Eco2 Vehicle Design: Self-evaluation report 2022

"Sustainable transport is fundamental to progress in realizing the promise of the 2030 Agenda for Sustainable Development and in achieving the 17 Sustainable Development Goals. Sustainable transport supports inclusive growth, job creation, poverty reduction, access to markets, the empowerment of women, and the well-being of persons with disabilities and other vulnerable groups. It is also essential to our efforts to fight climate change, reduce air pollution and improve road safety." – UN High-Level Advisory Group on Sustainable Transport (2016)[1].

1. The Eco2 story

We in the *Centre for ECO² Vehicle Design* (Eco2) are contributing to sustainable transport – a "fundamental" of sustainable development.

1.1. Towards a Sustainable Society

The essential question of sustainable transport

As the excerpt from the UN's report above succinctly summarises, transport is intertwined or *interdependent* with the economic, social, and environmental dimensions of sustainability and the achievement of the Sustainable Development Goals. The excerpt also alludes to the dichotomy or *conflict* at the heart of sustainable transport – that transport is both an enabler of a sustainable future, and at the same time a major contributor to current unsustainable impacts. It even indicates the large *scales* on which the consequences of transport occur – global growth, climate change, etc. These macroscales contrast with the microscales on which constituent elements of transport are developed, for example, when designers are selecting the orientation of fibres in a composite material *concept* that must fulfil some *function* in a vehicle such as bending stiffness.

Together, these attributes make developing sustainable transport complex and particularly challenging. Yet, it is precisely this important challenge that Eco2 is addressing, with the essential research question being:

> *How to deal with interdependencies and resolve conflicts, and enable concepts that are more efficient in providing functions, in terms of the large scale of needs and consequences involved in sustainable transport?*

Although this is quite a complex question, it captures the essence of the problem we are addressing. The question could be applied to different elements of transport, but for us in Eco2, the focus of our efforts is centred on improving the most essential element of transport – the vehicles. Vehicles are also centrally important to sustainable growth in Sweden.

Sweden's opportunity

While achieving sustainable transport is a global challenge, Sweden is well positioned to lead the way, and at the same time ensure sustainable growth in its vehicle industry. Volvo's XC90 has been highlighted as a good example of Sweden's role in in the global supply chain[2]. It shows how Sweden is one of few countries in the world to possess the competence to cover every step of the value-chain – from idea to finished product – while the manufacturers are multinational companies, suppliers from around the world are involved, and benefits and burdens originating in design choices here are felt globally. So, harnessing

[1] Mobilizing Sustainable Transport for Development: Analysis and Policy Recommendations from the United Nations Secretary-General's High-Level Advisory Group on Sustainable Transport. 2016.
[2] Debate Article in Dagens Nyheter by Mikael Damberg, Business and Innovation Minister, Swedish Government.

this capacity in Sweden to improve vehicles will contribute to sustainable transport worldwide and see Swedish industry increase its market share in a growing global economy.

Addressing the challenges posed for the Swedish vehicle industry by sustainability requires coordinated efforts. This is, firstly, because the essential research question, stated above, requires new knowledge to overcome the showstoppers that the industry faces. So, for example, new knowledge is needed to significantly reduce rolling resistance, while at the same time satisfying other interdependencies such as safety, and enable electric heavy-duty vehicles. It, secondly, requires provocation of existing organisational structures to encourage multidisciplinary collaboration, competence development and innovation. So, for example, integration is needed of fast-moving SMEs into research projects that traditionally are bilateral industry-academia and disciplinary focused. These developments do not occur on their own and must be supported. We in Eco2, again, directly address the challenge of coordinating efforts and provide a platform for collaboration.

Eco2's mission is to contribute to the wider Swedish-based vehicle industry's efforts to deal with its sustainability challenges, through developing the required knowledge and competence and encouraging a provocative and innovative partnership. This contributes to both sustainable growth in Sweden and global efforts towards sustainable transport and achieving the SDGs.

In this report, we outline what we are achieving, how we are doing this, what the impact of this is and how we plan to continue. Firstly though, we look more at where improving vehicles fits into achieving sustainable transport to illustrate the context for Eco2 and discuss some of the fundamental ideas and values that shape Eco2's activities.

1.2. Improving vehicles for sustainable transport

An approach to sustainable transport

Improving the environmental performance of vehicles through technological innovations is a cornerstone approach towards sustainable transport[1]. It complements other approaches, which target different levels of the transport system, such as shifting travel to improve trip efficiency[3], and avoiding inefficient travel where appropriate to improve the system efficiency[4]. Each approach has a contribution to make towards sustainable transport. However, in addition to minimizing emissions and other environmental impacts, improved vehicles will also provide greater mobility of people and goods. With a growing global population, this greener mobility will advance economic and social development to the benefit of present and future generations. Achieving this broader spectrum of sustainability benefits, through technological advancements, will also have wider applicability and require limited social change – presenting significant advantages when it comes to practical implementation. Despite this motivation, achieving improvements in vehicles that simultaneously benefit environmental, economic, and social dimensions remains challenging and much work is needed.

The convergence of new core technologies offers opportunities to transform vehicles, and the transport system[5], and are the most public face of efforts to improve vehicles. Attention, here, often focusses on disruptions such as electric powertrains, alternative energy carriers (such as batteries), digitalization, autonomous driving, and new materials. These clearly are important pieces of the improving-vehicles puzzle. For example, battery electric vehicles (BEVs) directly eliminate all tailpipe emissions. However, as with the wider sustainable transport challenge, conflicting interdependencies arise here when disruptions are applied within the vehicle architecture, which may compromise some other features. So, continuing with the BEVs example, it is commonly known that the range is compromised to reduce tailpipe emissions compared to traditional vehicles.

[3] For example, through more efficient combinations of transport modes, improved logistics or moving to off-peak travel.
[4] For example, through teleworking, improved city planning, or shortened supply chains.
[5] Seba. Clean Disruption of Energy and Transportation, Beta edition, 2014.

Disruptions and interdependencies

For transport vehicles, these interdependencies are fundamentally physical in origin. To illustrate the point, it is worth briefly considering here a comparison that is sometimes made about the transformation of vehicles being like the historical step from mechanical typewriters to electronic tablets. In this analogy, future vehicles become like *iPads on wheels*. While parts of the analogy are insightful, such as electric vehicles will have fewer moving parts and software updates may become relatively more important in future incremental improvements, the analogy overlooks a major difference. This is that while the word-processing function of typewriters could be easily maintained when switching to an electronic representation, the same is not true for vehicles. The physical function of vehicles cannot be so readily switched or removed.

