Roadmap – Intelligent vehicles and systems

The requirements on our vehicles are developing continuously, which leads to increased complexity in both the vehicle itself and the development process, creating a whole set of research and development challenges. The thematic area *Intelligent vehicles and systems* (Theme 1) has its focuses on the energy consumption in vehicle powertrains seen as systems and their interaction with the vehicle, driving mission, and infrastructure. The research and congregated competence contribute to the development of competitive hybrid and electric vehicles by addressing methodological challenges, i.e. those that cannot be addressed by studying the individual sub-systems in the vehicle. We do this by developing methods and algorithms, necessary for efficient development and for providing hybrid and electric vehicles with the best overall designs and control possible. A central part of the research utilizes dynamic models, computational methods, and simulation techniques to study system properties and optimize the powertrain designs in system and mission settings, so we get energy-efficient electromobility solutions.

Scope and boundaries

The thematic area develops methods and algorithms, which are adopted and utilized in a hybrid and electric vehicle setting by utilizing dynamic models, computational methods, simulation techniques, and optimization. The main topics are mathematical modeling, dynamic simulation, performance analysis, control design, optimization, and fault detection and isolation. The research is focused on methods and analyses related to hybrid and electric vehicles on a *vehicle system level*. This means that questions, which are primarily related to a single component or sub-system in the vehicle, are generally not addressed within this thematic area. Another boundary is that basic research to develop general methods and tools is not pursued within the center, while the area adapts and uses such general methods specifically on hybrid and electric vehicles. Further, questions which require detailed knowledge of the industrial aspects like business cases, integration in the vehicle or manufacturing processes are not included in the thematic area, as they require insight into confidential information and are more effectively handled by the industrial partners.

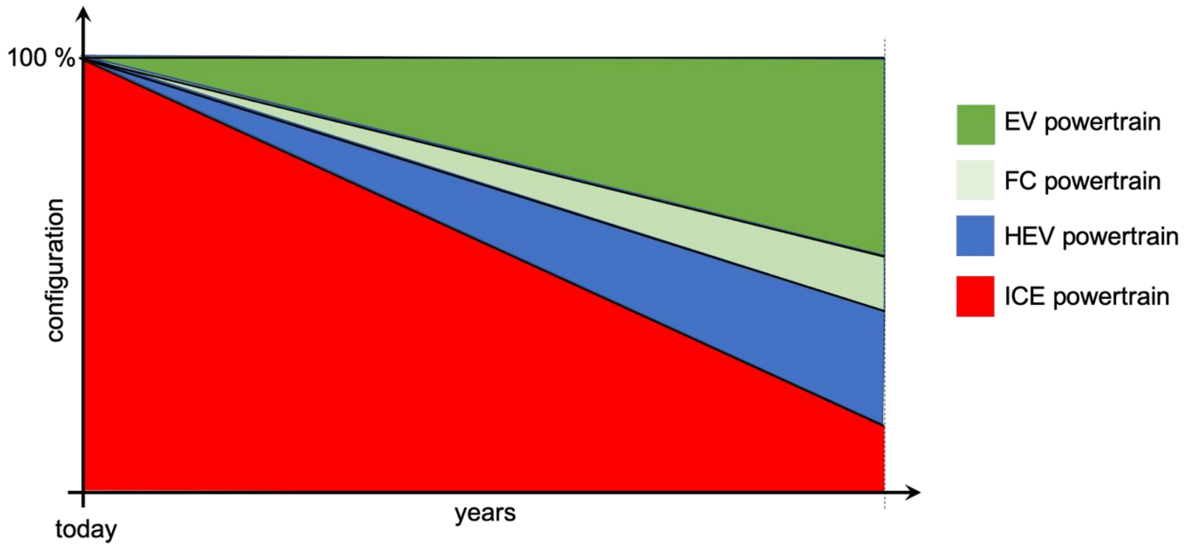
The long-term objectives concern methods and guidelines to be used by the industry to leverage the research and development within electrified vehicle systems and to build competence within this area. To ensure the usefulness of the results to all parties within the Swedish Electromobility Centre, the objectives should be general in nature and not specific to some configuration, solution or part. At high level, two major and over-arching long-term objectives may be recognized:

- To develop effective methods for *model-based systems engineering* that specifically address the needs for hybrid and electric vehicles. Such methods include requirements and systems analysis, as well as design of functions for control and monitoring, calibration, testing and certification, reconfiguration and adaptation, etc. The focus of these techniques is to reduce development time and effort.

