frequency of thematic meetings, activities and knowledge transfer activities has been high during the past year with monthly discussion meetings and workshops.

Program council, Industrial council and management
The board had five board meetings during 2016. Two were phone meetings and the remaining took place at Linköping, Lund and Uppsala universities.

One new person has been invited to the program council, Anders Berndtsson from the Swedish Transport Administration. Anders contributes both with new insights and important information from the Transport Administration, which is important both for the universities and companies but most of all for the research projects related to the traffic environment.

The Industrial council had two meetings during the year where they discussed and commented on the research proposals.

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Emilia Lundgren, Communications officer  
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Francisco Márquez-Fernández, Thematic researcher  
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Matilda Klett, Thematic researcher  
Mikael Askerdal, Thematic researcher
Project reports

The projects of each theme are presented in alphabetic order.

System studies and methods

Energy efficient driving using electric wheel corner functionalities

PARTICIPANTS
Lars Drugge, KTH, Project manager
Annika Stensson Trigell, KTH
Jenny Jerrelind, KTH
Mats Jonasson, Volvo Cars (affiliated)

PARTNERS
KTH

FINANCING
Cash financing: 360,000 SEK. Funding organizations: SHC and KTH

DURATION
2016-2017

Electrification of powertrains provides a mean for reducing the environmental impact of vehicles by reducing fuel consumption or replacing fossil fuel. Electrified powertrains also enable cost-efficient implementation of active control of vehicle subsystems (traction/braking/steering etc.), which until now has mostly been studied regarding enhanced manoeuvrability and safety.

This project focuses on how the combination of wheel angle (steering/camber) and propulsion control can be utilised to reduce the motion resistance of a vehicle using for example electric wheel corner modules. By building on recent research results, the aim is to develop knowledge on how these subsystems can be used to reduce motion resistance for different manoeuvres.

So far, a pre-study has been performed to investigate how propulsion control influences the energy efficiency during cornering and the consequence it has on the understeer gradient of the vehicle. Furthermore, a simplified vehicle model with linear tyre properties for lateral and longitudinal forces as well as camber thrust has been developed. The model has been used to evaluate the total slip losses due to lateral and longitudinal forces during steady-state cornering. A genetic algorithm has been used to find optimal solutions for different combinations of control variables (steering, camber, torque vectoring) at different velocities and lateral accelerations. The results from the linear model show that torque vectoring control contributes to a reduction of the power losses of about 1-2 % during a steady-state cornering manoeuvre whereas camber control can reduce it by 5-20 %, depending on vehicle, velocity and lateral acceleration. Therefore, both camber control and camber control coupled with torque vectoring show promising results to achieve a more energy efficient driving.

The next step is to analyse the influence of vehicle model simplifications on the energy loss estimations. Here, the tyre model is important. By expanding the tyre model to a non-linear model, also taking into account effects of combined lateral and longitudinal forces,
the combination of forces that affects the tyre properties in each direction are taken into account. Thereby making the analysis more valid also in manoeuvres where large lateral and/or longitudinal forces are occurring.

Collaboration with Volvo Cars is established through the participation of Mats Jonasson who is affiliated to the project. The affiliation of an industry partner to the project has provided valuable knowledge regarding torque vectoring implementation aspects and practical information about actual vehicle model properties and attributes important for the simulations.

Additionally, we expect fruitful collaboration with the Centre for ECO2 Vehicle Design at KTH through the project “Innovative lightweight vehicle concept with wheel corner modules”, where an extended brush tyre model has been developed for rolling resistance studies within vehicle dynamics simulations. The project also collaborates with two KTH-CSC PhD students at KTH Vehicle Dynamics.

In December 2016 an extended abstract entitled “Analysis of camber control and torque vectoring to improve vehicle energy efficiency” was submitted to IAVSD 2017, the 25th International Symposium on Dynamics of Vehicle on Roads and Tracks, 14-18 August, Rockhampton, Queensland, Australia.

Interdisciplinary post-doc cluster for future hybrid vehicles

PARTICIPANTS
Tomas McKelvey Chalmers, Project leader
Adrian Ilka, Chalmers, (Control part of the project)

PARTNERS
Chalmers

FINANCING
Cash financing of Control part: 1,000,000 SEK. Funding organizations: Chalmers AoA Transport and AoA Energy.

DURATION
2015-2016

In this multidepartment project we are developing a concept for a hybrid vehicle using a spark ignited (SI) engine and NOx reducing emission after treatment system (EATS), i.e. a three way catalyst (TWC). This concept focuses on the control of the combustion engine and the effect of temperature variations in the exhaust after treatment system on emissions for a hybrid vehicle.

The project has three parts representing the involved departments:

- The post-doc at the Department of Signals and Systems is working on a system level control where the overall control of the SI engine, the electrical engine and the three way catalyst is determined.
- The post-doc at the Department of Applied Mechanics is working on a combustion engine part with focus on the modelling of the engine and transmission to reduce emissions and fuel consumption.
- The post-doc at the Department of Chemistry and Chemical Engineering and will study lean NOx reduction at low temperature in the catalyst part.

The focus around this common concept promotes new interactions between these three departments and further enhance connections that today exist through the KCK and
The rest of this report is focused on the control part of the post-doc cluster project.

The main purpose of the project is to develop a system wide control method (supervisory control) using a model-based framework for a hybrid vehicle using a SI engine and TWC. This type of overall control system is required to obtain an efficient vehicle that minimizes fuel costs and obey legislative emission limits. Hence, models suitable for control design and calibration efforts need to be assembled, which are capable to predict emissions and fuel consumption given a load cycle and environmental conditions. For a given model and work-cycle the open-loop optimal control problem can be considered, which can provide a solution which directly gives the lower bounds on achievable minimal fuel consumption for a given emission level. However, the open-loop optimal control solution is not realizable nowadays in a real application, so control structures which are realizable in a vehicle need to be considered, i.e. more conventional feed-forward and feedback structures. Specifically, one of the purposes is to develop such structures such that partial look-ahead information can be utilized to improve the overall performance over a work cycle/use case.

For hybrid applications the so-called power split control problem has been well studied in the literature for various load cycles including transient cycles. However, 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 EATS 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. Particularly there are several trade-offs between using different combustion modes (with a fuel penalty), using the electric motor (with a battery penalty) and controlling the EATS (e.g. by dosing the reducing agent, with an associated cost). Therefore, it is necessary to develop overall control strategies which includes the temperature variation in the EATS, and to develop such optimal and model predictive control approaches that are technically implementable.

The results we have reached so far contribute to the theoretical part of the project. We successfully developed a less conservative advanced discrete-time gain-scheduled PID controller design technique for non-linear systems with input constraints. The controller design guarantees the optimal controller parameters and closed-loop system stability and can be used as low/middle layer optimal controller. Furthermore, we developed a new gain-scheduled controller design technique for non-linear switched systems, since many parts in the EATS can be modelled as hybrid-switched system. Finally, to implement look-ahead information, a novel preview filter and a new finite horizon linear parameter-varying based off-line LQR control strategy was developed for middle/supervisory control. This allows using a cheap and low energy requiring guaranteed cost controller with the same (or very similar) performance quality as with the non-linear model predictive controller. The achieved theoretical results are promising, and hopefully they will be beneficial in the application part too.

The next step is going to be the application part, where the obtained theoretical results will be implemented and validated on a detailed simulation model. First, the control oriented model will be finalized and then calibrated using the detailed and tuned simulation model in GT-Suit and/or AVL Cruise. Secondly, different controllers will be designed using the developed controller design techniques. Finally, the obtained control strategies will be implemented and compared on the detailed simulation model.
The project collaborates with Volvo Cars and Volvo Trucks within an FFI project on Multivariable Methods for energy efficient Engine Control (MultiMEC) and with Volvo Cars within the FFI project VCloud II. On an international level, there is collaboration with researchers like Vojtech Vesely from the Slovak University of Technology in Bratislava.

Publications and conferences 2016


Modelling of hybrid powertrains and exhaust after treatment systems

PARTICIPANTS
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Mathias Björkman, Scania
Mats Andersson, AB Volvo
Torbjörn Eliassen, Scania
PARTNERS
Linköping University, Chalmers, AB Volvo, Scania

FINANCING
Cash financing: 300,000 SEK. Funding organization: SHC

DURATION
2016

The purpose of this project is to develop a simulation model of open source character that can be used to investigate the interplay between the hybrid and after treatment systems in a hybrid truck or bus that is powered by a diesel engine.

To meet the demands of customers and legislators, vehicles are becoming increasingly complex where it is straightforward to design the system and the controls. This is especially true for hybrid vehicles where a hybrid system can result in more cold start transients for the after treatment systems. More knowledge is needed to develop a systematic design for such systems.

So far, vehicle and driving data has been provided by the industrial partners, a first version of the model has been implemented and is running. The model has been shown and discussed at a workshop on December 15, 2016. The next step is to produce a report that will be made available on the SHC document sharing site.

The reference group and industry partners have provided invaluable input on the requirements and provided measurement data that would have been impossible to get without the collaboration.

Pre-study Information management for the energy efficient vehicles of the future

PARTICIPANTS
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Johan Bjernetun, AB Volvo
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Lars Eriksson, Linköping University
Mathias Björkman, Scania
Mikael Askerdal, Chalmers
Sören Eriksson, Volvo Cars

PARTNERS
AB Volvo, Scania, Volvo Cars, Chalmers

FINANCING
Cash financing: 400,000 SEK. Funding organization: SHC

DURATION
2016

In this project a study has been conducted, where a simulated hybrid truck with an advanced predictive energy management strategy was fed with corrupted positioning information. The energy consumption was compared to the case with positioning signal without disturbances. The project shows that poor information regarding vehicle positioning can have a large negative effect of the energy management system of a vehicle
resulting in increased energy consumption and sometimes vehicle stop and software failure. The study has been done on a truck but there is no real reason to believe that the result would be different for other road vehicles such as cars and buses.

Another part of the project was to conduct a literature study and interviews to elicit the needs of the industry, in order to find an area for a thematic research project. The result from this study are developed further in the project report for “Vehicle independent road resistance estimation”.

The main contribution from this project is the high-lighting of information quality as a key factor to improve energy efficiency, range estimation and route planning.

AB Volvo, Scania and Volvo cars have all be involved by giving input to the industrial research need.

The project was done as a pre-study for further research in the area of information management for the energy efficient vehicles of the future. It resulted in the project “Vehicle independent road resistance estimation” which will focus on how to improve the information of the road resistance that is available for the vehicles.

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Test bench for Optimal Design and Control of Energy Buffers for Minimizing Energy Consumption

PARTICIPANTS
Mikael Hellgren, KTH/Integrated Transport Research Lab (ITRL), Project manager
Lei Feng, KTH

PARTNERS
KTH

FINANCING
Cash financing: 150,000 SEK funded by SHC and 200,000 SEK funded by ITRL

DURATION
2016-2017

Researchers in KTH/Mechatronics are today looking into the area of optimization of hybrid drive systems. The problem is that they have no test bench to test their result in. This project will lead to test equipment consisting of a hybrid vehicle and a “rolling road” facility.

