Roadmap Theme 1 – Intelligent Vehicles and Systems

Introduction

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 of Intelligent vehicles and systems (Theme 1) addresses total cost optimization of the vehicle system, with a focus on energy efficiency and ownership experience. The research and congregated competence contribute to the development of competitive 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 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 and sustainable electromobility solutions at the vehicle or vehicle fleet level.

Scope and boundaries

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 a high level, two primary and over-arching long-term objectives may be recognized:

- To develop effective methods for model-based systems engineering that specifically address the needs for electrified vehicles. Such methods include requirements and systems analysis, as well as the 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. These methods aim to support the development on a vehicle system level where the vehicles are adapted and optimized for their societal context.

The thematic area develops methods and algorithms, which are adopted and utilized in hybrid and electric vehicle settings by utilizing dynamic models, computational methods, simulation techniques, and optimization. The main topics are mathematical modeling, dynamic simulation, performance analysis, control design, optimization, AI, machine learning, and fault detection and isolation.

The thematic research is focused on methods and analyses related to vehicles on a vehicle system level. This means that questions 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 electrified vehicles. Further, questions that 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.

Trends in the area

The overall trend is "zero emissions" and electrification. Compared to a few years ago, the complete industry, from OEMs to suppliers has its mind set on electrification as the way to the future. 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, off-road machines, airplanes, ships, etc. 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.

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 the optimality of subsystems may be in conflict with optimality at the vehicle and system levels. To achieve system optimality, there is the need for system integration, and a more holistic view of the complete vehicle system, 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 or the thermal management system must collaborate with the energy management system to prepare the vehicle for fast charging. 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.

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, and the traffic situation is ahead of the vehicle and the charging/re-fueling infrastructure. This gives new *opportunities*, and a lot of functions that are 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 for our thematic area to build functionality.

Research Agenda

The core question for the thematic area of *Intelligent Vehicles and Systems* is, how to optimize the ownership experience? 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. The research agenda and strategic research areas are centered around *total cost optimization of the vehicle system*, with a focus on energy efficiency and ownership experience. Addressing the problem requires knowledge of the vehicle's current state and predictions of future driving behavior. Moreover, there is a trade-off between energy efficiency, performance, durability, and comfort. AI, mathematical modeling, dynamic simulation, control design, optimization, and machine learning are valuable methods for addressing this problem.

Strategic Research Areas

The thematic group members 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 wishlist is placed as a long list at the end of the roadmap. The wishlist has been restructured and organized into 7 strategic research areas: cost-efficient planning and control, durability and state of health, energy management, state of vehicle estimation and prediction, traffic flow modeling, user adoption, and vehicle concept analysis.

Cost-efficient planning and control addresses questions that are related to the operation of electrified vehicles, from the automated system (driverless) to support functions for the driver/operator. Vehicles cannot always carry their own energy for their complete mission. An interplay between the vehicle and the infrastructure needs to be addressed. From a systems perspective, we must look outside the vehicle and consider how to refill the energy. Methods for design, especially optimization or learning-based methods, of when, where, and how to charge/re-fuel are essential questions to address in the area. This includes charging batteries, battery swapping, hydrogen, electric roads, etc.

Durability and state of health are related to understanding how the usage of the vehicle affects the system components. As electrification is a new area for the industry, there is a need to understand how to use the system components and monitor the health of these components. 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, and 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 estimated. The state of health modeling and monitoring is related to batteries and applies to electric machines, fuel cells, and other components. Furthermore, the development of new methods for detecting faults and also for doing online diagnosis of the vehicle or the components is needed.

Energy management is essential to make the best use of the energy that we have stored onboard the vehicle and not waste resources. Energy management covers 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 or the auxiliaries.

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 also information about future driving, i.e., **state of vehicle estimation and prediction**. 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)? The area also covers how information from external sources, like V2X, can be used to predict future driving or charging needs and functional architecture for distributed computing. The area aims to develop methods and guidelines for *prediction system design*. This includes methods for information fusion and analysis methods concerning 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 estimation.