- To develop methods that support the *engineering of more flexible and complex vehicle functions, and transportation systems* emerging as a response to the increased demands for energy efficiency, fuel flexibility, and other vehicle attributes. The goal of these methods is to support the development on a vehicle system level where the vehicles are adapted and optimized for their societal context.

Trends in the area

The overall trend is "zero emissions" and electrification. How fast the transition to hybrid and electric vehicle systems will go, is difficult to foresee and it will also be different for different vehicle categories, like passenger cars, commercial vehicles, construction equipment, airplanes, ships, etc.



Compared to a few years ago, the complete industry, from OEMs to suppliers has its mind set on electrification and hybridization as the way to the future. A common way to work has been to put *intelligence* in the subsystems, and there is big creativity to invent new functionality in the subsystems. This often leads to suboptimal designs, since optimality of subsystems may conflict with optimality at the vehicle and system level. The common view nowadays, in the automotive industry and in academia, is the need for system integration and vehicle system optimization, i.e. the internal combustion engine must collaborate with the electric drive system and the exhaust gas after-treatment system in order to fulfill global goals on vehicle and fleet emissions. In addition, the electric propulsion system must be considered in its environmental context and interact with the surrounding charging/grid infrastructure to maximize electric driving range and/or energy efficiency. And as electrification is a viable solution to achieve "zero-emissions", complete vehicle energy management is becoming an even hotter topic in the area and is not limited to just energy used for propulsion of the vehicle it also includes energy use in vehicle subsystems, like cooling/heating of batteries or electric machines, and passenger comfort, like HVAC systems.

Another huge trend is the combination of *"big data"* and "*connected vehicles"* where information about the vehicle and the outside world, provide system knowledge of how the vehicle is driven/charged, where it will go, the traffic situation ahead of the vehicle and the charging/re-fueling infrastructure. This gives new *opportunities*, and many functions using this knowledge are being developed right now. Vehicle manufacturers have already *look-ahead* functions and *cloud information-sharing* systems in the vehicles on the market. This gives an excellent platform for developing new system functionality, such as route management planning, range estimation, and traffic flow control. This area is sometimes called Vehicle-to-X (V2X) and is an enabling technology on which our thematic area is building functionality.

Research Agenda

The goal of the center is to support the transition from fossil-based propulsion systems, so we get a society that has sustainable mobility and transport. A core question for our thematic area is how to manage the energy in the best possible manner so that it satisfies the customer's needs. To address this requires knowledge of the customer, the vehicle, its subsystems, and its surroundings and it is easy to see that there are many interactions and dependencies between these systems. As it is a wide subject area with a lot of subtopics the members in the thematic group were asked to collect their most important desired research questions that we can address within the thematic area and form strategic research areas around. The result of this roadmap work is collected and reported as a partner wishlist that is placed as a long list at the end of this document. The wishlist has been restructured and organized into an inventory of research needs.

Inventory of Research Needs and Areas
The research questions put forth by the members span many subject areas and we have structured them into three main categories: one related to vehicle energy management, one to driving and ownership experience, and one to vehicle concepts.

Vehicle energy management addresses not only questions related to how to manage the vehicle's onboard energy for propulsion but also questions like how to use it for cooling and heating the powertrain components and the compartment. It requires knowledge of the vehicle's current state and predictions of future driving behavior. It also aims to develop methods for optimal control relating to *energy management*; both offline and real-time methods are considered as well as centralized or distributed approaches. The goal is to make the best use of the energy that we have available in the vehicle and not waste resources.

Total ownership experience addresses questions that are related to the operation of electrified vehicles, from the automated system (driverless) to support functions for the driver/operator. This includes finding energy-efficient ways of getting the vehicle to perform its mission and transferring this knowledge to the automated system or the driver/operator through driver modeling for energy-efficient operation. It also includes the development of new operating concepts to cost aspects for ownership of the vehicle or the vehicle fleet, like total system cost and second life/owner. The goal here is to develop functions that will facilitate the adoption and dissemination of these new sustainable vehicles and technologies.