With this setup the researchers will be able to test their ideas about optimal control design that are now theoretical. Research ideas will be tested on the test bench and the produced articles will cite the test bench.

So far, data from test with our Shell Eco Marathon car has been collected. These data shall be used for calibrating our test bench later on. Six students are currently working with the bench and it has been partly tested for the first time. The version 1.0 of the test bench will be presented and demonstrated the 12th of December.

When the students are ready with their work, the bench will be tested and further enhanced. The idea is to have a tested and calibrated bench in the end of the project so results could be used in papers.
Vehicle independent road resistance estimation

PARTICIPANTS
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Jonas Hellgren, AB Volvo
Martin Sanfridsson, AB Volvo
Martin Sievertsson, VCC
Per-Åke Lofdahl, Scania
Rickard Arvidsson, VCC
Tenil Cletus, AB Volvo

PARTNERS
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FINANCING
Cash financing: 1,520,000 SEK. Funding organization: SHC

DURATION
2016-2018

Road resistance is commonly divided into a few different components such as rolling resistance, wind resistance and resistance from road gradient (hills). The total sum of road resistance is the force that must be delivered by the powertrain to the wheels of the vehicle in order to maintain speed. The different components of the road resistance have been studied in a number of different projects and a lot is well known. However, in most studies the model parameters used are often dependent on both the vehicle, the road and the surroundings. Some exceptions exist though, especially when it comes to the rolling resistance. The idea with this project is to find models for each of the different components of the road resistance where the input parameters used are either purely vehicle dependent or purely dependent on the road and the surrounding conditions and to develop a method to estimate the data of the surrounding conditions from a large population of vehicles (big data). The advantages with this approach is that data from any vehicle can be used to improve the estimation and that all vehicles can benefit from the estimated data. In the long run, this can lead to a system that dynamically calculates the surrounding parameters of the road resistances and that adapts rapidly to changing conditions such as wind and wet road surface.

The project is expected to:

- Point out a number of vehicle independent road resistance coefficients
- Point out a number of road resistance independent vehicle parameters
- Develop an estimation method from measurements from a large population of vehicles
- Develop a method for approximating the energy consumption of a road segment from the road resistance coefficients and the vehicle parameters

The result is expected to be useful for:

1. Improved range estimation of battery electric vehicles
2. Improved vehicle energy management
3. Energy efficient and economical route planning.
The purpose is to improve the road resistance estimation by separating road resistance parameters into two sets of parameters. The first set including parameters that are solely depending on the vehicle itself and the second set including parameters that are independent of the vehicle. The idea is also to investigate if the vehicle independent parameters can be estimated from vehicle log data.

Estimates of road resistance can be used for range estimation, energy management and route planning. Today, road resistance estimates to be used for range estimation and predictive energy management are done on-line in vehicles. These estimates can only use past data. That means, that the road resistance estimation of the upcoming road are based on data from the road behind you. This can be very wrong if, for example the road surface changes from concrete to dirt or if there is a sudden change in weather conditions such as strong head winds or snow on the surface. Some of these problems can be overcome by storing data from past drives, but far from all of them. Rolling resistance is for example very much dependent on the surface and can change rapidly if it starts to rain or snow. Air resistance will change if there is change in wind speed or direction.

Furthermore, the state of the art for route planning is to use static information or even constant values for the road resistance of the possible routes. Dynamic information of the road resistance could therefore improve route planning by avoiding routes with temporary high road resistance due to disadvantaging conditions such as strong head wind and snowy roads.

If the road resistance parameters could be shared between vehicles, these changes could be detected before the vehicle enters a road segment with changed conditions and therefore adapting the range estimation and energy management in advance improving both the range and the range estimation. However, parameters sharing is not possible as long as the road resistance parameters are depending on the vehicle itself. Hence, this project is important as an enabler for sharing road resistance parameters between vehicles. The idea is that this would lead to improved range estimation, energy management and route planning.

The results so far comes from the more general pre-study called “Information management for the energy efficient vehicles of the future”. The aim of the pre-study was to set the scope to the main project (i.e. “Vehicle independent road resistance estimation”) and to investigate how errors in the information given to a predictive energy management strategy affect fuel consumption and overall vehicle performance. The second result from the pre-study was that poor information (i.e. poor gps-positioning) will have a strong influence on both fuel consumption and vehicle performance. With a non-robust implementation, the vehicle will come to an unwanted stop if the e-horizon system tells the energy management system that the road slopes downwards when it is actually going up-hill. And picking the wrong path as input information when running on a hilly road can result in a 60% increase of fuel consumption. The importance of this result is that advanced deterministic algorithms are only beneficial if the input information is correct. Otherwise, they might perform worse than simple algorithms.

The next step of the project is to collect vehicle data and from that evaluate different ways of splitting the road resistance parameters into vehicle dependent parameters and vehicle independent parameters.

In the project work, there is collaboration with several research projects at the participating industrial partners. There is also some collaboration through knowledge sharing with the network Complete Vehicle Energy Consumption (CVEC). In the future, more collaborations are likely with for example research projects within institutes like SP and VTI.
The industry partners are vital for providing the project with relevant measurement data, simulation environment and expertise. The reference group will be useful for prioritize and set the direction of the project.
Electrical machines and drives

48V mild hybrid Electrically Excited Synchronous Machine

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Sören Eriksson, Volvo Cars
Jonas Forsell, Volvo Cars
Joachim Lindström, Volvo Cars
Stefan Olofsson, Volvo Cars

PARTNERS
Chalmers, Volvo Cars

FINANCING
Cash budget: 300,000 SEK. Funding organization: SHC

DURATION
2016

In this pre-study project, Volvo Cars and Chalmers cooperate around the investigation of a so called Electrically Excited Synchronous Motor (EESM) for 48V mild hybrid application. A prototype machine has been designed and built during the project. The project collaborates with another project within SHC: “Variable flux machine for electric vehicles”, financed by the Swedish Energy Agency/Energieffektiva vägfordon.

The purpose is to verify the performance and potential of the flexible-flux machine concept by prototyping for a low-power application (48V mild hybrid drive). The budget of this project is used mainly for prototype building. The design and development, as well as testing are covered by the collaborating PhD project.

The developed concept has flexible magnetization control compared to the state of the art solutions with rare earth permanent magnets. This enables potential for high power density and an environment friendly product. The prototype machine is designed according to the specifications from Volvo Cars. The machine is under manufacturing and expected to be ready for test in February 2017.

The results of this pre-study led to a new application for PhD project on “Integrated drives for electrified vehicles”, which is granted by The Swedish Energy Agency / Energieffektiva vägfordon.

The knowledge has been shared with Volvo Cars and a conference paper was published in 2016 together with the project “Variable flux machine for electric vehicles”.

We got help from the reference group and industrial partner (Volvo Cars) in:

- Introduction about applications (48V mild hybrid drive)
- Specifications and requirements
- Feedback on design

Publications and conferences 2016
Field Intensified PM Machine for an HEV Application

PARTICIPANTS
Torbjörn Thiringer, Chalmers, Project manager
Mikael Alatalo, Chalmers
Joachim Lindström, Volvo Cars

PARTNERS
Volvo Cars, Chalmers

FINANCING
Cash financing: 300,000 SEK. Funding organization: SHC

DURATION
2016

In this project VCC and Chalmers cooperate around the investigation of a so called field intensifier machine. The inherent machine properties and potential performance are analysed and compared to a state-of-the-art V-shape IPM design (reference machine).

The purpose is to investigate under which circumstances a propulsion PMSM with $L_d > L_q$, a so called field-strengthening machine can be beneficial. Driving cycles with high average speed as well as cycles with low accelerations seems to be possible benefit areas.

Today we are totally stuck with the conventional $L_q > L_d$ for interior PMSM. However this might not be the ultimate solution always. In particular when using Ferrite magnets the field strengthening machine can provide benefits.

So far a couple of possible layouts have been brought forward for investigation. The next step is to start evaluating a first layout, and then put the results in relation to a conventional PMSM for traction applications.

Within this project, we have a thesis worker from Aachen University available. His examiner is located at this University. The VCC industrial representative is already active in the layout discussions as well as discussions with the Master thesis worker.

We have had valuable input from the reference group at the start-up meeting. In particular Oskar Wallmark from KTH has worked with a key Japanese researcher and could provide valuable links and proposals.

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

PARTICIPANTS
Oskar Wallmark, KTH, Project manager/Supervisor
Mats Leksell, KTH, Supervisor
Mojgan Nikouei Harnefors, KTH, PhD student

PARTNERS
AB Volvo, KTH, Scania, Eskilstuna Elektronikpartner AB

FUNDING
Cash financing: SHC 3,580,000 SEK, Vinnova (2015-08-15 – 2016-12-31) 300,000 SEK
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 overall goal of this research project 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.

Until now, key results include:

- 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.](image)
A general algorithm for stabilizing the capacitor voltages on each submodule has been proposed with an extended journal submission.

Converter operation with four submodules and a permanent-magnet motor load has been successfully demonstrated.

In collaboration with Eskilstuna Elektronikpartner AB (funded by the Vinnova within the “Smartare elektroniksystem” program), high-current (100 A) PCB converters are presently being manufactured and are planned to be delivered in January 2017 (see Figure 3).

A machine design scheme incorporating potentials/limitations of the converter topology has been proposed 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.

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

PhD student Mojgan Nikouei Harnefors is presently working on finalizing two additional prototype converter boards for evaluating submodule fault-handling strategies.

A water cooling arrangement for cooling the high-current PCBs (see below) has been designed by Mojgan and is presently being manufactured.

The next step is to evaluate the developed control algorithms for continuous operation as well as fault handling on the full-scale modular converter prototype that presently is being manufactured.
On Sept. 15th 2016, the project’s collaboration Eskilstuna Elektronikpartner AB was presented at the Smartare elektroniksystem’s yearly summit held at Tekniska museet, Stockholm. On Dec. 5th 2016, selected results were presented at the STandUP for Energy workshop given at KTH, Stockholm.

The project leader also leads the activities within the, to SHC associated project, “Modellering och analys av samverkan mellan batteri och spänningsomvandlare i elektriska drivlinor” (funded by FFI) in which actors from SHC-Theme 1 are also members. The results from the FFI project will be used in the SHC project in order to better quantify constraints and requirements of the dc-voltage capacitors used in the modular converter.

Dr. Sjoerd Bosga (ABB Corporate Research), presently guest researcher (20%) at KTH is now collaborating with the members in the research group at KTH focusing on modular electric drives.

The industrial representatives have provided useful input in term of specifications and important know how regarding automotive applications. It is expected that this project will contribute to the industrial partners with a detailed investigation of the advantages and challenges that modular integrated electric drives can bring when applied in automotive traction applications.