Vehicles' primary function is to transport a physical mass (people and goods) through physical surroundings between physical locations – this much remains unchanged despite disruptive enablers. So, again, returning to the BEVs example, the range issue originates in the physical fact that batteries have a considerably lower energy density (i.e., they have approximately 10-15 times greater mass per kWh) than traditional hydrocarbon fuels, which means that for similar mass vehicles, there is less energy carried and the range is reduced. The point here is that addressing the interdependencies, in this case between tailpipe emissions and range, will involve addressing the physical interdependencies, and not just updating the software. This example also points to the fact that the electrification of vehicles puts an added premium on reducing physical losses from, for example, shape-related aerodynamic drag and mass-related rolling resistance (i.e., mass reduction has approximately 10-15 times greater effect). So, mechanics disciplines like aerodynamics, materials, dynamics, etc., remain centrally important to improving vehicles – albeit with new preconditions – even as technology disruptions are providing new bits of the puzzle to include. In Eco2 we have these core competences and so a starting advantage when it comes to improving vehicles.

Improving the design

Improved vehicles as part of sustainable transport must provide mobility in a manner that is safe, affordable, accessible, efficient, and resilient, while minimizing emissions, such as carbon, and other environmental impacts across the full life cycle. Broadly speaking, to meet these wide range of *needs*, vehicle designers proceed by identifying the *functions* to be performed, developing *concepts* that achieve one or more of these functions, and implementing these concepts as *solutions* in the final product. The path from needs to solutions is not unique, and neither are the solutions themselves. With various pros and cons associated with each choice along the way, there are opportunities to find improvements for different situations.

Traditionally, it has been beneficial to decompose the problem as much as possible allowing separate disciplinary groups to work on separate functions independently, before assembling the separate functional elements – a framework referred to as integrated product development. However, this approach has downsides that can be improved upon.

These downsides of decomposition include, firstly, an inflexibility to integrate new elemental solutions. This is because new elements change interdependencies and can change the assumptions on which the decomposition was performed. For example, introducing electric motors not only changes, as discussed before, range- and energy-losses-type considerations, they also affect many other attributes such as noise and vibration management, thermal management, safety, etc. This means that old divisions of labour must be revisited, with new *multidisciplinary* approaches developed to enable the effective integration of technologies – and this feeds into Eco2's work.

The second downside with traditional decomposition is that it can be inherently inefficient. Notwithstanding the benefits of dealing with problems separately, such as reduced complexity, it often leads to excessive use of resources, with separate resources required by each separate element. For example, in the vehicle roof there are usually separate structures to fulfil structural, vibration, noise and thermal functions. This means that by integrating functions into *multifunctional* concepts, resources can be saved, and the efficiency of the concept can be improved – and this feeds into Eco2's work.

Thirdly, decomposition can result in a short-sightedness and a tendency for solutions to become locked-in. This is because functional requirements may be decomposed to a scale where they are only loosely related to overall requirements through a static boundary condition that may be questionable. For example, environmental impacts reduction may be reduced to lowering energy consumption which frequently is reduced to light-weighting, so a designer of a vehicle structure may have a requirement to carry a load with the lightest material available. However, if the lightweight constraint is followed strictly and myopically, it can lead to material choices that have a sufficiently high production or end-of-life energy demand to undermine or even negate the use-phase improvements. This is a disconnect across scales, raising the question – is it low weight in the vehicle component, or low energy use over the full life cycle, that is desired? – and can lead to components locked-into globally sub-optimal solutions. So, decomposition must be done in a way that maintains the wider perspective. This means that a *multi-scalar* perspective must be included in the conceptual design to ensure globally improved vehicles – and this increasingly feeds into Eco2's work. This need for a multi-scalar perspective is growing as the wider requirements are changing with time because of complex and emerging sustainability challenges.

In developing improved vehicles for sustainable transport, the industry must therefore fulfil functions using less resources – i.e., increase the *resource efficiency* of the vehicles – by increasing *multifunctionality*, while resolving *interdependencies* that are *multidisciplinary* and *complex*, and do this in a way that can exploit *multi-scalar benefits*. As such, the challenge here goes beyond the identification of current conflicts and resolving them through trade-offs based on informed choices. Increasingly, the ability to make informed choices is lacking. While the vehicle industry has a long and successful experience of continuously improving vehicles to meet the evolving needs of customers, conditions are changing. This is because of both a rapid development in disruptive technologies and a widening of vehicle requirements – from customers' vehicle needs to society's sustainable mobility needs. So, the need for *new models to evaluate new interdependencies* is growing at the same time as *the scope of the design challenge* is expanding, making designing vehicle towards sustainable transport more complex.

A need for joint efforts

Given the scope and complex nature of the challenges involved in improving vehicles towards sustainable transport, a competence centre – such as Eco2 – is much needed. Organisational units within academia, industry and elsewhere have developed historically following analytical thinking and decomposition, with separate groups to work on separate elements, such as aerodynamics, vehicle dynamics, structural components, noise and vibration, etc. While these groupings have been very effective in meeting traditional needs, the challenges associated with sustainable development increasingly means that future needs cannot be broken down into elements within traditional boundaries. Instead, greater emphasis must be placed on how the substantial competences that exist within traditional elements and groupings can be effectively developed further and combined with each other to meet these broader needs – i.e., a greater emphasis on *synthesis*, alongside analysis. So, having a competence centre, that can bring relevant competences out of their respective organisational silos and effectively combine them, is essential to improving vehicles – in much the same way as *SDG17 Partnership for the goals* is essential to dealing with the complexities and scope of the SDGs.

1.3. Eco2 fundamentals

A successful track record

Eco2 is the foremost competence centre addressing the challenge of improving vehicles towards sustainable transport. We started Eco2 in 2006 to bring together the main stakeholders within Sweden with an initial focus on integrating the *ecological* and *economic* dimensions into vehicle design – hence the name "*Eco2"*. In the intervening years, the centre and its focus has continued to develop and mature, and today we are a strong and robust partnership. The fundamentals of Eco2, however, remain largely the same – there is a need for improved vehicles; improvements need to be set in a holistic context; there is a need for competence development because of new interdependencies; conditions exist within Sweden both to address these challenges and for the results to benefit Sweden and others; and the partnership needs to be supported in an effective and inclusive way. This continuity is testament to the fact that we

are addressing the right question, using the right approach, and achieving the right results. That "the problem has not been solved" in this time is because of its inherent complex and emergent nature, and that there has also been a tremendous change in the whole system balance due to sustainability. When we started 15 years ago battery-electric trucks were almost unthinkable. However, this is changing, and our work has helped our industry partners to stay ahead of the game. This also shows how our approach has not only been vindicated but also become more relevant with time.

The details of the research, structure and impacts are presented in greater detail in Sections 2-4. However, here, we firstly focus on some basic attributes of Eco2 – our central ideas and values or *Eco2 fundamentals* – which are important to communicate before proceeding. It is also useful to set out the historical progress of these fundamentals and the step changes in our development and understanding of the challenges we are addressing – seen in Figure 1.

