Roadmap Theme 1 – Intelligent Vehicles and Systems

Introduction

The requirements for our vehicles are evolving continuously, increasing complexity in both the vehicles themselves and the development process, and creating a range 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. Research and collective competence contribute to the development of competitive vehicles by addressing methodological challenges that cannot be addressed through the study of individual vehicle subsystems. 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 uses dynamic models, computational methods, and simulation techniques to study system properties and optimize powertrain designs across system and mission settings, enabling energy-efficient, sustainable electromobility solutions at the vehicle or vehicle fleet level.

Scope and boundaries

The long-term objectives concern methods and guidelines for the industry to leverage research and development in electrified vehicle systems and build competence in this area. To ensure the results are useful to all parties within the Swedish Electromobility Centre, the objectives should be general rather than specific to a particular configuration, solution, or part. At a high level, two primary and overarching 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 at the vehicle system level, where vehicles are adapted and optimized for their societal context.

The thematic area develops methods and algorithms adopted and utilized in hybrid and electric vehicle settings that leverage 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 focuses on methods and analyses for vehicles at the vehicle-system level. This means that questions primarily related to a single component or subsystem in the vehicle are not addressed in this thematic area. Another boundary is that basic research aimed at developing general methods and tools is not pursued within the center. At the same time, the area adapts and uses such general methods, specifically for electrified vehicles. Furthermore, questions that require detailed knowledge of industrial aspects, such as business cases, integration within the vehicle, or manufacturing processes, are not included in the thematic area, as they require access to confidential information and are better addressed by the industrial partners.

Trends in the area

The overall trend is "zero emissions" and electrification. Compared with a few years ago, the entire industry, from OEMs to suppliers, has its focus on electrification as the path to the future. The timing of the transition to hybrid and electric vehicle systems is difficult to predict and will vary across vehicle categories, including passenger cars, commercial vehicles, off-road machines, airplanes, and ships. As electrification is a viable solution for achieving "zero emissions," complete vehicle energy management is becoming an even more pressing topic in the field. It is not limited to energy used for vehicle propulsion; it also includes energy use in vehicle subsystems, such as battery and electric machine cooling/heating, and passenger comfort, such as HVAC systems.

A common approach has been to distribute intelligence to subsystems, and there is considerable creativity in inventing new functionality within them. This often leads to suboptimal designs, as the optimality of subsystems may conflict with that of 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 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.

The automotive industry is undergoing a paradigm shift from hardware-centric design to software-driven innovation. A new generation of vehicles where functionality, performance, and user experience are primarily enabled and continuously improved through software rather than fixed hardware components. Software-Defined Vehicles (SDV) is an emerging concept that encompasses centralized computing architectures for modular deployment, secure and reliable over-the-air updates, robust cybersecurity and functional safety frameworks, AI-driven features with efficient data management, and industry-wide standardization for interoperability.

Another huge trend is the combination of *"big data"* and "*connected vehicles*," where information about the vehicle and the outside world provides the system with knowledge of how the vehicle is driven/charged, where it will go, and the traffic conditions ahead of the vehicle, as well as the charging/re-fueling infrastructure. This creates new opportunities, and many functions that leverage this knowledge are currently being developed. Vehicle manufacturers have already *examined the functions and cloud-based information-sharing systems in* vehicles on the market. This provides an excellent platform for developing new system functionality, such as route management, range estimation, and traffic flow control. This area, sometimes referred to as Vehicle-to-X (V2X), is an enabling technology for our thematic area to develop functionality.

Research Agenda

The core question for the Intelligent Vehicles and Systems thematic area is: how to optimize the ownership experience? Addressing this requires knowledge of the customer, the vehicle, its subsystems, and its surroundings; it is evident that there are numerous interactions and dependencies among 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 prioritized strategic research areas: automated driving functions; cost-efficient planning and control; durability and state-of-health; energy management; software-defined vehicles; state-of-vehicle estimation and prediction; user adoption; and vehicle concept analysis.

1. Automated Driving Functions

Research focuses on how automated vehicles and advanced driver assistance systems can enhance safety, efficiency, and comfort while interacting with other actors in the transport network. Synergies between automation and electrification are central, including real-time environmental perception and its impact on energy use.

2. Cost-Efficient Planning and Control

This area addresses the optimization of vehicle and fleet operations, considering energy constraints and interactions with infrastructure. Key topics include charging strategies, hydrogen refueling, and electric road systems, using optimization and learning-based methods to determine when, where, and how to recharge.

3. Durability and State-of-Health

Understanding how usage affects critical components such as batteries, electric machines, and fuel cells is essential. Research includes modeling and monitoring state of health, fault detection, and online diagnostics to ensure reliability and cost efficiency.

4. Energy Management

Efficient energy use is vital for propulsion and auxiliary systems. Research explores strategies for thermal management, powertrain optimization, and minimizing energy waste under varying operating conditions.

5. Software-Defined Vehicles (SDVs)

SDVs shift automotive design toward software-driven innovation. For electromobility, research focuses on integrated energy management, predictive charging strategies, and software-controlled powertrains to improve efficiency and battery life. Sustainable hardware-software co-design and lifecycle management are critical to ensure adaptability and maintainability.

6. State-of-Vehicle Estimation and Prediction

Accurate estimation of unmeasurable quantities (e.g., state of charge, vehicle mass, external loads) and prediction of future driving needs are key challenges. This area includes information fusion, V2X integration, and predictive architectures for robust and reliable control.