Publications and conferences 2016


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Hybrid Drives for Heavy Vehicles

PARTICIPANTS
Mats Alaküla, Lund University, Project manager
Rasmus Andersson, Lund University, PhD student
Anders Hedman, AB Volvo
Avo Reinap, Lund University
Johan Hellsing (until end of 2012)

PARTNERS
Lund University, AB Volvo

FINANCING
Only in-kind from AB Volvo in SHC Phase III

DURATION
2010-2018

This project is an industrial PhD student in collaboration with Volvo GTT and IEA at LTH, Lund University. It is looking into Electric Machine design for commercial hybrid on road vehicles such as trucks and busses. A difficulty with introducing a hybridised drivetrain, in particularly affecting the truck applications, is related to the commercial aspect. The increased investment cost must not be higher than the potential savings in fuel. One way to reduce the investment cost is to reduce the component size and thereby material cost in the bill of material. The objective is to do so, with focus on the electric traction machine.

The main purpose of 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.

Finally the goal is also to present an electric machine design that can be used for electric traction in heavy hybrid road vehicles in a strictly limited geometrical space.

The project result so far is a Licentiate degree in the field of electric traction machine design for heavy hybrid vehicles. The design, build and testing of four machine prototypes have also been completed within the project. This has resulted in improved knowledge in electric traction machines within industry (Volvo). The full insight in an Electric machine design and how it affects the performance is valuable knowledge when discussing with
different electric machine suppliers. Furthermore, the general knowledge in commercial vehicle aspects has been improved within academia (IEA, Lund University).

Three of the prototypes have been produced within the FFI financed project called: “ExSAM drive for a Commercial Vehicle Hybrid Transmission”. Except for LTH and Volvo, two other companies, Sibbhultsverken AB and MagComp AB, have been partners in that project.

Publications and conferences 2016

The conventional three-phase radial flux PM machine has been described at three conferences during 2016:


Investigation of state-of-the-art of additive manufacturing of electric machine components for EV/HEV applications

PARTICIPANTS
Oskar Wallmark, KTH, Project manager

Partners:
KTH

FINANCING
Cash financing: 100,000 SEK. Funding organization: SHC

DURATION
2016-2017

It is clear that additive manufacturing (AM, “3D-printing”) will be applied in a wide range of industrial applications, including several in the automotive industry. Important reasons for this are that AM allows key components to be produced with greatly reduced amounts of residual materials and with fewer operations compared to conventional manufacturing techniques. This project maps international activities in the field of AM of magnetic and electrically conductive electrical machine components for hybrid and electric vehicles. In addition, existing national AM initiatives will be mapped. The overall goal is to accumulate knowledge that will serve as a basis for planning and coordination of activities in future larger research applications (e.g. in the FFI program).
NB: The planned activities during 2016 have, due to time constraints, been delayed and the project is planned to be executed during 2017.

Multi physical modelling of a hybrid cooling circuit and its attached components for an electrified vehicle

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Alessandro Acquaviva, Chalmers, PhD student
Yujing Liu, Chalmers

PARTNERS:
Chalmers

FINANCING
Cash financing: 4,950,000 SEK. Energimyndigheten/Energieffektiva fordon

Duration:
2016-2019

Today, energy efficiency calculations in vehicles are typically conducted at a certain assumed temperature on the cooling fluid, ignoring that the temperature of the cooling fluid typically vary with speed, time and outer climate conditions. With the results of this project such calculations will be made possible.

The purpose of the project is to include the temperature of the hybrid cooling path into loss calculations for the electrical components. This will enable more accurate energy efficiency calculations as the losses that are temperature-dependant will be calculated with better accuracy. Moreover, this can be utilised by having an altered cooling strategy that can reduce the energy consumption.

The project has only been running for 6 months. The results reached so far are energy efficiency calculations of a SiC equipped inverter. In addition, calculations using Comsol multiphysics have been made on the ability of a cooling fluid to cool a heat-sink. The next step is to do the loss calculations with thermal consideration for the inverter. After that it is time to model the complete chain of electrical components connected to the hybrid cooling path.

Exchange with theme System studies and methods is expected next year. Similar activities are also being conducted at Volvo Car Corporation and knowledge exchange is taking place.

Pre-study: Power Conversion Challenges with an All-Electric Land Transport System

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This pre-study aimed to find out those research topics that present the highest interest for SHC’s industrial partners in order to set up a proposal for the main project of Electrical machines and drives’ thematic researcher. The main delivery was a full project description for the main project, which is planned to span over 20 months after the conclusion of the pre-study.

The direction of the pre-study is towards charging solutions and main related issues for different types of vehicles, different forms of charging, for safety and automation, in a societal perspective, also including the electric utility grid impact.

An all-Electric land transport system solution requires the following four fundamental systems:

1. A cost- and space-effective Electric Traction System in the vehicle.
2. An on board Electric Energy Storage providing a certain range, typical: 50...500 km.
3. An Opportunity Charging System, allowing an extension of the range within a reasonably short charging time, typical: << 1 hour.
4. A Continuous Charging System (SlideIn/Dynamic Charging/Electric Road System), without which a full electrification of e.g. Long Haul/Coach Bus/BRT will not be feasible and a full electrification of cars would require 5…10 times more batteries and a vast number of opportunity charging systems than would be the case if a Continuous Charging System for cars was available.

The first two of these systems have currently reached an industrial maturity level allowing a wide industrial introduction of hybrid, plug in hybrid and full electric vehicles in some niches, in particular cars and city buses, but not in heavy or light goods transport, not in coach bus applications and not in BRT applications.

The reason for this is to be found in the last two systems. Heavy goods transport, Coach Bus applications and BRT need a continuous charging solution. Light goods transport needs a low cost opportunity charging system. Light goods transport is particularly sensitive to opportunity charging, without which the battery weight for a full day operation would otherwise compete too much with payload capacity.

Neither a continuous charging solution, nor a low cost automatic opportunity charging solution is commercially available today, but a strong development is ongoing, in particular of continuous charging solutions, and to a lower extent on low cost, high power, automatic opportunity charging solutions.

This is a new territory for knowledge building on future electric land transport solutions. There are several issues to address, e.g.:

1. The most promising continuous charging solutions do NOT provide an electric ground connection for chassis potential limitation, which is most of a challenge at low speed in e.g. city operation. There are solutions underway, not building on a PEN (Protective Earth Neutral) but on a PEM (Protective Earth Minus) connection.
2. The need for on board galvanic isolation of the on board systems at high powers for continuous charging cannot, due to cost and size, be made with an isolated DC/DC converter, but requires “smarter” solutions.

3. A low cost opportunity charging solution for e.g. distribution trucks can probably not be made with a DC supply, also due to cost.

4. The grid impact of a vehicle charging and even more so – of many vehicles charging simultaneously. In particular, charging at high power levels brings about a stability problem on the electric utility grid. Today, opportunity charging of buses faces the problem of high local grid load that sometimes needs some kind of reinforcement of the electric utility grid. Whilst at present this problem is limited to these cases, it will grow fast with a growing full electric land transport.

5. The effect of a game-changing technological or societal breakthrough in the aforementioned topics. Examples of this may be the irruption of graphene batteries in the market with 4 times the energy density of current LiIon batteries or the generalization of autonomous driving vehicles allowing for faster / higher power driving.

The research field depicted above is to a large extent left untouched up to now, since most of the focus has been on driving the vehicles rather than charging them. It is not so that none of the above issues are unaddressed. Research is ongoing and it is clear that the solutions in many cases involve the re-design of the electric traction system on board as a part of the energy transfer from the grid to the energy storage and eventually the wheels. It is equally clear that detailed knowledge on electric safety, chassis potential limitation and electric grid impact in the grid connected vehicle is of fundamental importance to a successful all electric land transport system.

It is thus the intention that the SHC Thematic Area 2 researcher shall take a lead in the direction of charging solutions, including the design of the traction drive and other related on board systems, vehicle safety and grid impact – with a large scale introduction of full electric vehicles in the land transport system as the expected vision.

The intention is to, together with all industrial and academic partners of SHC, in a pre-study develop a detailed project description in this field.

This project is a pre-study aimed to deliver a full project plan within the specified research area. The main activities carried out during the pre-study are:

- Selection of reference group members from each industrial partner.
- Initial meetings with each partner separately to understand the technical challenges they are facing within the proposed research area.
- Identify the primary focus items for the full project among the commonalities found between the partners.
- Meeting with each industrial partner to define their in-kind contribution to the full project.
- Writing of the full project proposal based on the information collected from the previous meetings in coordination/collaboration with the partners.
- Final meeting with the partners to present and agree on the final full project proposal and pre-study report.
- Initial meetings with International research partners for planning of joint research efforts and identification of potential funding sources. A full detailed plan with related funding applications is not within the scope of this pre-study, but it will be a part of the full project.
The main result for this pre-study is a full project proposal for the full project for the Thematic Researcher in Electrical Machines and Drives. The project results were presented to all involved SHC partners in a draft version in the middle of August. The final project report resulting from this pre-study was presented to the SHC Advisory Board for approval in September.

During the pre-study two collaborations were established within the main project frame:

• A collaboration with the Energy and Power Group in the University of Oxford, UK
• A collaboration with Vattenfall

In both cases, the collaboration aims to increase the competence level in the project regarding power grid modelling, in order to evaluate the potential grid impact of high power highly dynamic electric loads, such as those originated when fast charging EVs.

Thermo-mechanical fatigue of electric machine windings

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FINANCING
Cash financing: 300,000 SEK. Funding organization: SHC

DURATION
2016-2017

Due to the intermittent operation of electric machinery used in electric and hybrid-electric vehicles, thermo-mechanical fatigue is an important concern. The goal of this project is to determine whether thermo-mechanical wear is an important aging factor and to set up models for how this aging can be modelled.

NB: The planned activities during 2016 have, due to time constraints, been delayed and the project is planned to be executed during 2017.

Traction System parameter identification and condition monitoring via modulation spectra response

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FINANCING
Cash financing: 300,000 SEK. Funding organization: SHC
PWM modulated electrical drives are designed and used at fundamental frequency to transfer and convert energy. High efficiency is expected from the intended energy conversion process. The remaining and undesired high frequency energy is considered as losses and are unwanted and even disregarded.

With modern control hard- and software it is possible to retrieve significant information from the previously unwanted harmonic spectra. This information in turn, has a potential to be used for parameter estimation and condition monitoring of connected machines and transmissions, as well as sources like batteries and DC network. Such information may prove valuable to optimize control in real time and to provide preventive maintenance and avoid malfunction.

Therefore the goal for this pre-study is exploring and unifying the expertise and experience of high frequency effects on components and electric drive system as a whole. Consequently the outcomes from this work become the base for establishing and formulating upcoming projects.

The starting point of this pre-study is the works done on parameter identification, lifetime estimation and condition monitoring of electrical machine windings in ongoing projects like Dymedec and EMcost. This accumulated knowledge on high frequency effects is extended towards the other components in the electric drive system with the ambition on improved knowledge on the drive system architecture, component design and maintaining diagnostics.

The primary interest of this pre-study is the preparation work needed for the potential upcoming projects on the field of electrical engineering but also networking between different research groups, institutions and universities.