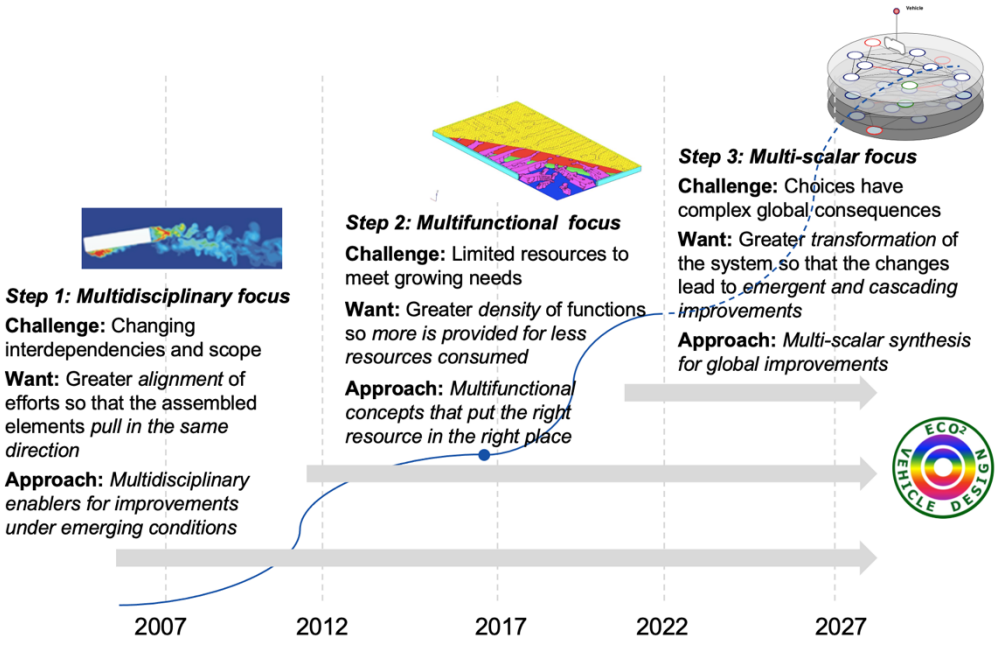


Figure 1: Eco2's development over the years.

Aligning the efforts with the needs

From the start, Eco2 brought together most of the major Swedish-based vehicle manufacturers[6], university and research institute groups, public agencies, and SMEs, to work on the challenge of including economy and ecology dimensions in vehicle design. Much of the early research focussed on identifying showstoppers or conflicts that needed to be overcome to improve environmental and economic performance. For example, an early project (that has continued to present day) looked at how models for vehicle dynamics and aerodynamics could be coupled to enable vehicles to become lightweight while remain safe when exposed to crosswinds that could potentially push them off the road. So, projects like this brought together partners form different disciplinary groups in academia and industry to jointly develop new multidisciplinary knowledge and competence. This not only created enablers for improvements in vehicle design but saw a growing understanding of how working together, or pulling in the same direction, leads to improvement in terms of connecting the disciplinary models, the functions they represent and the people from different groups. Out of this understanding has grown the notion of increasing *alignment* between different elements to overcome new interdependencies and emerging conflicts in the vehicle architecture.

[6] Volvo Cars joined in 2017 to complete the inclusion of all the large Swedish-based vehicle manufacturers.

Integrating functions

Working together in the projects, and through wider discussions in the Centre environment, also brought about a step change in our approach from the earliest work to focus on *functions* rather than the more limited scope of enabling a solution to a current problem – i.e., functions are technology and scale independent. This development had several benefits including making it possible for competing partners to work together on pre-competitive topics (i.e., the research outcomes could be fed into product development processes independently at partners rather than requiring a joint product development); functions also are more amenable to innovative concepts and less oriented around finding fixes to current problems; but they also offer a path to improvements through functional integration. This functional integration can lead to multifunctional concepts, which are more amenable to optimisation and can fulfil the functional needs or provide more functions for a given or reduced resources. So, for example in one project, a multifunctional vehicle roof panel concept was developed and evaluated that fulfilled structural, vibration and acoustic requirements while being lighter than current roofs composed of single function assemblies. This roof panel was also constructed to demonstrate the benefits. This result, together with other project findings, can be framed in terms of an increased *resource efficiency*. This idea not only fed into our current work on increasing functional *density* – i.e., more function, less resources – but also became the focal point of our vision for how Eco2 is contributing towards sustainable transport.

Improving efficiency

We have found in Eco2 that vehicles' resource efficiency is a useful concept for tying together the constituent challenges involved in improving vehicles. Firstly, it works as a unifying focus, from enablers for improved efficiency such as reducing rolling resistance, to design concepts where efficiency is improved directly, to the wider system where the functions of vehicles, transport and mobility are provided more efficiently. Secondly, resource efficiency is flexible in terms of the resource in question and can, for example, be the mass of material in vehicle, energy provided to the vehicle, volume of space occupied in an urban environment by vehicles, time to deliver goods for different vehicles, etc. This also illustrates why we have not adopted a narrow focus on driveline technology (i.e., combustion engine or electric) but rather have a neutral perspective on this that looks at the enabling and consequences of different technologies on the vehicle architecture and surroundings. Thirdly, resource efficiency is compatible with how the vehicle industry has worked, albeit with the resources expanding from, for example, fuel consumption to a wider scope of resources. Fourthly, it is a concept that is already established within other surrounding initiatives such as efforts towards resource efficient transport and eco-efficiency, but we apply it to vehicles. It similarly ties into efforts towards a circular economy, with resource efficiency being an overlapping and complimentary concept with resource efficiency focussing on doing more with less while circular economy focusses on resource management – both contribute to a decoupling of economic growth and resource use. Finally, and following from the previous points, resource efficiency has proven to be a topic that can engage wider interest – as we experienced when starting our Resource Efficient Vehicles Conference – and is a focal point to build an international network of engineers, environmental scientists, economists, etc., to find improvements in the wider vehicle system and achieve sustainable transport. So, resource efficiency (like functions) is technology and scale independent, which makes it an amenable and robust concept to build partnerships around. All these benefits are important in connecting Eco2's work to sustainable transport.

Transforming the system

Another step change in our understanding took place as we worked more with resource efficiency and how it could be used to connect design decision on a vehicle or component level with the higher system levels where sustainable consequences are expected. Here, for example, we have led the way with our work on using life cycle energy as a proxy for resource use and environmental impacts within a design optimisation framework. This work is one example of how such a formulation can synthesize or build up vehicles, with all life cycle phases combining to find the best solution. This contrasts with more traditional 'design then analyse' approaches, which cannot exploit connections in the life cycle phases in the same way. The potential with such work feeds into Eco2's current work to leverage wider connection across life cycle phases or across the scales in the wider component-vehicle-transport-society system. Such

leveraging could result in cascading or domino-effects that would truly bring about a *transformation* of the system to a more resource-efficient state.

Together these ideas around *alignment*, *density,* and *transformation* and how they contribute to resource efficient vehicles have been formative in defining our research objectives, how we formulate the projects, and organise the project clusters. They are also illustrative of how over the span of the Centre's history, we have not only produced individual pieces of new knowledge in our research, but also managed to draw a wider understanding of what we are doing, that provides momentum to a new step in our development. This wider understanding also is central to the competence development of the individuals and partners within this competence centre.