7. Vehicle Concept Analysis and User Adoption

Research addresses system-level modeling and optimization of electric and hybrid architectures, balancing energy efficiency, performance, and comfort. User adoption studies explore driving experience, eco-coaching, and new control paradigms to accelerate the transition to sustainable transport.

Road map items

The identified strategic research areas encompass many topics and subtopics. The topics and subtopics have been prioritized according to the figure below.

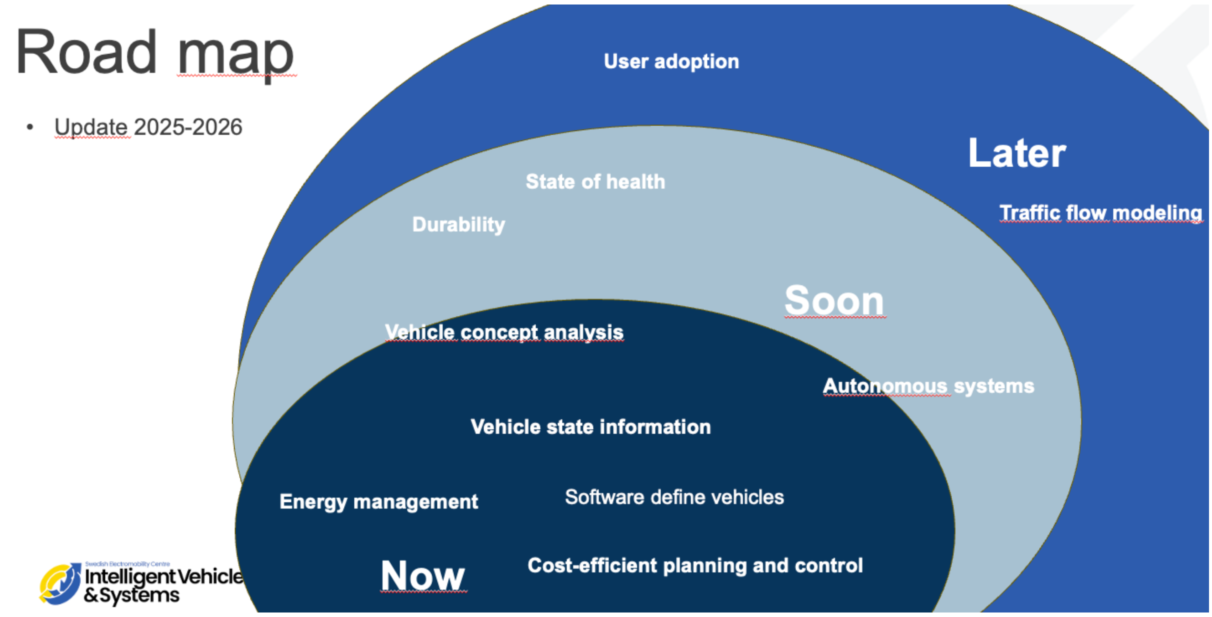
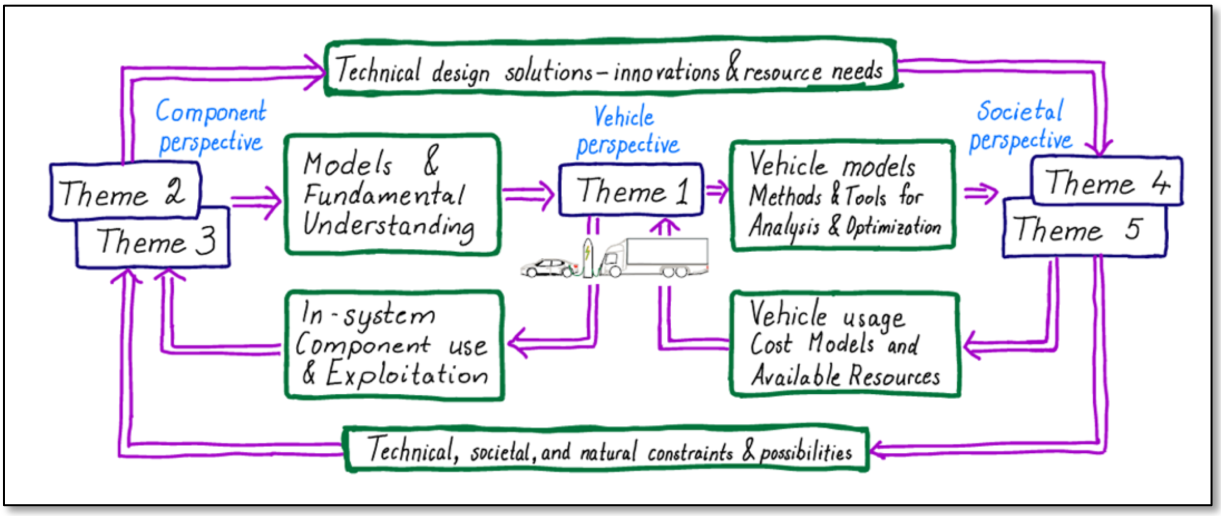


Figure 1. Prioritized strategic research areas.
The areas are grouped into three categories, ordered from most urgent (Now, Soon, Later).

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 topics the partners have identified as important, and we keep it here so they 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)

Software-defined vehicles

- Overall energy modelling and control, incl aux, computers, AD + EV — 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
  - CO2 normalized by mass (weight) - what effect does this have?   Later (3)
- Certification on range   Later (3)