Electrical drive systems transfer and convert energy, they take advantage of controlled switched electric power and their components are designed according to criteria for energy efficiency and competitive cost. Basically, the prime design focus is rather on concept selection and specification, which is formulated in design for manufacturability, than design for foreseeable functionality and state of health. Traditionally, design has been connected to construction and manufacturing while diagnostics is more related to maintenance. The purpose of connecting design and diagnostics is to identify and specify these explicit details of the drive system components that are crucial for foreseeable functionality and state of health estimation. Even if this expression, design for diagnostics, might sound unusual or even novel, there is nothing new, there are decades of experience, in which some is written into books and some published in scientific literature. Therefore, the main purpose of this pre-study project is basically to increase the competence on various aspects related to design for diagnostic of drive train component, primarily electrical machines. An electrical traction machine for vehicular application and its high frequency characteristics are the initial points of the study. The investigation is based on literature review and existing experience on high frequency and transient effects on 1) electrical machines in 2) drive systems and the outcome of this literature research organized into four categories:

1. High frequency characterization of electrical machines – models vs measurement methods,
2. Energy propagation and load distribution in the machine windings – E-field distribution,
3. AC losses in windings and stresses in the insulation systems, and
4. Reliability analysis based on failure mechanism and detection method.

The project report focuses on literature review on aforementioned four categories and applies this competence to design of electrical machines. Three recent permanent magnet excited synchronous machines for traction application are selected for investigation. This list of three non-standard PM machines is extended with a standard induction machine so that different windings as well as machine types are presented. A geometric model, which is used for machine design in finite element analysis, is extended for HF analysis of the electrical machine. The advantage of detailed knowledge on geometry, materials, etc, is used to focus on different modelling aspects on the four categories: 1) models vs measurements with focus on high frequency and transient insulation currents, 2) transient nonlinear voltage distribution in the machine winding (Electric Stress), 3) AC loss characterisation (Thermal stress), and 4) machine design aspects towards fault tolerant design / diagnostic monitorability of insulation system.

Mikael Askerdal represents theme System studies and methods in the reference group. The purpose of involving this thematic area is to prepare for possible future cooperation in subsequent project proposals. The study on component level in this short time project is not developed to a level that the system studies could take advantage of it. It is expected in continuation that the combined expertise on various aspects of component design and topological arrangement gives an opportunity for contributing to system architecture initialization, development and finalization steps.

The gained competence from this short term pre-study project (IV/2016), which primarily focuses on machine construction and high frequency effects in pulsed power system, is used to contribute to the other on going projects and PhD studies. More specifically the outcomes from this project is used for 1) power losses and inefficiency analysis in a traction machine for Hybrid Drives for Heavy Vehicles / FFI-ExSAM, 2) FEM aided parameter identification for FFI-Dymedec, and 3) machine design development and evaluation aspects in FFI-EMcost. The industrial collaboration takes place via aforementioned projects. This project establishes also useful modelling experience for ongoing project on induction traction machines (based on Teslas E-motor).

Goal oriented academic work and increased scientific knowhow in behalf of industrial needs and competence via ongoing dissertations is the mutual benefit of this project. The next step is to continue working on design for diagnostic with specialisation on these aforementioned categories, which is the groundwork for a number of new projects.

Publications and conferences 2016

Ultra Compact Cost Effective Fast Charger Stations

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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/Litre 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.

The first prototype for the dc/dc part is now constructed and under test. The next step involves the construction of the whole setup.

A collaboration is established between the project and Chalmers Innovation office, and also with a team of researcher from Sharif University of Technology. A PhD student will stay at Chalmers for 6 months to work with some part of the project.

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

**Publications and conferences 2016**


Saeid Haghbin, and Torbjörn Thiringer, “A Reliability Analysis and Enhancement of the AC/DC Stage of a 3.3 kW Onboard Vehicle Battery,” in Eleventh International
In this project, the design and performance of an asynchronous propulsion machine are examined through student projects at Chalmers, KTH and Lund University.

The vast majority of electric vehicle manufacturers have chosen permanent magnet machines for vehicle propulsion and on board generation of electricity for propulsion. An interesting alternative is the use of an asynchronous machine. An asynchronous machine is in general slightly larger than a permanent magnet machine of equal performance.

Thus a research gap opens: To investigate the performance of an asynchronous machine in comparison to a permanent magnet machine of the same volume.

The project will be carried out as a student project at Chalmers, KTH and Lund University. Modelling and calculation of performance will be implemented through student projects at the three schools. The goal is to increase the interest in electric machine design among students, and thus enhance the competence base of students who may be employed in the automotive industry.

The goal includes:

1. Traction induction machine modelling conducted in student projects

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FINANCING
Cash financing: 300,000 SEK. Funding organization: SHC

DURATION
2016-217


• Presenting geometry data for a hypothetical vehicle asynchronous machine
• Presenting performance calculation of an asynchronous traction machine. The calculations are made as thermal and magnetic FEM analysis of the machine, assuming the magnetic material grades and cooling circuit parameters.
• Disseminating the results further in the industrial group and in the SHC network is another important purpose.

So far, there are no performance calculations of vehicle asynchronous machines comparable to permanent magnet traction machines. The uniqueness of the project lies partly in the cooperation between the three schools, and partly in the results in form of a quantification of what can be achieved with a vehicle asynchronous machine instead of a permanent magnet machine.

Variable flux machine for electric vehicles

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FINANCING
Cash financing: 4,250,000 SEK. Funding organization: Energimyndigheten/Energieffektiva vägfordon

DURATION
2016-2019

The electric machine is one of the key components in electric and hybrid vehicles. The knowledge on alternative solutions than PM machines is required by Swedish automobile industry. This project aims to develop a more sustainable motor solution for future large-scale electrification of vehicles. The solution is to vary the magnetic flux with the help of the rotor winding and brushless transformer to achieve the desired torque. The advantage is that the motor does not need expensive rare-earth permanent magnets that are environmentally destructive at extraction and difficult to be recycled. The solution has not only high performance in terms of energy efficiency, maximum torque, and safety, but also potential for low cost and good recyclability for mass production.

The project aims to develop a more sustainable motor solution for future large-scale electrification of vehicles. The solution is to vary the magnetic flux with the help of the rotor winding and brushless transformer to achieve the desired torque. The advantage is that the motor does not need expensive rare-earth permanent magnets that are environmentally destructive at extraction and difficult to be recycled. The solution has
not only high performance in terms of energy efficiency, maximum torque, and safety, but also potential for low cost and good recyclability for mass production.

The target specifications of the new motor include:
1. peak torque 350% (PM motors: 200-250%);
2. speed range 1:4 (PM motors: 1:2 - 3);
3. efficiency > 95% for 80% operating points (PM motors: 95% for 40%);
4. clutch-free axial coupling (PM motors: clutch for high-speed disconnection).

Our earlier pre-study disclosed the superior performance of a new motor concept, which is especially suitable for electric vehicle applications. The concept is based on the principle of the synchronous machine with variable rotor flux. The rotor is equipped with copper windings and therefore does not need the expensive rare earth permanent magnets (NdFeB) that are used in the most electric/hybrid vehicles. The controllable flux in the machine makes it possible to boost the peak torque at low speed and achieve high efficiency over a very wide operating area. This project is targeting to verification of the superior performance of the variable flux concept by in-depth study including design optimization, prototyping, and measurements on a test bench. Uniqueness and newsworthiness in the project compared with the state of art include 1) dual-current control method for peak torque boosting and optimal thermal management; 2) new rotor design for wide speed range up to 1:4; 3) high efficiency rotating transformer for brushless rotor flux creation; 4) unity power factor control (UPFC) to achieve high drive-cycle efficiency.

Results so far:
- The new motor concept has been developed and simulated toward both high efficiency applications and high power density application. Different control strategies are studied.
- The prototype machine is designed according to the specifications from Volvo Cars. The machine is under manufacturing and expected to be ready for test in February 2017.
- The conceptual design of the electronic converters for both stator and rotor are completed. The detailed designs for 48V converters are ongoing.

In the first part of 2017, we will concentrate on the testing and control of the prototyped machine (20 kW/48V). We will build the 48V converter to drive this motor. In the second part of 2017, we will make the second-round of the prototyping of the 48V motor, which can be tested together with the integrated converter (developed in a sister project: Integrated drives for electrified vehicles). The combined motor/converter unit is expected to be tested together with the combustion engine if possible at the industrial partner facilities. The bigger motor design with high efficiency for pure-electric vehicles will be developed during 2017.

The project collaborates with the SHC Project “48V mild hybrid electrically-excited synchronous machine”. Our publication and presentation at an international conference (ICEM2016) drew a lot of attention from both academic and industrial participants.

The knowledge from this project is shared with Volvo Cars. We got help from reference group in:
- Introduction about applications (48V mild hybrid drive and heavy duty vehicles)
• Specifications and requirements (48V mild hybrid)
• Feedback on design (48V mild hybrid)
• (Volvo Cars) Discussions about associated converter design. The discussions are very helpful to form a new research project (Integrated drives for electrified vehicles). This is a good example for collaboration of academia and industry toward research with both highly industrial relevance and academic novelty.

Publications and conferences 2016


Efficient and Safe Battery Operation – Aspects of Expansion and Utilization

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FINANCING
Cash financing: 1,520,000 SEK. Funding organization: SHC.

DURATION
2016-2017

Efficient yet safe operation of Li-ion batteries is a main consideration for their application in electric and hybrid electric vehicles. Observations of swelling of commercial cells during cycling pose a serious safety concern and motivate the study of expansion and pressure effects on cell performance and on local conditions and dynamics within cells. The use of mixed active material electrodes in commercial (e.g. LiNi_{x}Mn_{y}Co_{z}O_{2} / LiMn_{2}O_{4}) and near commercial Li-ion cells (Si/graphite), some of which suffer from large volume expansion, further encourages this direction of research and also motivates investigation of material utilization. The mixing of different active materials is motivated by their complementary properties regarding for example capacity, power, safety, or stability. Their competing kinetics within one electrode can be expected to have effect on material utilization and local conditions within the cell during complex cycling, such as hybrid vehicle cycling. Using electrochemical models, the interior of batteries can be probed, with information of local conditions in relation to cell performance. The development of physics-based models in close communication with experimental observations serves to create diagnostic tools to increasing our understanding of Li-ion batteries and their continuous development for vehicle applications.

This proposed project spans from June 1 2016 – December 31 2017 and entails electrochemical modeling studies and experimental characterizations of different battery/electrode chemistries where the interplay of pressure/expansion and electrode dynamics is of interest. A focus is kept on commercial cells and cell conditions relevant to usage in electrified vehicles. KTH Royal Institute of Technology is the main applicant, and the projects is performed within Swedish Electric and Hybrid Vehicle Centre, with collaboration from industrial partners Scania, AB Volvo and Volvo Cars Corporation, and academia with Uppsala University. The budget for the project is 1 520 kSEK and it is part of SHC Energy Storage thematic area.
The overall objective of the project is two-fold: to improve our understanding of, and investigate causes for, cell swelling; and to study the effect of swelling, mixed electrodes, and pressure on electrochemical characteristics, material utilization, and dynamic behaviour and their incorporation in electrochemical models. In the longer perspective, this will help develop strategic consideration in how to safely and efficiently operate different Li-ion batteries in vehicles.