A centre of people

This evolution of Eco2's activities and understanding over the past 15 years, as we address the challenges of sustainable transport, has been built around some core values – dialogue, shared responsibility, consensus, teamwork, trust, gender-balance and personal development. While many of the individuals who established the Centre are still involved, many more new members have joined and come to share these values. For us, "what's in it for me" comes second to "what can we achieve together". These values feed into all aspects of the Centre, but particularly into how we work towards an inclusive and gender-balanced environment. Vehicle engineering, the vehicle industry and transport has a very gender-biased track record[7]. A lack of women in these areas is problematic since it affects gender balance (human resources) in recruitments undermining the creation of an inclusive working environment. It also affects gender dimension (research content) meaning that vehicles and transport have historically been from an androcentric perspective – e.g., vehicle safety features based on men's dimensions have been to the detriment of women's safety. By definition, gender dimension is needed to design sustainable transport (i.e. SDG 5), and although most of work is not directly concerned with the gender dimension of vehicle design, it can become relevant for our work on motion sickness and psychoacoustics where users are involved. We are aware of gender issues and has been working actively to address since the start of the Centre. For example, we have been involved in organising the Gender Data Gap Conference in 2021, and pursue a gender balance within our organisational groupings. So, gender-balance is central to our values as a centre and has been one of our intended outcomes since 2016, and has shaped how we have formed the centre.

Eco2's strategy

Since 2006, we have been learning and developing both terms of the research needs we address and the values we support as a partnership. This has continued during the most recent phase since 2017, but also has expanded as we understand more about how *alignment*, *density* and *transformation* can bring us towards *resource efficient vehicles*. These ideas now shape the research we undertake and, also, are consistent with the strategy we have pursued for a long time of promoting cross-fertilisation of ideas, tackling multifunctional conflicts, and supporting a cross-scalar perspective. In the past five years it is this latter strategy, which is accelerating, with the content of our research now increasingly and directly connecting our core competences with higher scales of the system. In this way, our growing understanding is helping us connect the pieces and is leading to the transformation of the transportation system to become sustainable.

[7] Criado-Perez. Invisible Women: Data Bias in a World Designed for Men, Abrams Press, 2019.

2. The centre's research excellence and attractiveness

2.1. Setting our research agenda

A common vision

Our vision in Eco2 is to drive resource efficient vehicles in a sustainable society.

We mean this vision both in the sense that we want our present activities to be a driving force for efforts in Sweden and beyond, and that we want our efforts to significantly contribute to the realisation of this goal. To achieve this vision, as discussed in Section 1, we have identified that research is needed to increase the *alignment* between different elements and thus overcome emerging conflicts in the vehicle architecture, to develop and evaluate new concepts that increase functional *density*, and to leverage connections across the wider system scales to bring about a *transformation* of the system. This is quite a unique vision and approach to improving vehicles, that complements other international initiatives.

Eco2 in relation to other initiatives

Eco2's research agenda stands out from other international efforts, that are listed in the Table 1. These initiatives have different research focusses such as multidisciplinarity, digitalisation, or sustainability in general. The Eco2 approach stands out as the one where vehicles and vehicles' connections to the surrounding systems are tackled in a holistic way, from enablers to consequences, showing that the research focus of Eco2 is a unique proposition in an international context. Moreover, it shows the potential for Eco2 to lead others in efforts towards improved vehicles and sustainable transport – something Eco2 is in fact already doing. This is best illustrated by our identification of a research and dissemination gap around the topic of resource efficient vehicles, which led us to create and run the first conference on Resource Efficient Vehicles – *rev2021*. This Eco2-led move was welcomed in the wider community and the plan is to build on this together with this wider community, with the next conference to be held in Graz in 2024. This means the Centre is not only of interest to sustainable transport efforts in Sweden but occupies and interesting scientific position globally.

Table 1: Overview of surrounding initiatives

Name	***Location***	***Focus***
Chair of Sustainable Manufacturing and Life Cycle Engineering	Technische Universität Braunschweig, Germany	manufacturing; vehicles and components; light weighting; material selection; LCA
Sustainable Manufacturing and Life Cycle Engineering Research Group	UNSW, Australia	manufacturing; broad sustainability; energy eficiency in manufacturing; EOL; batteries;
Eco-design of Sustainable Systems (EcoSD) Network	France	broad sustainability; ecodesign; circularity in automotive systems; complex systems;
SystemX IRT (Institute for Technological Research)	Paris-Saclay, France	digitalisation; mobility; autonomous vehicles; environmental sustainability; human centered mobility; AI;
MOVING - Mobility and Vehicle Innovation Group	Università degli studi Firenze, Italy	mobility; safety; multi-objective optimisation; electrification of vehicles; ecodesign
Wim Dewulf / Joost Duflou Groups	KU Leuven, Belgium	LCA; manufacturing; societal sustainability; batteries; EOL;
Center for Sustainable Systems	University of Michigan, USA	interdisciplinarity; systems engineering; electrification of vehicles; light weighting; material selection; LCA;
Automotive Research Center	University of Bradford, UK	vehicle engineering; quality; failure avoidance; brake systems; optimisation;
Transportation Sustainability Research Center	UC Berkley, USA	social sust.; environmental sust.; economic sust.; transportation; human centred mobility; vehicles concepts; LCA; last mile delivery; energy; transportation choices;

Virtual Vehicle Centre	Graz, Austria	virtualisation; autonomous driving; safety & security; electrification/lightweighting/energy/NVH coupling; data-driven methods; testing of vehicles and components.
Fraunhofer LBF	Darmstadt, Germany	lightweight design; safety and reliability; functional integration; societal sustainability; future mobility; multi vehicle;
STEPS+ Sustainable Transportation Energy Pathways	UC Davis Institute of Transportation Studies, USA	multi vehicle; interdisciplinarity; infrastructure; policies; environmental sust.; economic sust.; transport business models; system dynamics; sustainable transport
The Institute for Transport Studies	University of Leeds, UK	policies and regulations; mobility provision; system dynamics; connected and shared mobility; environmental sust.; social sust.; human centred mobility; digitalisation;
Smart Mobility	TU/e, The Netherlands	Smart Mobility; transport externalities; safety; clean mobility; efficient use of infrastructure; policies for spatial planning; public transport; digitalisation; mobility provision;
Trottier Institute for Sustainability in Engineering and Design (TISED)	McGill University, Canada	broad sustainability; consequential LCA of products and processes; environmental sustainability; resource efficient processes, infrastructure & transport; energy efficiency; renewable energy; new materials; urban development
MIT Energy Initiative	MIT, USA	alternative fuels and powertrains, electrification, future mobility; data-based driver behaviour studies; resource & cost efficiency; decarbonization of the transportation system;
Virginia Tech Transportation Institute	VTTI, USA	multi-vehicle; autonomous & connected vehicles; data & analytics; human centred factors; electrification; transportation modelling; environmental assessment; energy modelling; vehicle safety; automotive performance simulation; sustainable mobility & infrastructure; policy analysis
DLR - Institute of Transport Research	DLR, Germany	multi-vehicle; env. & soc. sustainability; mobility choice modelling; transport demand assessment and forecasting; acceptance and usage of electromobility; urban mobility; policy analysis; socio-technical assessment for achievement of climate targets; human factors in mobility;

Eco2's Research Objectives

Eco2's primary activity is to perform research and produce new knowledge. As such, our direct Research Objectives are:

1. To develop multidisciplinary enablers with the aim of increasing functional alignment.
2. To evaluate multifunctional concepts with the aim of increasing functional density.
3. To synthesize multi-scalar consequences with the aim of bringing about system transformation.