Hybrid and electric vehicle concepts and control is related to modeling and control of electric and hybrid drive systems with a focus on system or vehicle level optimization, including fuel cell powertrains and off-road vehicles. The area is cross-disciplinary and spans both vehicle energy management and total ownership experience. The area aims to develop methods and guidelines for *efficient systems analysis* of different hybrid and electric vehicle topologies, including sub-systems, *with respect to vehicle features, safety, and total cost of ownership*. It addresses the coupling between system sizing and control of the utilization with respect to vehicle features and energy management.

Strategic Research Areas

Based on previous and current roadmap work, the thematic area has identified the following strategic research areas that will help and boost the transition to sustainable transport and mobility.

Vehicle Energy Management
This area encapsulates optimization of the usage and storage of different energy types in a vehicle that is performing a driving mission as well as the planning of the energy usage along a route.

State of vehicle estimation
As on-board vehicle energy management is a complex task and to do it in the best possible manner, it requires knowledge of the vehicle’s current state and information about future driving. Unfortunately, all information needed is not easy to access or measure, so it needs to be estimated and predicted. Interesting research questions to address include: How to estimate “unmeasurable” quantities like state of charge, vehicle mass, and external load factors (rolling resistance, air drag etc.)?

Prediction models
The area also covers how information from external sources, like V2X, can be used for predicting future driving/charging and functional architecture for distributed computing. The area aims to develop methods and guidelines for *prediction system design*. This includes methods for information fusion, as well as analysis methods with respect to robustness, availability, reliability, and sensitivity concerning prediction data. The prediction system may either be used in predictive control or to “feed” prediction models for electric range estimations.

Charging strategies and routing
Vehicles cannot always carry their own energy for their complete mission. There is an interplay between the vehicle and the infrastructure that needs to be addressed. From a systems perspective, we need to look outside the actual vehicle and consider how to refill

the energy and the infrastructure for it. Methods for design, and especially optimization methods, of when, where, and how to charge/re-fuel important questions that are to be addressed in the area. This includes charging batteries, battery swapping, hydrogen, electric roads, etc.

Thermal management (modeling and control)
The area collects both the areas of modeling and control of the thermal system of the vehicle with a focus on HW/SW co-design and optimization. There is a need for efficient thermal energy management, such as waste heat recovery, complete powertrain thermal management, and exhaust gas after-treatment system design. Apart from the actual problem of converting the heat energy to a more useful energy type, it makes sense to store the energy for later use, because energy is dissipated as heat when no extra energy is needed for propulsion or vice versa. All in all, electrification and thermal management make up a great combination for vehicle system optimization. Further, HVAC and other auxiliary systems have a great influence on the comfort and performance of the vehicle and need to be included in the system analysis and vehicle optimization. The area aims to develop methods and guidelines for efficient thermal energy management of different hybrid-, electric-, and fuel-cell vehicle topologies by considering vehicle and system features.

Total Ownership Experience

The ownership experience including usage and information presentation together with the second owner market plays an important role in the acceptance, adoption, and successful transformation to sustainable transportation and mobility systems.

Missions Specification and Modelling
The research area is related to the analysis of vehicle usage. As vehicles become more and more connected to the outside world and also collect data on-board of how it has been used, this provides a knowledge base for the understanding of what demands to put on the vehicle. This understanding can be used for generating tailored missions and charging strategies. The area aims at providing understanding in terms of models of operators and missions that can be used for efficient systems analysis or energy management. The area is not restricted to manually operated vehicles and could also include automated systems.

Transport flow modeling and control
The area is related to modeling and control of transport flows with a focus on energy usage optimization. Electrification of the transport system can lead to changes in the transport flows and also in driving behavior. The area aims to develop methods and guidelines for efficient systems analysis for transport flow modeling on a macroscopic level. Another research topic from a systems perspective looking outside the actual vehicle is charging and charging infrastructure. Methods for design, and especially optimization methods, of how to size, allocate and distribute charging are important questions that are to be addressed in the area.

UX-design

User adoption is important to speed up the transition to sustainable transportation systems. For vehicle systems, this is related to driving experience and there is interest in using new techniques for controlling the vehicle, like (semi-)automated systems, “one pedal drive”, or how to guide the operator for energy-efficient operation, and eco-coaching. For example, the trade-off between energy efficiency, drivability, and comfort is interesting to study for one-pedal drive solutions. In connection to this, also eco-coaching is an interesting topic, as it is related to the interaction and adaptation between the operator and the vehicle.