The interest and market for e-mobility is expanding from pure hybrid electric vehicles to include plug-in hybrid electric and pure electric vehicles. To accommodate for this trend battery manufacturers are shifting focus to energy-optimized cells and there is a push towards high-energy density electrochemical couples. For this reason, materials and systems that can provide higher voltages are being used and tested for vehicles. Layered oxides (LiNixCoxMnxO2) chemistries, especially with higher Ni-content, are contestants for increasing potential and specific capacity. However, with high potential follow challenges of stability, cell swelling, and gas evolution. Cell swelling is an aging phenomenon that can create safety challenges as it can affect the mechanical integrity of cells. The coupling between electrochemical and mechanical properties in battery aging hence become important. In the push toward higher energy densities, the mixing of several active materials within one electrode is often found in commercial (and near-commercial) cells used for vehicles. The motivation for blending several materials is to improve cell performance using materials with complementary properties. Here, a better understanding is needed of how these different materials interplay in dynamic situations (e.g. vehicle utilization), and how local conditions can be affected. Local conditions, in terms of potential, SOC, etc., can have impact on aging processes, such as gas evolution. Variation in local conditions can also influence the efficiency of material utilization in the cell and will depend on the drive cycle and load. Here, improved battery usage strategies can be developed based on this efficiency and impact on degradation. For the near-commercial case, the introduction of silicon to the graphite negative electrode will also have strong mechanical aspects, as volume expansion is an intrinsic property of this material and connected to kinetics, degradation, and aging.

The project is divided in work packages (WP1-4) that concerns WP1) mechanisms causing cell swelling; WP2) electrochemical characterization of harvested NMC-LMO electrodes; WP3) theoretical studies on i) utilization of mixed electrode during dynamic cycling and ii) interior cell dynamics and swelling; WP4) comparison of Si and graphite kinetics in a blended Si-graphite electrode.

It is clear that for the chemistries that are under investigation on the commercial side (NMC, NMC-LMO vs graphite), gas evolution is the main culprit to the massive cell swelling (and sudden death) that has been observed in some harsh conditions of fast-charging that has been investigated in the related project of “Fast charging of large energy-optimized Li-ion cells for electrified drivetrains”. The complementary on-line pressure measurements planned in WP1 have not yet started, but will be an essential part to better study conditions during the cycling under which gas is produced. With these pressure measurements over different SOC, other changes in cell dimension over time not relating to gas evolution can be probed. For model building, it is also important to characterize the electrode materials. Experimental information about the electrodes has been collected in terms of impedance, capacity, and thermodynamic data. Additionally, the detailed morphology of the electrodes (porosity, tortuosity, surface area) have been collected by CT-tomography using FIB/SEM on the non-aged NMC-material to provide a base case framework on which to build a model. This was done in collaboration with Denmark Technical University. In addition to that, experimental data of NMC kinetics at
different temperatures have been collected (10, 25, 40 °C), which also is important for model building. Currently, this information is in the process of being synthesized to a performance model (data-validated) on which to add the specifics of swelling and degradation dynamics, as more of that information becomes available in the progress of the project.

For the mixed positive electrodes (WP2-3) initial electrochemical data has been collected. However, certain experimental variation has been seen, and a suspicion that the battery material obtained from the industry partner had been stored too long in disassembled state. This will have to be further looked into. On the modeling side, both AC and DC models have been made with multiple active materials, however, at this stage, the model parameters are taken from literature, and need to be fitted and validated to experiments, to further investigate model discrepancies, before investigating material utilization under different loads/drive conditions.

Mixture of Si and graphite in electrodes (WP4) and effect on cell performance is investigated. The large area of Si in the electrode, tend to make the experimental measurement less sensitive to variation in kinetic parameters, and discussions are ongoing with Argonne on any additional data that could be provided by them. In the work related to volume expansion in Si-graphite cells, performance and degradation in these systems have been evaluated in a continuation from previous work (2015), and resulted in a few publications and presentations. It is clear that already small fractions of silicon mixed into graphite (up to 15 %) have a very detrimental effect on cyclability and stability.

In the coming period of the project, there will be a push to start the on-line pressure measurements to follow cell swelling during use. This data is necessary for the project. A coming focus will also be on the model fitting to collected data, and to gather the somewhat scattered pieces of experimental information for the modelling effort.

Measurements on commercial cells need to be coupled to simpler systems, such as smaller lab-cells for model development. Collaborations therefore also expand to colleagues at the division of Applied Electrochemistry, KTH, for lab-scale test on pressure and degradation, and electrochemical measurements of half-cells and reference electrode set-ups.

The project interacts with the SHC ongoing projects “Fast charging of large energy-optimized Li-ion cells for electrified drivetrains”, and “Electrochemical studies of durability aspects in large vehicle batteries”. So far, all work related to silicon-containing electrodes and performance of Si- containing cells, have been in collaboration with Argonne National Laboratory, USA.

The project has benefited from the industry partners so far by their providing of materials from cycled commercial cells. In the coming stage of the project, the support from the industrial partners will expand: the set-up and testing of on-line pressure measurements, to be performed at Scania, have been in the planning but have not yet started, so this will be of importance in the coming stage of the project. Additionally, some other battery materials and input on drive cycles to test electrochemical models will be required.

**Publications and conferences 2016**

**Conference presentations (posters):**

“Performance Degradation Characteristics of Layered Oxide/Silicon-Graphite Full Cells” M. Klett, J. Gilbert, J. Baren, S. E. Trask, B. J. Polzin, A. N. Jansen, D. W. Dees, D. P. Abraham, 18th International Meeting on Li Batteries, June 2016, Chicago, USA
“Effect of Pressure on Li-Ion Battery Ageing”, A.S. Mussa, M. Klett, R. W. Lindström, G. Lindbergh, 18th International Meeting on Li Batteries, June 2016, Chicago, USA

“Performance Changes in NCM523//Graphite Cells Resulting from High-Voltage Cycling”, J. Gilbert, M. Klett, J. Barenco, D. Miller, V. A. Maroni, D. P. Abraham, 18th International Meeting on Li Batteries, June 2016, Chicago, USA

“Temperature Dependent Behavior of LiNi1/3Co1/3Mn1/3O2 in Li-Ion Batteries “ M. Varini, M. Klett, G. Lindbergh, 67th International Society of Electrochemistry Meeting, Aug 2016, The Hague, Netherlands


Peer-reviewed original research


M. Klett, J. A. Gilbert, S. E. Trask, B. J. Polzin, A. N. Jansen, D. W. Dees, D. P. Abraham, “Electrode Behavior RE-visited: Monitoring Potential Windows, Capacity Loss, and Impedance Changes in Li1.03(Ni0.5Co0.2Mn0.3 )0.97O2/Silicon-Graphite Full Cells”, J. Electrochem. Soc. 163 (2016) 6, p A875-A887


Electrochemical modelling for prediction of long-term battery power

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The battery management system (BMS) of an electrified vehicle contains model-based algorithms to estimate and predict battery status, such as state-of-charge (SOC) and available power. Since the on-board computing power is limited and the number of cells is large, it is common practice to use simplified equivalent circuit models to describe the current-voltage characteristics of the battery cells. These models have the advantage of being simple enough for on-board implementation, and the parameters are also observable from current and voltage measurements. This is important since it enables updating of the model to handle changed characteristics due to ageing or varying operating conditions.

A drawback of the equivalent circuit models is that they do not consider the underlying electrochemistry and transport phenomena in the cell, which means that there are behaviours which they cannot predict. One example is a voltage drop observed when discharging a cell with high power for a longer time. The voltage drop depends on both time-independent and time-dependent processes behind the transient behaviour of mass transport in both electrolyte and electrode active material. Capturing this behaviour is important for long-term (~30s) power prediction needed for safe and efficient operation of electrified vehicles.

The aim of the project is to solve the problem of long-term battery power prediction for use in the BMS, which is still an open-ended research question. Starting from physics-based electrochemical models and applying methods from Automatic Control, the goal is to find a simplified model suitable for on-board implementation where the age dependent parameters are observable from measurements available in the vehicle.

In a longer perspective, the goal is also to establish a collaboration between the cell level research performed at KTH and system level research performed at Chalmers and Volvo Cars.

The purpose of the project is to develop an improved battery model that can be used in the battery management system. The model will primarily be used to improve the accuracy of long-term power prediction (~30s prediction horizon).

For the safe and optimal battery usage, predicting the long-term available power is important. Today it is common practice to use equivalent circuit models in the battery management system to estimate for instance power. This works very well for short time horizons (~1-2s). For longer time horizons (~30s) the predictions are not accurate enough for the application, mainly due to poor performance of the models used.

Based on laboratory measurements from Volvo Cars, KTH have developed a first version of a first principles cell model programmed in Comsol. Volvo Cars and Chalmers will examine the model with the aim of building a simplified model that can be used in battery management applications.

The main collaboration from Chalmers and Volvo Cars side is with the research project “Effektivare batterianvändning i elfordon” financed by The Swedish Energy Agency. The plan is to initiate a collaboration with BEST at Penn State University during spring 2017.
Electrochemical study of durability aspects in large vehicle batteries

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PARTNERS
KTH

FINANCING
The total project budget is 2,311,000 SEK, financed by Energimyndigheten / Energieffektiva fordon

DURATION
2016-2017

The project concerns electrochemical studies of durability aspects in large vehicle batteries. Many issues arise as we scale up the in-house constructed laboratory scale batteries to large batteries intended for vehicle applications. Distribution of current, temperature and pressure arise both in a large single cell and cells connected in series or parallel. This project aims to examine how uneven pressure, temperature and power distribution affects the aging of the cell locally as a function of cycling rate and depth. Uneven distribution may accelerate ageing through weak points and further redistribution on the parameters may occur which creates additional ageing scenario. It is also possible that failure may occur at the weak points and may propagate throughout the system. In addition to ageing factors distribution due to size and cell construction issue, manufacturing non-uniformity in large number of cells connected together may exist and create similar durability issue. The goal is not only to observe the aging mechanisms but also to develop methodologies to be able to electrochemically quantify performance losses, using small cells at controlled operation conditions. The project is carried out by a graduate student within the program Energy efficient vehicles but collaborate also close to the SHC’s battery fond project Fast charging of large energy optimized Li-ion cells for electric powertrains. So far in the project, commercially available NMC/C and laboratory small cells have be studied and two publications are in preparation and another three are planned for next year.

The purpose is to study the effects of pressure and temperature combined with electrochemical measurements by investigating different cells with varying operating conditions should also be able to couple together to simulate a big cell or a cell module. Further the project aim to support the fast charging project with post-mortem analysis to relate aging effects of electrode materials in electrochemical data. For the study the experimental equipment as well as electrochemical methods are developed, especially electrochemical impedance spectroscopy and dV / dQ analysis for detailed studies of the performance and aging of lithium-ion batteries, and evaluate experimental data with mathematical models.