These three objectives are directly related to increasing alignment, density and transformation, and so increasing resource efficiency in vehicles and ultimately sustainable transport (as discussed in Section 1). They can be understood in other words as providing the tools to be able to resolve conflicting interdependencies, to reduce resource consumption while meeting the functional need, and to connect the pieces together to improve the wider system. This explicit formulation of our research objectives is new since the Follow-Up Process in 2020. However, these objectives were implicit in our work long before then.

Achieving these research objectives can be seen as the most direct outcome of the Centre and provide building blocks for our partners and others to go about realising resource efficient vehicles. However, they are only part of our intended outcome as a competence centre. Also, significant are the development of new competences within the people and organisations involved in the Centre, and how secondary effects and wider impacts spill-over from the knowledge and competence development processes. These will be discussed more in Sections 3 and 4.

To understand how these research objectives translate more concretely into the research content of our projects, the following details our project clusters and selected examples of our publications.

2.2. Meeting our research objectives

The project clusters

To meet our three research objectives, each project in Eco2's project portfolio focusses on some specific aspect or application connected to one or more of the research objectives. The projects are also organised into project clusters to support the different focusses or perspectives – namely, *Alignment*, *Density* and *Transformation,* as can be seen in Figure 2. To give an idea of the research activities in these clusters, a few projects are selected and briefly described in relation to their cluster. More details about all the projects within each cluster can be found in the Annual Reports. Later we will present two papers from each cluster, so the projects associated with these papers are excluded in the selection to avoid overlap.

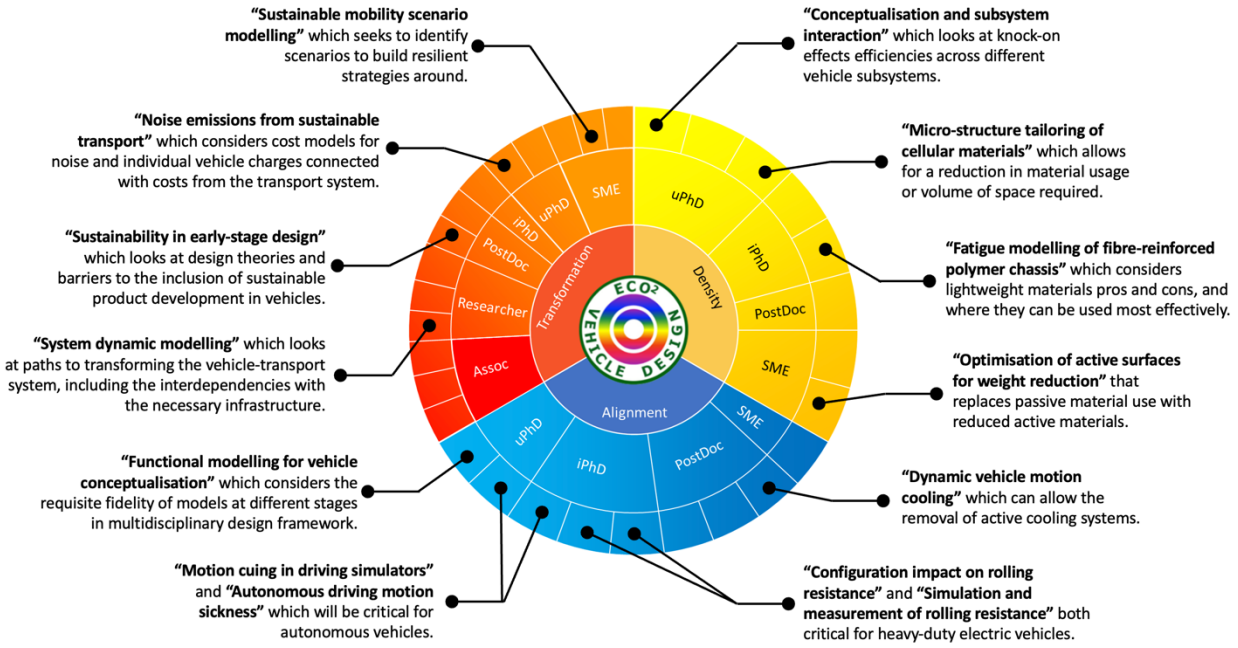


Figure 2: Overview of Eco2's project portfolio including the clustering into Alignment, Density and Transformation with a selection of 14 of the 33 projects described to illustrate their content. "iPhD" is an industry PhD and "uPhD" is a university PhD.

The *Alignment* cluster mainly focusses on multidisciplinary enablers, corresponding to the first research objective. In total, since 2017 there have been 10 projects in this cluster with 7 still ongoing. These projects each address critical enablers whose requirements must be aligned within the vehicle system in order to achieve improved resource efficiency.

The *Density* cluster mainly focusses on multifunctional concepts, corresponding to the second research objective. In total, since 2017 there have been 9 projects in this cluster with 5 still ongoing. These projects each address some direct concept to reduce resource use and increase multifunctional density.

The *Transformation* cluster mainly focusses on multi-scalar synthesis, corresponding to the third research objective. In total, since 2017 there have been 14 projects in this cluster with 9 still ongoing. These projects each address some aspect of how vehicle-scale considerations connect to global-scale considerations so that multi-scalar transformation can be achieved.

The three clusters directly connect with the Centre's research objectives and the projects contribute to achieving resource efficient vehicles. Furthermore, the clusters create a sense of common purpose between the PhDs, postdocs and SME researchers, but importantly push them towards higher questions. So, in the "Noise emissions from sustainable transport" it would, for example, be easy to narrow in on traditional acoustics considerations around accuracy and validation. However, the cluster here (and the discussion between the members of it) keeps the perspective on what modelling is needed for multi-scalar synthesis, which in this project's case results in the use of a micro-scale traffic simulation. Another benefit of the clusters is to create opportunities to exploit synergies between the projects, an obvious example here is in the "Configuration impact on rolling resistance" and "Simulation and measurement of rolling resistance" projects which involve different partners (An industry PhD at Scania, and a PhD at VTI and supervisors at KTH). Another such example is detailed in the context of joint project generation, see Section 3.1.