Traffic-flow modeling is related to understanding how surrounding traffic affects energy usage on vehicle and vehicle fleet levels. 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 micro-, mezzo- and macroscopic levels.

User adoption is important to speed up the transition to sustainable transportation systems. For vehicle systems, this is related to the 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. For example, the trade-off between energy efficiency, performance, and comfort. In connection with this, eco-coaching is also an exciting topic, as it is related to the interaction and adaptation between the operator and the vehicle.

Vehicle concept analysis is related to modeling, control, and analysis of electric and hybrid drive systems, focusing on system-level performance. The area aims to develop methods and guidelines for *efficient system analysis* of hybrid and electric vehicle topologies, including sub-systems, with respect to vehicle features. It addresses the coupling between system sizing and control of the utilization with respect to energy efficiency, performance, comfort, and durability. Modeling, dynamic simulation, control, and optimization are suitable analysis methods.

Road map items

The identified strategic research areas include a lot of topics and subtopics. The topics and subtopics have been prioritized according to the figure below.

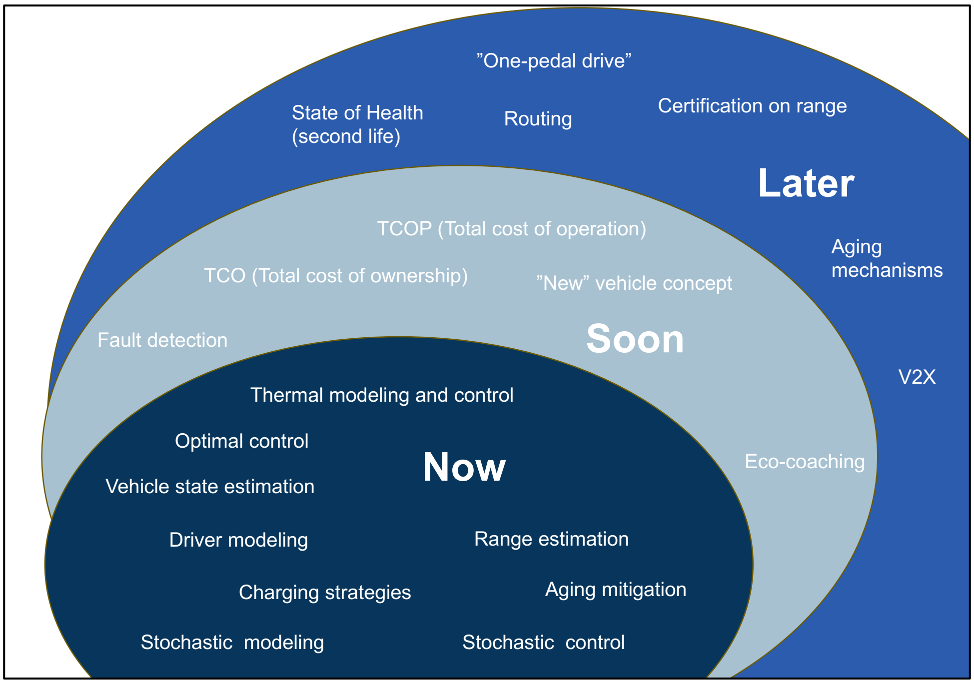
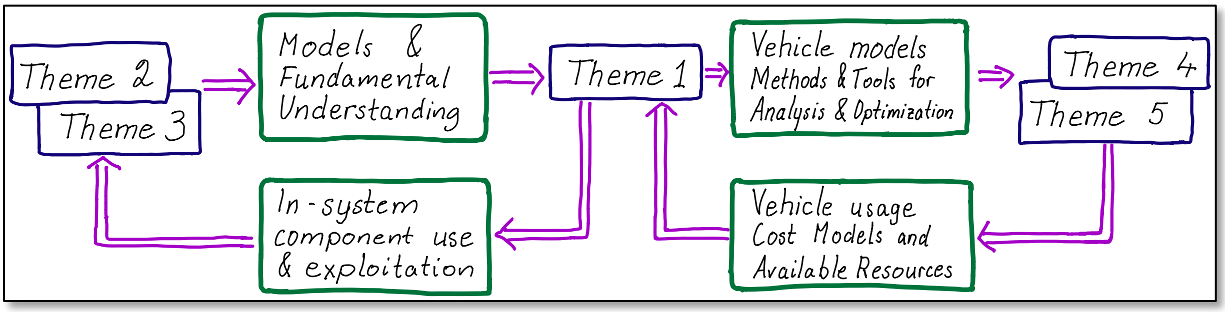