Most of studies in the current state of the art focus on durability issues, which occur in single cells considering ageing as a global phenomenon. But, as we use large vehicle batteries or cells connected series or parallel, distributions of current, temperature and pressure occur which affect battery durability in a way different from small-scale cells. This aspect of lithium-ion batteries ageing have not been studied much and this study will contribute to narrowing knowledge gap in this arena.
So far, two studies have been finished. Manuscripts are in progress and will be published in January 2017. The titles of manuscripts are:

- **Fast charging to a partial state of charge- A comparative ageing study**
  This study has compared three different charging strategies on NMC/C 18650 cells; (i) 1.5C CC charging to 4.2 V (80% SOC), (ii) 0.5 C CC to 4.2 V (90% SOC); (iii) 0.5 C CCCV to 4.2 V (100% SOC) and found that the fast-charging (i) had lowest aging rate followed by the CC (ii) and CCCV (iii) showed the fastest capacity loss rate. This is due to the larger effect of SOC range than the current level. The same ageing mechanisms were observed in all three cases, namely cyclable lithium loss and NMC active mass loss. The impedance rise was mainly observed on NMC electrode due to charge transfer resistance increase. This results will be presented at ISE Topical conference Boenes Aires spring 2017 and International symposium on Advanced Battery Power, Aachen spring 2017.

- **Effect of stack pressure and pressure distribution on li-ion battery ageing.**
  Small laboratory NMC/C cells subjected to different levels of pressure 0.66 -1.98 MPa has been compared. The results show that there is an optimal pressure around 1.3 MPa in which the cells age less. This is related to less cyclable Li loss. Evaluation the influence of inhomogeneous pressure distribution by coupling the cells with different pressure in parallel show that there is a current distribution, however, not significant enough to cause ageing distribution. This results have been presented in a Poster at International Meeting Lithium Batteries, June 2016, Chicago.

  Evaluation of electrodes from the fast charging project has started.
  The next step is to finalize and publish the results from the above-described studies. During the spring new studies on the effect of temperature distribution on ageing behaviour of large vehicle batteries and the effect of impedance and current distribution on series and parallel-connected li-ion cells will be started. In addition post mortem evaluation of electrodes from the fast charging project will be carried out.
  The knowledge has been shared through a presentation at SHC’s fast charging network meeting and through scientific publications and conferences.

*Publications and conferences 2016*

*Conferences:*
Uneven SEI Growth Across Depth in Aged Li-Ion Battery Graphite Electrodes
Matilda Klett†, Pontus Svens, Carl Tengstedt, Antoine Seyeux, Jolanta Światowska, Göran Lindbergh, Rakel Wreland Lindström, Poster at 67th Annual meeting of the International Society of Electrochemistry, 22-26 August, 2016 Hague, The Netherlands

Effect of Pressure on Lithium-ion Battery Ageing, Abdilbari Shifa Mussa, Matilda Klett, Göran Lindbergh, Rakel Wreland Lindström, Poster at IMLB 2016 - 18th International Meeting on Lithium Batteries, 19-24 June 2016, Chicago, USA.

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Fast charging of large energy-optimized Li-ion cells for electric powertrains

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Jens Groot, Volvo GTT, Project manager
Johan Scheers, Volvo Cars
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.

The project is a formed by a broad cooperation between all parties within the Swedish Electric & Hybrid Vehicle Centre (SHC) Theme 3 to ensure high technical and scientific level. Three post-doc’s and research efforts by senior researchers from industry is included as well as cycle life testing and cooperation with other national R&D projects.

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.

Fast-charging ability is a highly desired feature of both EVs and PHEVs. Despite a comparably rapid development, and existing charger solutions, fast-charging has been identified as a strong ageing factor. Earlier work has indicated that the ageing is severely non-uniform within battery cells, probably due to a distribution of temperature and current. This non-uniformity is likely to be even more severe in large-format energy-optimised cells.
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

Work package 1 & 2 – studies of electrode materials, electrolytes and interfaces
All performed tasks within this project can be seen as method development and/or initial tests for the more comprehensive analysis of cell material that is planned for 2017 and 2018 based on the cycled cells from work package (WP) 4. Preliminary measurements have been made on samples of electrolytes from calendar aged cells delivered by Scania. These measurements are included in the method development planned within this work package. Furthermore, a new test cell for measuring the temperature in operando has been designed and a new measurement set-up for electrolyte studies has been purchased. Post-mortem analysis has been performed on a total of 11 samples from cycled cells derived from WP4.

WP3 – Electrochemical modelling
A non-isothermal model in 3D has been made available, adapted for the prismatic NMC (Panasonic) cell that is one of the cells evaluated in this project. The activities are therefore now focused at adding ageing mechanisms in this model. This requires a separate characterisation of aged cell material to be made in order to quantify ageing and select the most important mechanisms for performance loss. Hence, this WP as expanded its activities to include an experimental part as a basis for modelling work.

So far, all modelling and characterisation work has been made for the same prismatic NMC cell cycled with 4C-rate charging, a test case that resulted in “sudden death”, in turn due to massive gassing according to the preliminary analysis made by Scania. The cells have since been opened jointly by the parties and a first round of post-mortem analysis has been bade on the harvested material. The result of this analysis has been used to set-up side reaction model with gas development. At present, the evaluation of the results to some extent arbitrary, where the kinetic parameters are missing and parts of the model relies on various literature values. Upcoming activities in finding ways for the validation of how gas development can be included in the model, along with continued electrochemical characterization of the possible inclusion of other ageing mechanisms.

Work package 4 – applied modelling and ageing
All vehicle manufacturers (Volvo Cars, Volvo AB and Scania CV AB) are participating in WP4 where the main deliverable is electrochemical and thermal battery models, including ageing, for large commercially available cells.

AB Volvo and Scania CV AB have mainly performed life cycle tests of two different cells, both representative of the type targeted by the project. Different charging currents and charging levels have been evaluated using a total of 22 lifetime test, with lifetimes ranging from a few days to more than 8 months. Some tests are on-going but are expected to be completed in January 2017. The cycled cells are an important delivery to all other WPs since the post-mortem analysis of the electrodes and electrolytes is the fundament for further modelling. Furthermore, the applied model development has begun by performing extensive parameterisation tests and by setting up models in COMSOL®, the modelling tool that all partners use the project to exchange models and results.

Volvo Cars has, as main activity during the period, prepared the experimental set-up for thermal modelling. Three different cell holders based on standard cell holder for cell cycling has been designed and equipped with both enhanced passive cooling via heat sinks as well as through active fan cooling. In addition to the standard current and voltage sensors, these cell holders have been equipped with 14 temperature sensors for the recording of temperatures in selected points. A cell holder with thermal isolation has also been constructed to obtain additional thermal properties for the thermal model design. Initial tests have been performed on a pouch cell, showing promising results, but also that the thermal leakage has to be reduced and that the effect of power cabling has to be minimised.

The next step includes:

- Firstly, cycled cells from WP4 will be opened and material (electrodes and electrolytes) will be distributed to the other WPs early in 2017. Special effort will be made to synchronise this activity with all partners to ensure that harvested cell material can be analysed as soon after cell disassembly as possible to reduce the risk for contamination and additional, unintentional degradation.

- Secondly, a new set of ageing tests will be performed by the industrial partners using at least two different cell types.

- Lastly, the modelling activities will be synchronised between the partners and expanded to include performance, thermal characteristics and ageing.

This 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 participation in EU-funded research we collaborate indirectly on an international level.

The three industrial partners are very active in this project as they perform all ageing tests and participate in the modelling activities. This is also reflected in the budget where each industrial partner has allocated 2-4 man-months per year to this project. The knowledge has been shared internally through several project meetings, within SHC through Energy storage meetings, and externally through presentations at open seminars / workshops. A conference presentation is planned for January 2017 (AABC Mainz).
Pre study High energy density battery materials – understanding their endurance with the help of modelling (pre-study)

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FINANCING
Cash budget: 200,000 SEK. Funding organization: SHC

DURATION
2016

High volumetric energy density rechargeable batteries are currently the most attractive for fast route both to full electrification of smaller vehicles or hybrid systems in general. This project contributes by combining atomistic modelling techniques with experimental work to understand and mitigate the chemical processes leading to the poor endurance and safety compromise in the state of the art battery materials such as Li-rich layered transition metal oxides.

In this pre-study until the end of September 2016, the collaboration with the partners within SHC interested in this study will be established and work contributions planned. Secondly, the usefulness of atomistic modelling techniques in understanding the aging of lithium batteries is evaluated for whether it can be used to calculate the most relevant properties of an artificial protection film (such as Al2O3) at the electrode-electrolyte interface – the SEI layer. The reaction conditions are related to that measured in the real, but unprotected cells.

The pre-study focuses on the alumina (Al2O3) coating which serves as a benchmark for any artificial or natural passivation film in Li ion battery. NMC electrodes protected by ~1nm thick Al2O3 coating showed increased lifetime when compared to the non-protected ones but degraded over longer time. Little is known on the endurance of such protective films in the battery environment. Therefore, here the focus is on in-depth understanding of the performance of such protective films.

The atomistic models give new mechanistic insights into the limits of the use of high-voltage electrode materials in terms of degradation and aging. This would guide making better protective films, either by direct deposition or, by the choice of specific electrolyte additives. From the battery integrator’s perspective, better understanding of the battery health at high State of Charge (SOC) allows developing more efficient battery management routines.

So far, literature has been evaluated for the existing models and experimental data for the protective films. The promising modelling approaches identified are: i) calculating the electron tunnelling rate (~electrolyte degradation rate) through different films; ii) film resistance to Li-ion current and iii) film dissolution at high potential.

Surface selectivity on the electrolyte reactivity is demonstrated in DFT calculation (LiS4 on TiO2: 1eV stronger binding energy on 001 surface than on 101 surface).
Al-ions identified in G-electrodes from dismantled cells (in collaboration within “Fast-charging project” with F. Lodi Marzano, UU).

Collaboration is planned with the ALD-group at UU (M. Boman) for an experimental study with such protective films if external fundings granted – to be proposed as an SHC associated project.

The next step includes planning for a Theme III workshop on the high-voltage electrode materials in Q1-Q2 2017. A follow up by research project is planned after the pre-study for more in-depth studies based on the prioritized cases after the completion of the pre-study. The results will published in international peer-reviewed journals and presented at the conferences.

Matilda Klett (KTH) is consulted on merging with the physical models developed in KTH; the parameters needed in the physical models that could be obtained from the atomistic modelling are identified. (SHC Theme III meetings). Jens Groot (AB Volvo) and Pontus Svens (Scania) are consulted on the aging phenomena in the commercial cells within another SHC project (“Snabbladdningsprojekt”); the important mechanistic factors that need the atomistic modelling approach are identified. (SHC Theme III meetings).

Pre-study results have been presented at the theme meetings (9 Sept. 2016): Industrial partners gain new insights into the electrode protection mechanisms and prospects to increase the capacity utilisation.
Vehicle analysis

Decision support for implementing electric buses in public transport

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FINANCING
Cash financing: 5,000,000 SEK. Funding organization: Demoprogrammet för elfordon/Energimyndigheten

DURATION
2016-2017

This project aims to develop and test a new sustainability-oriented decision support for procurement of public transport with electric buses. Business models and electric bus system selection method are two of the main issues to be studied. Previous studies have shown the need for a procurement of electric buses that is adapted to include new technologies such as charging infrastructure and minimizes the risks for the parties involved.