It is also worth noting here that the establishment of these projects and project clusters and the research activities within them has been done in close collaboration with all the partners. This involved significant dialogue between all the partners during project generation workshops in 2017 and subsequent meetings and constitutes a success for the Centre – i.e., these are Eco2 projects, shaped by *Eco2's fundamentals* and not just a loose network of projects. More details about what this means and how it is achieved are given in Section 3. The point here is that thanks to the Centre's emergent environment, the projects become more than would be separately.

Our plan is to continue to add new projects to these clusters and this is discussed more in Section 5.

Selected publications

Previous reviews and evaluations (with our ISAB and Vinnova Follow-ups) have concluded that we have an excellent track record for producing scientific research that is excellent in its quality. So here we summarize two recent scientific publications from each of these three clusters to highlight how they contribute to increasing alignment, density, and transformation and how they connect into resource efficient vehicles (REV). These six selected publications best illustrate how our research is increasing the resource efficiency in vehicles following our *alignment*, *density* and *transformation* thinking. As such the selection is not based on greatest number of citations, etc. Rather they show how the recent results of Eco2 PhDs and researchers follow this thinking and are achieved by assembling competences and developing them further in a problem-orientated way.

Alignment	*Tunay et al "On coupling methods used to simulate the dynamic characteristics of heavy ground vehicles subjected to crosswind", Journal of Wind Engineering & Industrial Aerodynamics, Vol. 201, p. 1-15, article id 104194, 2020.* **REV:** Lighter vehicles require less energy to move, and so have an increased resource efficiency. **Constraint:** However, they must also safely maintain road position when exposed to crosswind gusts. **Alignment:** This means that in lighter vehicles, the interdependency between vehicle dynamics and aerodynamics is more pronounced, so new coupled *multidisciplinary* models were needed to find the *alignment* between these functions. **Specifics:** This work extended previous work to include roll dynamics along with lateral and yaw dynamics in both one-way and two-way coupled aerodynamics and vehicle dynamics simulation. **Outcome:** Results showed that two-way coupled simulations gave greater accuracy in terms of lateral displacement. **Conclusion:** Helped to illustrate the effect of modelling differences on the lateral displacement of vehicles on the road. This is knowledge is *enabling* the design of comfortable and safe lightweight vehicles.

	Papaioannou et al, "Multi-Objective Optimisation of Tyre and Suspension Parameters during Cornering for Different Road Roughness Profiles", Applied Sciences, E-ISSN 2076-3417, Vol. 11, no 13, article id 5934, 2021. **REV**: Energy efficient driving through trajectory planning and chassis control leads to increased resource efficiency. **Constraint**: However, comfort, noise, wear and safety must also be taken into account. **Alignment**: As electric vehicles are expected to be heavier, increased particle pollution from tyre wear needs to be balanced with rolling resistance, comfort and vehicle handling. Models including over-actuation in advanced drive systems are required to facilitate this. **Specifics**: This work studies how tyre and vehicle suspensions, including over-actuation, shall be designed to minimize tyre wear without neglecting passenger comfort and vehicle safety. **Outcome**: Tyre wear illustrates a linear relation with handling and a conflicting relation with comfort, implying that increased levels of tyre deflections, i.e. more wear, lead to more discomfort. **Conclusion**: Comfort illustrates the same conflicting relation with wear and with vehicle handling. This means that an increase of the suspension travel leads to more comfort but at the same to worse handling and tyre wear.
Density	*Larsson et al. "Mass minimization with conflicting dynamic constraints by topology optimization using sequential integer programming", Finite elements in analysis and design, Vol. 200, article id 103683, 2022.* **REV:** The right type of material at the right place, in the right form and in the right amount. This saves on physical resources such as, actual raw material, physical space, e.g. a thinner wall structure allows for more interior space in a passenger vehicle. **Constraint:** However, the structure needs to carry both static (from e.g., equipment) as well as dynamic loads (originating due to the actual motion of the vehicle). **Density:** This means that the number of functions (load, thermal insulation, acoustics, etc.) provided in a component or part of a vehicle is balanced relative to the volume of space required. **Specifics:** This work has resulted in a new method for mass minimisation through topology optimisation where conflicting load constraints are concurrently active. **Outcome:** The amount of solid required for a certain load case is to a larger extent controlled by the static loads and that a successively increasing dynamic load level leads to topological changes. **Conclusions:** Have shown that the static and the dynamic loads are distributed differently through the vehicle structure. The minimum mass configuration is met where the structure is fully utilised in absorbing both these and no further removal of material is possible.
	Mao et al. "Twist, tilt and stretch: From isometric Kelvin cells to anisotropic cellular materials", Materials & design, Vol. 193, 2020. **REV:** The characteristics of materials used in light weight vehicle designs, is governed by their micro-structure. By designing the micro-structure such that the material re-directs the applied forces, the same functional performance can be achieved using less space. **Constraint:** However, the material is often required to be multi-functional and to have both a dynamic as well as an acoustic effect. **Density:** This means that the amount of functions (load, thermal insulation, acoustics, etc.) provided in a component or part of a vehicle is balanced relative to the volume of space required. **Specifics:** This original work has resulted in a new class of programmable materials where the directional properties may be continuously controlled. **Outcome:** The same material performance may be reached using only a fraction of the thickness as compared to a classical design. **Conclusions:** For approximately constant material density (i.e. same weight for same thickness) acoustic materials that provide high absorption with significantly thinner layers as compared to current state-of-the-use. This means that less space needs to be sacrificed and that less material would be required for achieving a required noise control performance.