TCO - Concepts and strategies

Another driving factor for speeding up electrification is cost or cost efficiency. Total cost of ownership (TCO) is a research area, that requires knowledge from several domains, not only domain-specific knowledge but also numerical optimization, economics, etc. TCO problems usually lead to complex multidisciplinary optimization problems, and such problems are difficult to solve. Making justifiable approximations in order to reduce the complexity of the problem while preserving the properties is an important research topic. This research area is interesting for all transport solutions.

State of health modeling and monitoring

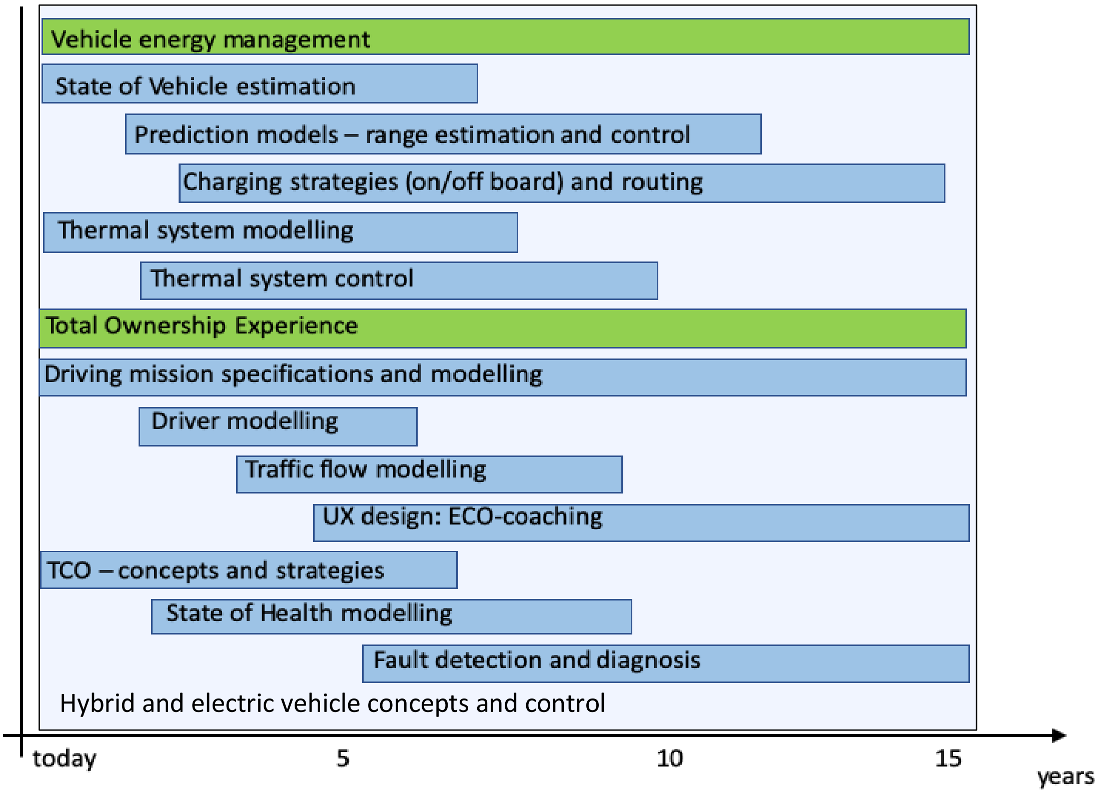
The second owner of the vehicle is another property that is important. There is a need for research about how to monitor the usage of the vehicle or the components to estimate its health. This requires knowledge of the physical components and estimation theory. For example, the battery is a fragile and cost-driving component in an electrified vehicle. It is important to make sure that the battery is handled with care, and that information related to the health of the battery can be presented to the second owner of the vehicle or if the battery is used in another application, second life. State-of-health modeling and monitoring is not only related to batteries but also applies to electric machines, fuel cells, and other components.

Fault detection and diagnosis

As electrification is a new area for the automotive industry, there is a need for development of new methods for detecting faults and also for doing online diagnosis of the vehicle. Furthermore, the new opportunities with connected vehicles (V2X) open up new possibilities in terms of computational resources, model complexity, and so on. The area aims at providing an understanding of the systems, their faults, and the consequences of these in terms of models that can be used for detection and diagnosis. This research area is closely related to the previous research area.