Previous studies and investigations in the bus industry have shown a need for customized procurement of electric buses that include charging infrastructure, minimize risk for the parties involved, and lead to a sustainable future. The project therefore wants to develop and test new sustainability-oriented decision support for procurement of public transport with electric buses. This is achieved by

1. Based on existing projects with electric buses identifying real yearly averages of costs, energy use and availability.
2. Measuring noise (incl. from acceleration) from several electric buses and based on the results propose a new EU noise measurement standard for buses that includes acceleration.
3. Integrating from 1 and 2 in a process and business model for procurement.
4. Testing and further developing an electric bus system selection method for procurement feasibility studies. This should enable a sustainability-oriented selection of battery sizes and charging infrastructure per line.

The project meets a previously identified need of bus operators, transport companies, public authorities and other stakeholders. In order to be able to take the plunge and introduce electric buses, a new business model on the procurement procedure of public transport is needed that sees to the procurement of charging infrastructure, the costs of new technologies, training of staff, energy use and other related costs. The stakeholders also need a common methodology to choose battery size and charging infrastructure for each bus route. This system will be dimensioned according to criteria such as energy efficiency, the lowest total cost of ownership and strategic sustainability.

So far, an analysis of business models has been performed, to see how the partners collaborate in building an electric bus system. The next step is to analyse a number of bus
routes in selected Swedish cities, considering how the systems can be built, cost and sustainability aspects.

The results have been shared in presentations for Västra Götalandsregionen, Västtrafik, Svensk Kollektivtrafik, Skånetrafiken, Hallandstrafiken, Scania and AB Volvo. Collaboration with different organisations, such as public transport authorities, is vital for the project.

Driveline configurations for fuel cells

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FINANCING
Cash financing: 300,000 SEK. Funding organization: SHC

DURATION
2015-2016

This project is a study of different road vehicle driveline configuration with Fuel cells to find which type of fuel cell drive lines seems most promising for road vehicles, mainly regarding total cost of ownership. The results show that Fuel cell drive lines have a very different cost structure than battery electric drive lines, which makes both of them cost effective but in very different market segments. Both fuel cells and battery electric drive lines requires long total driving distance during the vehicle life to become cost effective. Battery electric drive lines are the ones which has the potential for really low operating cost, but only a few special type of vehicles can fully exploit this since a low cost for the battery is only possible if the battery is charged many times per day. Fuel cells, on the other hand, have their strength typically when it is not possible to charge often and therefore the vehicle is required to store a lot of energy on board.

The project has the purpose to analyse the potential for fuel cells for road vehicles. An important extension compared to many existing comparisons, is that the analysis will be made for different vehicle segments to better understand the strengths and weaknesses of fuel cells and thereby better understand which niches are likely to be introduced.

As battery electric vehicles have been the main focus of many vehicle OEMs the battery electric drive lines have developed very much and are today becoming a standard product on the market, however yet with a very small fraction of the sales. Despite the successful development of battery electric vehicles there are several types of vehicles for which they have significant drawbacks, and the cost of the battery drive line is still very high. The fuel cell drive lines have some distinct advantages over battery electric drive lines and therefore it is important to better understand in which type of vehicles the different drive line technologies are competitive.
The project has made a survey of existing fuel cell vehicles, both prototype vehicles and commercial vehicles. Data of the 109 vehicles found are collected in a database to show what type of vehicles have been developed and what specifications they have. This database is complemented with an analysis of differences in total cost of ownership, which identifies that the total cost of ownership is so radically different between fuel cell drive lines and battery electric drive lines that it is unlikely that any of the two driveline types can meet the needs for all segments on the market. The fuel cell drive lines seems most competitive for vehicles with a long range and a rather long total driving range during the vehicle life length. It is also found that the battery utilization factor, i.e. how much energy the battery has delivered over its life divided by the battery capacity, is a very good parameter to analyse in order to understand when battery electric vehicles are most cost effective. It is found that it is very difficult to get low TCO for a battery electric vehicle unless the battery is charged more than once per day. I.e. typical private cars are not the best segment for battery electric vehicles, but one should instead look at some types of commercial vehicles and city busses to find the best niches for battery electric vehicles.

This project is finalized, but there is a follow-up project planned for 2017, which will focus on analysing fuel cell drivelines for heavy trucks in more detail. Heavy trucks is a segment for which battery drive lines does not seem to meet the requirements, and therefore the fuel cell drive lines will be analysed in more detail to find how they compete with some alternative drive line technologies.

The project is led by Viktoria Swedish ICT and is a cooperation between their electromobility group, Vätgas Sverige and SHC’s Vehicle analysis theme. The steering group helped focus the project in the start-up phase, and the dialogue with Volvo cars and Scania both helped interpreting what the results may mean for the future implementation of fuel cell vehicles. They also made it clear that the results where interesting and gave ideas for how they can be made more detailed in the following project.

The results have been presented at a Swedish fuel cell conference 2016-11-29, and have also been presented and discussed with Volvo Cars and Scania.

Effects of the automated transport system – SEVS for AD

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FINANCING
Cash budget: 1,976,350 SEK. Funding organizations: Drive Sweden/VINNOVA

DURATION
This pre-study has used a set of tools within the process The SEVS Way to identify potential effects from autonomous drive concepts in relation to the Swedish transport political goals. The SEVS Way, which is a workshop based process, has earlier shown to be a powerful tool for multi-disciplinary teams to work cross-boarders in a structural way, but also a powerful communication tool that facilitates the inclusion of new stakeholders along the journey.

The work within the pre-study has been performed through a number of work packages focusing on:

- A driving force model, which is a very useful tool to find the mechanisms and driving forces which determine how AD influences the society.
- A scenario methodology, with further developed scenarios that consider an AD environment.
- Use cases that describe the daily agendas and movements of actors and goods. The use cases should identify barriers and opportunities with autonomous vehicles (stage 4 and 5) in order for the actors to carry out the daily activities, and for the goods to be transported, delivered and picked up.
- Methods for measuring and estimating effects related to AD, and how such concepts contribute to the fulfillment of the Swedish transport political goals.

Results from the pre-study include:

- The driving force model used in the pre-study is a good candidate when analyzing effects of AD. The outcome is just preliminary results which can be used as starting point for other investigations, but should be used with care until they have been further verified.
  
  In addition, it is important that the driving force model is only one of the tools in the SEVS analysis of societal effects of autonomous drive. It can identify important driving forces, likely effects and explain why and when they are likely to happen. However, an analysis of how likely these changes are will always need to be based on deeper analysis of critical mechanisms. One example of that is the use cases and transport selection analysis which are necessary to analyze a very critical point in the driving force model, namely how the user needs, preferences and possibilities will influence what transport solution will actually be chosen.

- The use cases for goods movement have been prepared in broadly the same style and following a similar methodology to those prepared for personal mobility. This is to help in understanding the interaction between personal mobility and goods movement which is likely to be more significant as AD develops. In addition, it allows the two overlapping systems to be considered in a similar way which is helpful when trying to understand trade-offs and changes that arise from trip substitution (a personal mobility trip is replaced by a goods movement trip). The interaction between mobility and goods movement will be followed up in more depth in the SEVS 3 for AD ecommerce project that started in late December 2016.

- Existing work looking into potential effects of AD-concepts is dominated by studies focusing on user expectations and system simulation studies. This is natural since few (hardly any) autonomous vehicles are on the roads for users to test at the moment.

- Three main factors that impact the transport political goals for the use-cases in the prestudy, were identified:
Transport choice. I.e. does the AD-concept induce different choices regarding transport modes? E.g. a more comfortable car solution could increase car use.

- The amount of transport and impact on congestion.
- Vehicle functionality and operation. Vehicles can be tailored to fit certain needs better and operation can be optimized, e.g. regarding speed, or regarding usability for disabled drivers.

- Methods evaluating effects of AD-concepts need to be able to handle both technical aspects and performance of vehicles and systems, as well as behaviors and perceptions of users.
- By working according to The SEVS Way methodology the pre-study has followed a structured process and been able to handle the complexity both on a Macro system level as well as on a Micro level. The SEVS components created a model of different societies (scenarios), in which we let a specific actor interact with different mobility solutions in its context (use cases), and analyse in depth if the system solutions fulfil the functional and consideration requirements on a micro level (customer) as well on a macro level (The National Transportation goals).

The project is finished.

Energy transfer solutions for electrified bus systems (2015-2016)

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FINANCING
Cash budget: 3,068,000 SEK. Funding organizations: FFI /VINNOVA, Västra Götalandsregionen, AB Volvo, Göteborg Energi Nät AB

DURATION
2015-2016

All-electric bus systems are seen as an opportunity to reduce emissions, noise and dependence on fossil fuel. The bus systems can have different energy storage systems that can be supplied with energy in different ways, e.g. when stationary, during movement, battery replacement, etc. Various demonstration projects underway around the world test various techniques but a methodology to analyze these alternatives including from a total cost perspective is missing.

The main goal of the project is to research and further develop a methodology that is used for a robust and cost efficient design of energy supply systems for electrified bus traffic in a complex route network with variety of bus flows. The idea is that the developed methodology should be used for comparisons between different electrified vehicle systems in the planning of several interconnected lines or an entire network.

The project is finished. The final report is available here:
Energy transfer solutions for electrified bus systems (2016-2017)

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FINANCING
Cash financing: 5,218,000 SEK. Funding organization: Demoprogrammet för elfordons/Energimyndigheten.

DURATION
2016-2017

All-electric bus systems are seen as an opportunity to reduce emissions, noise and dependence on fossil fuel. The bus systems can have different energy storage systems that can be supplied with energy in different ways, e.g. when stationary, during movement, battery replacement, etc. Various demonstration projects underway around the world test various techniques but a methodology to analyze these alternatives including from a total cost perspective is missing.

The main goal of the project is research and further development of a methodology that is used for a robust and cost efficient design of energy supply systems for electrified bus traffic in a complex route network with variety of bus flows. The idea is that the developed methodology should be used for comparisons between different electrified vehicle systems in the planning of several interconnected lines or an entire network.

The project is a continuation of a previous project, “Energy transfer solutions for electrified bus systems/ Analys av elförsörjningsalternativ för elektrifierade bussystem (2015-2016)” that was carried out by the same partners and mainly financed by FFI/VINNOVA.

The purpose of this project is the further development and use of a method for analysis of technically, economically and operationally efficient charging systems for electric buses. The project aims to conduct research on methods for solving challenges identified within the project “Energy transfer solutions for electrified bus systems (2015-2016)” funded by Vinnova by Fifi and Västra Götalandsregionen, by developing a user-friendly tool for analysis, suitable to be used by non-experts.