Transformation	*Bouchoureb et al. "The inclusion of end-of-life modelling in the life cycle energy optimisation methodology", Journal of Mechanical Design, Vol. 143, no 5, article id MD-20-1233, 2021.* **REV:** The resource efficiency of a vehicle design is ultimately only meaningful at the system level, and the design paradox makes it to a large extent already predetermined during the earliest concept development stages. Using cumulative energy demand as a composite measure, a cross-scalar optimisation can be established, where the vehicle design, in terms of geometry and material composition, is arrived at through minimising the vehicle's total Life Cycle Energy (LCE). **Constraints:** The vehicle subsystem must carry localised and distributed loads, while satisfying dynamic requirements and simultaneously having a minimal environmental footprint through a minimised LCE. **Transformation:** Using the LCE as a proxy allows for cross-scalar tradeoffs that enable the translation of the societal need for transport with a diminished environmental impact through LCE optimal vehicle designs. These designs' macro-scale performance is not only dependent on the materials' typical micro-scale mechanical properties, but also on their embodied energy and recycling potential. **Specifics:** This work extends previously developed LCE models to include the effect of the End-Of-Life (EOL) phase of the vehicle subsystem, while also increasing the modelling complexity of the latter. Effectively, this development penalises design decisions that stem from optimality with respect to a single discipline, as they are likely to lead to suboptimal impact shifts. **Outcome:** The results showed that the inclusion of an EOL model in the LCEO methodology greatly impacts the design of vehicle structures. Fundamentally, a novel trade-off between space allocation and material use intensity is performed in order to achieve vehicle production system level energy efficiency. **Conclusion:** The LCEO methodology developed in this project allows to link the larger societal needs to the minutia of the vehicle's design. In doing so, it has led to material and space allocation patterns that constitute a significant departure from established vehicle design approaches, while being more in line with the material flow principles of the Circular Economy.
	Rumpler et al., "An observation of the impact of CoViD-19 recommendation measures monitored through urban noise levels in central Stockholm, Sweden", Sustainable cities and society, Vol. 63, article id 102469, 2020. **REV:** The transition towards an electrified transport system offers the prospect to also mitigate the increasing exposure to unhealthy noise levels in urban environment, promoting more livable cities. This shift may however not be sufficient in itself, and assessing the environmental impact of individual vehicles in relation to systemic effects is a necessary step to influence policy, and design or allocation of resource-efficient vehicles. Dynamic noise monitoring in dense urban environments responds to this underlying requirement. **Constraint:** The vehicle must be able to respond to the needs and constraints in terms of environmental emissions (including noise and particulate matter), traffic demand and efficiency. **Transformation:** Dynamic noise monitoring provides not only a means to assess the transformation of the transport system and the associated impact, but also an opportunity to close the loop back to singular traffic patterns and major contributors in the system, thus guiding both policy implementation and vehicle design. **Specifics:** This work illustrates the potential of noise measurements as a proxy to detailed analyses of the transport system. Here, noise monitoring performed in Stockholm is presented as a viable tool in order to assess the impact on the transport system of the COVID-19 pandemic and its associated restrictions or recommendations. **Outcome:** A very good correlation was observed between the major events during the pandemic (recognition as a pandemic, implementation or lift of restrictions and recommendations), and the evolution of the traffic and urban activity conditions. **Conclusion:** This measurement-based study highlights the potential of dynamic noise monitoring to investigate components of the transport system, including the relation between individual vehicles with their impact at a systemic level. The article received a lot of media attention, in particular due to its societal impact.

2.3. A stimulating and attractive milieu

Wider publication and research scope

In total there have been 124 journal and 98 conference articles since 2017, which have already attracted more than 1350 citations[8]. These statistics include an increasing trend in publications per year and, also, an exponential growth of citations, with articles from 2017 still attracting citations. A deeper discussion of the publications and citations trends can be found in our Annual Reports. These publications span across journals including the Journal of Cleaner Production (Impact factor: 7.246), the International Journal of Rail Transportation (Impact factor: 3.81), International Journal of Fatigue (Impact factor: 4.369) and many more[9]. This reflects that our research spans from quite fundamental enablers to more general sustainability, this is also visible when looking at individual articles such as Eliasson et al. (2019) "Fatigue and Damage Assessment of CFRP Material Using Digital Image Correlation", in Structural Integrity Procedia and Schöggl et al. (2019) "A design-theoretic review of Sustainable Product Development literature", in 22nd International Conference on Sustainable Innovation.

While it might be tempting to view some of our publications as either too narrow or too broad in scope, and potentially departing from the resource efficient vehicles focus, we believe retaining this depth and breadth is important. It should be noted that it is the same researchers who bring the depth and breadth of their knowledge to address research efficient vehicles. Furthermore, it should be noted the breadth and depth is a consequence of Eco2, with, for example, researchers from traditional mechanics disciplinary now publishing in broader sustainability journal such as Cleaner Production. So, narrowing the scope of what constitutes Eco2 research, in one direction or the other too much, would be counterproductive.

Eco2's work is built upon having access to core competences such as vehicle dynamics, structural mechanics, vehicle, development, sustainable product development etc. from all the assembled partners. These competences are needed as a starting point towards resource efficient vehicles. An added value of Eco2 is to bring these together with an incentive for those involved to develop beyond the traditional disciplinary boundaries of their respective groups and to meet the higher need or goal of *driving resource efficient vehicles in a sustainable society*.

Our research activities, are not set with hard boundaries but span to include associated projects that are partly externally financed such as from Region Stockholm, Swedish Research Council for Sustainable Development: FORMAS, EU CIVITAS, EIT Urban Mobility, Shift2Rail, Integrated Transport Research Lab, etc. Eco2 is both an enabler and beneficiary of this. The interaction with other activities at KTH is also reflected in each member is also affiliated to one or more other research group, again important for enable breadth and depth in the research content, but also in creating spill-over of knowledge within the wider organisation.

Research facilitation efforts

As a centre, we have always placed a lot of emphasis and considerable resources on creating a wider framework to support the research content. This includes our organisation structures (discussed more in Section 3) which are more about assembling competence and in-built collaboration, than fulfilling day-to-day tasks and simple network type interactions. It also includes our engagement in other forums, for example, the KTH Transport Platform[10], the KTH Centre Directors Network, and collaboration with other centres such as Road2Science in organising a Gender Data Gap Conference. Our research is also coupling into the education programmes at KTH, as discussed in Section 3, with a notable example here being Centre's PhD course "FSD3900 ECO2logy: Ecology and Economy in Vehicle Design".

Additionally, and most significantly, we have started the Resource Efficient Vehicles conference with the first edition held in June 2021. This initiative was undertaken because we had seen over the years that other existing conferences (something mirrored in journals also) were either too narrow and disciplinary

[8] 1364 citations according to Google Scholar on 17 March 2022.
[9] See "Publications affiliated with ECO²: Guidelines and strategy"
[10] Eco2 Leadership Team members Peter Göransson and Jenny Jerrelind are director and vice director of the KTH Transport platform.

or too broad such as dealing with sustainability in its entirety – i.e., there was a gap in the research community. We discuss more about what we have achieved in establishing this conference in Section 3. However, here we can highlight that the conference provides a focal point for the topic internationally and a neutral scientific platform to engage with others working in areas related to the topic. This is important in the long-term development of research on resource efficient vehicles beyond the Centre. This is because it aligns the multidisciplinary efforts (i.e., having an initiative called "resource efficient vehicles" makes it easier to build activity around it) and reduces obstacles to collaborating internationally (i.e., starting up an international project is a higher threshold than participating in a conference). The plan is to continue this as a conference series with Eco2 leading a *reVehicles* conference committee as an international network. This helps facilitate our own research activities.

This new conference initiative is also complemented by our participation in other conferences and networks. These often serve to add disciplinary depth to our work and, also, to showcase our multidisciplinary results with recognitions following such as PhD student Siddharth Venkataraman being selected for the EARPA (association of automotive R&D organisations) Young Researcher Pitch Competition. The networking at these events has also contributed to invitations to join, for example, two EU Joint Doctorate consortiums, EU CLEAR-DOC Programme, STINT Sweden-China, etc.

An attractive proposition

We continuously reflect on our project content and how to develop it. This has seen our research agenda develop over the years and we have also taken some lessons along the way that will shape how we continue.