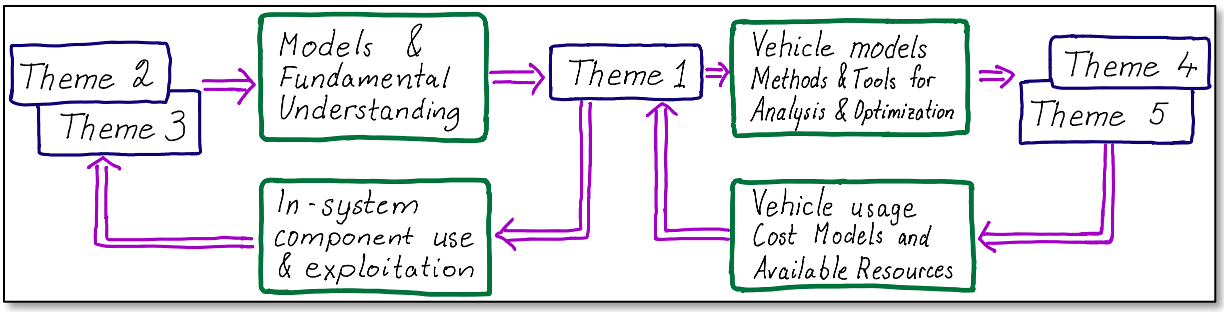
Road map items

According to the figure below, the different research questions have been aligned with a timeline of approximate time scale. Interactions exist between each mentioned research area, for example, range estimation depends on route, how the vehicle is operated, how the onboard energy is managed, if there are possibilities to charge, etc. It will also depend on vehicle concept architecture, so that dimension has been removed from the figure.



Relation between theme areas:

Interaction with other thematic areas is part of the thematic area activities, as well as interaction with external stakeholders.



Partner’s Wishlist - The Collection

The list is a compilation of the topics that the partners have brought up as important and we keep it here so that it won’t be forgotten.

- Thermal modelling and control
    - Heat battery to maximize charging
    - Active cooling
    - Air-condition and compartment climate
    - Heating of battery adapted to each driving style
    - Stochastic models and estimation
    - System level modeling, from cell to system (data-driven approach?)
- Range estimation
    - Consumption and states
    - Stochastic models and estimation
- Estimation of vehicle states
    - Mass
    - Trailer on/off
    - Rolling resistance (snow, rain, ...)
    - SOC
    - State of Energy (Temperature effects)
- Charging strategies
    - Where to charge (where to place charging stations)
    - Where to electrify (electric roads)
    - How to get enough energy onboard (electric trucks)
    - Charging infrastructures
    - Consequences of fast charging
- Control strategies
    - Zero-emission zones
    - Stochastic optimization
- Routing
- V2X
    - Data exchange between entities
    - Bridging the gap between theme 5 and theme 1 together with theme 5
    - Cooperative control
- Traffic flow modelling
    - Relevance for theme 4&5
    - Driver modeling
    - Stochastic models, micro, mezzo, macro levels.
- System efficiency vs power
- “One-pedal drive”

- Driveability vs energy-efficient driving
- Eco-coaching
- Legal requirements of fleet
    - CO2 normalized by mass (weight) - what effect does this have?
- Certification on range
- Aging of Batteries
    - Modeling of mechanisms
    - Mitigation strategies
    - Bridging the gap between theme 3 models and theme 1 models
- Aging of Fuel Cells
    - Modeling of mechanisms
    - Mitigation strategies
    - Bridging the gap between theme 3 models and theme 1 models
- Aging of X (specify)
    - Modeling of mechanisms
    - Mitigation strategies
- State of health
    - second owner (vehicle status)
    - second life (batteries, el. machines)
    - battery recycling
- TCO (Total cost of ownership)
    - Cost-effective powertrain design, dimensioning and control
    - Torque-vectoring concepts and control
- TCOP (Total cost of operation)
    - Cost-efficient path planning and powertrain control
    - Cost-efficient and safe autonomous driving
    - Electric cite
- Legal requirements
- Technology transfer
    - Other sectors
    - Industry, education
    - Tools, toolboxes
    - Dissemination
    - Open Source
- Driver modeling
    - Driver behaviour study
- Vehicle concept analysis
    - Torque vectoring
    - Energy efficiency vs vehicle performance
    - Energy efficiency vs comfort (active suspension / trajectory planning)

    - Torque vectoring for ships
- Safety vs weight