Passenger transport by public transport has more than doubled since the 1950s. In the last decade, travel by public transport has increased in absolute terms but also increased marginally as a proportion of total travel. Public transport is an important means to achieve growth but also plays a very important role in making passenger traffic more sustainable.
Electric power has great potential for energy efficiency, reduced emissions and quieter traffic in public transport. Train and tram services are already electrified in Sweden. Several cities have the ambition to electrify bus services, that have great potential to e.g. reduce carbon emissions provided that renewables and/or nuclear power is utilized.

Electrified buses are often studied from a vehicle perspective, but there are few studies that highlight electrified bus infrastructure from a systems perspective and try to compare different concepts and solutions with each other. There is currently no methodology to estimate the total costs of entire bus systems related to the required performance. There is also a lack of strategies to methodically take into account the synergies with other types of charging infrastructure for other vehicles in a city. The requirements imposed on the transport capacity of the bus system, maximum stop time, bus stop dynamics, topography and weather conditions are important conditions for the choice of power supply solutions.

Since the finalization of the previous project, “Energy transfer solutions for electrified bus systems (2015-2016)” a growing interest from public transport authorities in planning for future electric bus routes has been noted.

So far, the first version of the user-friendly analysis tool has been developed. The next step will be to analyse the bus route network in Göteborg and investigate how a greater number of bus routes, 10-15 routes in west Göteborg, could be electrified. The results so far have been shared at a workshop for invited guests outside the project, e.g. bus operators.

The project is a collaboration between industry, public transportation authorities, academia and research institutes. The collaboration is essential for the project. The project has been given access to AB Volvo’s technology watch of electric buses.
Technology watch of fuel cells

Bränslecellsdrift av tunga truckar – Potential inom processindustrin

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FINANCING
Cash financing: 225,000 SEK. Funding organization: Energimyndigheten

DURATION
2016

The process industry has implemented several measures to reduce greenhouse gas emissions, but was nevertheless accounted for 25 % of the carbon dioxide emissions in Sweden in 2014. In order to reduce the carbon emissions further it require s new measures which also must be economical to maintain the competitiveness of Swedish process industry. The process industry are also generating residues and by-products from the production processes which consist of heat and steam as well as various gas fractions, including hydrogen. These by-products are currently not utilized to full extent.

The internal logistics operation in the process industry includes significant internal transport and handling operations that are energy intensive and costly. The heavy industrial trucks that are used in this activity have usually a combustion engine and consume a large amount of mainly fossil fuel (diesel). There are therefore of interest at several process industries to use hydrogen produced in the plants to power fuel cell industrial trucks and other vehicles.

This pre-study is organized and performed by TFK – TransportForsK with the support and active involvement of the stakeholders linked to the study and intends to achieve the following objectives:

- To identify and describe which trucks and vehicles that in the future may be powered by hydrogen in fuel cells and to describe how these trucks and vehicles should be adapted for this.
- To quantify the effects of a shift to fuel cell operation of these trucks and vehicles from an energy efficiency and environmental perspective.
- To compile a picture of, and quantify the excess production of hydrogen gas and energy at the process industries. This is to evaluate the process industry’s future potential to produce hydrogen gas for use in fuel cells in industrial trucks and vehicles.
The result shows that switching to hydrogen-powered trucks can reduce the energy consumption by 30% and reduce the carbon emissions by 80% compared to diesel operation. A truck with fuel cells also means lower energy and maintenance costs compared to an equivalent diesel-powered truck. The study shows that the process industries in Sweden have large amounts of excess energy and that parts of it can be used to produce electricity to produce hydrogen through electrolysis alternative purification of gases to pure hydrogen. The study shows that most of the industries have the potential to produce enough hydrogen to power all heavy trucks that used at the facility. However, it requires large investments to enable hydrogen production from the industries excess energy and residual gases.

One obstacle to the development and implementation of fuel cell drive systems for heavy trucks is that the majority of them today are diesel-powered. For the development of a hydrogen-powered truck, the development costs will increase due to the development cost for an electric drive system. A major obstacle is the high investment costs for vehicles, fuel cells and hydrogen infrastructure. There is also hard competition from battery electric trucks with lithium-ion batteries and a critical factor for the future of fuel cell operation is probably the price development of fuel cells and batteries.

The study is finished. Download the report here: [https://energiforskmedia.blob.core.windows.net/media/22055/branslecellsdrift-tunga-truckar-energiforskrapport-2016-335.pdf](https://energiforskmedia.blob.core.windows.net/media/22055/branslecellsdrift-tunga-truckar-energiforskrapport-2016-335.pdf)
battery technology of today provides sufficient range even for professional cargo bike users, but that fuel cells could be very attractive if there is a need for extra power, for example in refrigerated transport. The project has also generated a design suggestion for a 4-wheeler cargobike equipped with a 150 W fuel cell system. The design work has considered the safety standard ISO 23273 and safety at traffic collisions.

The study is finished. Download the report here [https://energiforskmedia.blob.core.windows.net/media/22440/branslecelvesdrivna-lastcyklar-energiforskrapport-2017-368.pdf](https://energiforskmedia.blob.core.windows.net/media/22440/branslecelvesdrivna-lastcyklar-energiforskrapport-2017-368.pdf)

När passar bränsleceller bäst? – en studie av elektrifierade drivlinor

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FINANCING
Cash financing: 300,000 SEK. Funding organization: Energimyndigheten

DURATION
2014-2016

One part of the project investigates which powertrain configurations involving fuel cells that have been and are on the agenda. It also studies how the configurations are used for different applications and market segments. All main types of road vehicles are covered involving tractionary fuel cells, e.g. passenger cars, buses and other heavy vehicles. This part is primarily based on an analysis of publicly available data.

Hybrid fuel cell powertrains dominate among cars and buses. Thereby we mean vehicles predominantly propelled by hydrogen fuel cells with a battery pack as a power buffer. Among the few vehicle types on the market, this is the only solution until presently.

Bus development follows two paths. One path uses fuel cells specifically designed for buses, typically from Ballard. The other path, which appears to become dominating, uses the same stacks as for passenger cars but control them in a different manner. Moreover, two stacks are normally used. There are only a few trucks in the data and it is thus difficult to comment the choice of technology at present.

In the second part of the project a methodology is developed to enable a systematic study of how different propulsion types match different applications. The main guiding parameter is the cost of use. Against some assumptions, the cost is compared for the investment and use of fuel cell vehicles, battery electric vehicles, internal combustion engine vehicles with biofuel, and two battery electric vehicles with range extenders, one with fuel cells and one with an internal combustion engine.
The analysis indicates fundamental differences in how the cost for fuel cell and battery electric vehicles changes in relation to the range requirements and the total distance driven during the vehicle’s lifetime. It is clear that battery propulsion is most attractive when the range requirements are moderate and the total driving distance is long.

A comparison of all alternatives indicates that internal combustion engine vehicles with biofuels are most attractive for applications with short and moderate total driving distance. For long driving distances and long range per tank (or recharge), battery electric vehicles with fuel cells as range extenders are the cheapest. This part of the market does not have many vehicles but the application area extends down to the large bulk of passenger cars today, e.g. vehicles with a life time distance of 200,000 km and a range of 500 km.

Comparing the two parts of the project some differences can be noted. One important difference is that fuels cells as range extenders exhibit better economy than the present dominating solution, hybrid fuel cell vehicles that cannot be recharged from an external power supply. Decisive for this conclusion is the assumption that such vehicles are to 67 percent electricity from the grid and 33 percent hydrogen. This might be difficult to achieve in practical use. Another difference is that battery propulsion often is positioned as suitable for small vehicles driving shorter distances whereas fuel cell vehicles are larger and used for longer distances. The cost analysis does not reflect size (and weight) but with respect to driving distances, battery electric vehicles must be used a lot to be competitive. This does not match the segment city car, apart from taxi use. Fuel cell vehicles are more correctly positioned in this regard.

The project is finished. Download the report here

Technology review – Solid Oxide Fuel Cell

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FINANCING
Cash financing: 220,000 SEK. Funding organization: Energimyndigheten

DURATION
2014-2016

The commercialization of SOFC systems starts with in specific niche markets, such as on-site power generation for data centers (mostly in USA), small/scale CHP for individual
households (mainly in Japan) and in military applications (for example in USA). The future potential is enormous in the just mentioned areas as well as for APU s (or in some cases also for propulsion) in trucks and other vehicles as well as for MW-scale distributed power generation (expected to start in Japan and in South Korea). The development in recent years includes electrolysis as well, i.e., reversed electrochemical reactions to produce hydrogen and/or methane.

Volvo participated in some previous EU-funded SOFC research projects (e.g. DESTA) and is currently involved in EU-funded PEFC projects. SOFC development for the vehicle industry is carried out by AVL, Ebersprächer and Elcogen in Europe, as well as Delphi, Protonex and Ultra Electronics USSI in North America. SOFC developments for military applications are carried out by Fuel Cell Energy and MSRI in North America and Catator in Europe.

An electrical efficiency of 60 % (LHV) for an SOFC system as small as 1.5 kW SOFCs (Solid Power) has been reached, compared to 72.5 % (LHV) for a 200 kW SOFC system under development by SOFCMAN in China. The number of partnership/joint ventures is steadily increasing, so for instance Panasonic is a partner with Viesmann, Toshiba with BDR Therma and Aisin with Bosch. Daimler and Ford are collaborating with their joint-venture AFCC -Auto. Honda and GM are jointly developing FCs. Honda is also collaborating with Ceres Power. VW is working together with Ballard.

The number of companies developing fuel cell systems based on multiple technologies is increasing. Also in public funded programs (e.g. Callux in Germany and the ENEFARM in Japan), multiple fuel cell technologies are being installed. The Japanese government is pushing the development to make the 2020 Tokyo Olympics a showpiece for its hydrogen and fuel cell strategy.

The project is finished. Download the report here
Publications and conference contributions

This list contains publications actually published in 2016. Publications lists for ongoing projects are given in the project reports on previous pages. Complete lists of publications for finished projects can be found in the reports on the website.

System studies and methodologies


Electrical machines and drives


Energy storage


“Electrode Behavior RE-visited: Monitoring Potential Windows, Capacity Loss, and Impedance Changes in Li1.03(Ni0.5Co0.2Mn0.3)0.97O2/Silicon-Graphite Full Cells”, M. Klett, J. A. Gilbert, S. E. Trask, B. J. Polzin, A. N. Jansen, D. W. Dees, D. P. Abraham, J. Electrochem. Soc. 163 (2016) 6, p A875-A887.


“Performance Degradation Characteristics of Layered Oxide//Silicon-Graphite Full Cells”, M. Klett, J. Gilbert, J. Bareno, S. E. Trask, B. J. Polzin, A. N. Jansen, D. W. Dees, D. P. Abraham, 18th International Meeting on Li Batteries,


Vehicle analysis


"SEVS for Autonomous Drive”, J. Berg, VTI; M. Borgqvist, SP; M Browne, GU; Anders Grauers, SHC; Else-Marie Malmek, Malmeken AB/SAFER; Spyros Ntemiris, Chalmers; Anders Trana, SP, Final report, 2016.

Technology watch of fuel cells

**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.