Figure 1. Prioritized research items. The items are group into three categories, starting with the most urgent (Now, Soon, Later).

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 will not be forgotten.

Cost-efficient planning and control

- Charging strategies
  - Where to charge (where to place charging stations) — Later (3)
  - Where to electrify (electric roads) — Later (2)
  - How to get enough energy onboard (electric trucks) — Later (3)
  - Charging infrastructures — Later (3)
  - Consequences of fast charging — Now (4)
- Routing — Later (1)

Durability and state of health

- Aging of Batteries
  - Modeling of mechanisms — Soon (4)
  - Mitigation strategies — Soon (4)
  - Bridging the gap between theme 3 models and theme1 models
- Aging of Fuel Cells
  - Modeling of mechanisms — Later (3)
  - Mitigation strategies — Later (3)
- Aging of X (specify)
  - Modeling of mechanisms — Later (4)
  - Mitigation strategies — Later (4)
- State of health
  - second owner (vehicle status) — Later (2)
  - second life (batteries, el. Machines) — Later (2)
  - battery recycling — Later (2)

Energy management

- Thermal modeling and control
  - Heat battery to maximize charging — Now (5)
  - Active cooling — Soon (4)
  - Air-condition and compartment climate — Later (2)
  - Heating of battery adapted to each driving style — Soon (3)
  - Stochastic models and estimation — Next (4)
  - System level modeling, from cell to system (data-driven approach?)
- Control strategies
  - Zero-emission zones — Later (1)
  - Stochastic optimization — Now (4)

State of vehicle estimation and prediction

- Range estimation
  - Consumption and states — Now (5)

○ Stochastic models and estimation	Now (5)
● Estimation of vehicle states	
○ Mass	Later (3)
○ Trailer on/off	Later (1)
○ Rolling resistance (snow, rain, ...)	Now (4)
○ SOC	Soon (3)
○ State of Energy (Temperature effects)	Now (5)
● V2X	
○ Data exchange between entities	Later (3)
○ Cooperative control	Later (3)

Traffic-flow modeling (Relevance for theme 4&5**)**

● Driver modeling	Now (4)
● Stochastic models, micro, mezzo, macro levels.	Now (2)

User adoption

● One-pedal drive"	
○ Driveability vs energy-efficient driving	Later (5)
● Eco-coaching	Soon (4)

Vehicle concept analysis

● TCO (Total cost of ownership)	
○ Cost-effective powertrain design, dimensioning and control	Soon (4)
○ Torque-vectoring concepts and control	Soon (3)
● TCOP (Total cost of operation)	
○ Cost-efficient path planning and powertrain control	Later (2)
○ Cost-efficient and safe autonomous driving	Later (4)
○ Electric cite	
● Vehicle concept analysis	
○ Torque vectoring	Soon (4)
○ Energy efficiency vs vehicle performance	Soon (4)
○ Energy efficiency vs comfort (active suspension / trajectory planning)	Soon (4)
○ Torque vectoring for ships	Later (1)
● Legal requirements of fleet	
○ CO_2 normalized by mass (weight) - what effect does this have?	Later (3)
● Certification on range	Later (3)