Firstly, that we know where our core focal point lies – i.e., resource efficient vehicles. This means that as we seek to increase activities towards contributing to sustainable transport, we expand without losing touch with our core. We understand that this core is needed to be able to address the wider system challenge. Moreover, as a competence centre, it is the competence of this core that we are developing through our research and partnership activities, as opposed to connecting a loose network of projects. So, our clarity of vision creates a higher motivation and the security within the centre allows us to pursue "risky" or innovative research that brings about step changes in understanding by putting the pieces together. This is also central to our added value – that we are more than the sum of our parts.

Secondly, this clarity and security also allows us to build wider international network connection. In addition to understanding where our core lies, we identify where complementary initiatives can expand the efforts. This can be seen in our collaboration with the Christian-Doppler Laboratory for Sustainable Product Management and in the response to starting the *rev2021* conference – from recruiting Scientific Committee members to attracting submission. The centre's work in developing strategic links is also manifest in the recent and ongoing efforts to formalise collaborations with joint PhD agreements, leading to projects co-supervised with partner universities such as the University of Eastern Finland, the University of Le Mans, the Technical University of Munich, Gustave Eiffel University.

In summary, Eco2's research is addressing the goals we set out and is part of creating an attractive proposition for the partners, members, and the wider network.

3. The centre's sharing of knowledge and building competence

3.1. Built-in knowledge transfer

Assembling a critical mass

Eco2 works in a research area where there are significant base competences in Sweden. In fact, Sweden is one of few countries in the world to possess the competence to cover every step of the vehicle development value-chain. So, the challenge for us in Eco2 is to leverage this potential in a mutually beneficial way and contribute to resilience in the industry and sustainable transport.

The centre, which is hosted by KTH, brings together academic, industry, SME and public agency actors in a collaborative partnership. The consortium consists of KTH, Scania, AB Volvo, Volvo Cars, Alstom

(previously Bombardier prior to 2021), VTI (Swedish National Road and Transport Research Institute), Trafikverket (Swedish Transport Administration), FKG (Scandinavian Association for Suppliers to the Automotive Industry), Modular Management, Faurecia Creo, Yovinn and Marström Composite. Notable international academic network partners, which complement the Centre's competences and where Eco2 has formalised the collaboration, include the University of Graz (Austria) and the University of Eastern Finland (Kuopio, Finland). So, these partners include significant competences within engineering mechanics, vehicle engineering, vehicle development and manufacturing, modularisation, public policy, sustainable product development and optimisation – a good starting point for improving vehicles.

Creating a critical mass to undertake our research not only requires the assembly of the right quantity and quality (i.e., relevant base competences) of actors[11], it also depends heavily on the extent and quality of the interaction between these actors. Here, we work hard to build this interaction into the structures of the Centre. This is a more robust approach that complements less-formal interactions that occur within the network and has been especially valuable during 2020 and 2021 when normal interaction was restricted due to the COVID pandemic. The formal structures of the Centre are the Board, the Leadership Team (CMG, as previously referred to the Centre Management Group), the Centre Coordination Group (CCG) and a new grouping called the Researcher Group (RG). While the Board has a more traditional role, the other groupings create the emergent dynamism within the Centre. This means that they not only run the centre but more importantly create pathways for information flow, interaction, and collaboration.

An emergent organisation

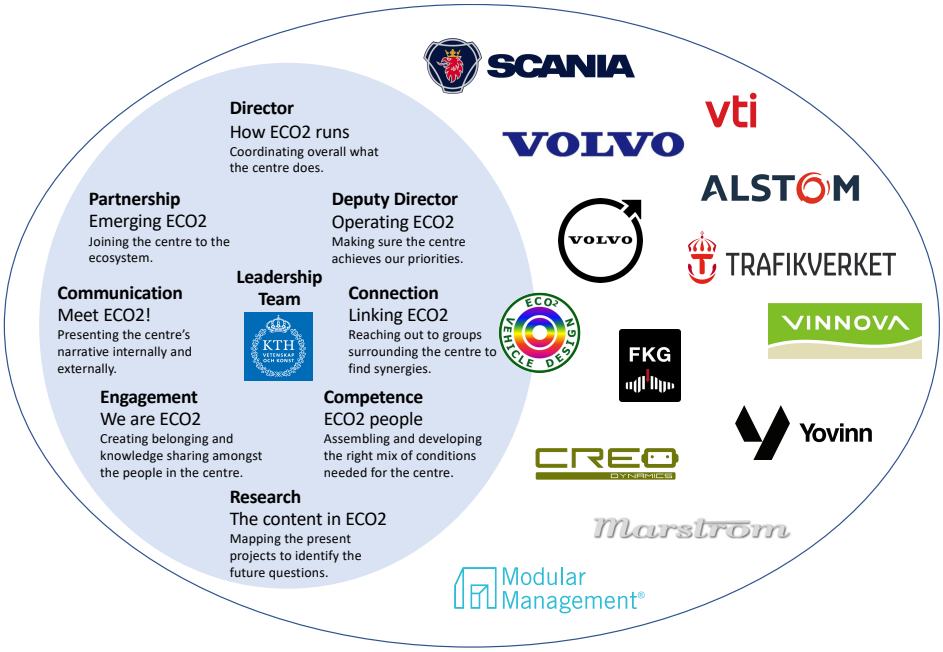


Figure 3: Eco2's Coordination Group (CCG) which includes the KTH-based Leadership Team with their distributed roles and the representatives from each partner and is an engine for collaboration in the Centre.

The Leadership Team (CMG) consists of eight academic staff members from different groups at KTH Engineering Mechanics[12]. The main responsibility for leading different development tasks within the Centre is distributed amongst the members, as shown in Figure 3. This individual responsibility is conditional on extensive dialogue amongst the team and builds on our values of consensus, trust and teamwork. This organisation brings together their individual competences and the dialogue creates knowledge transfer. Similarly, the Researcher Group, established in 2021, creates a dialogue amongst the PhD and postdoc researchers with rotating responsibility given to two members to lead activities such as discussions on "How to handle a PhD", publications strategies, informal social events, etc. These two

[11] Kenna and Berche, Managing research quality: critical mass and optimal academic research group size, IMA Journal of Management Mathematics, 2012.
[12] For the most part the same people have been involved throughout the last five years, although Mathilda Karlsson Hagnell left and Malte Rothhämmel joined.

Researcher Group representatives also attend Board meetings and interact heavily with the Leadership Team to create a good flow of information internally. Perhaps the most critical formal grouping in Eco2 in terms of knowledge sharing is the CCG, see Figure 3. The CCG consists of representatives from each partner (usually directly involved in R&D activities) and the Leadership Team and is a key driver for dialogue with the centre, including project generation and follow-up.

The strong complementary interaction between the partners and projects is illustrated in the example below. This example shows how a project idea originating at one partner can within the Eco2 environment be expanded to include multidisciplinary considerations, engagement from multiple partners, organised alongside complementary activities, and, most importantly, grow the multidisciplinary competences of those involved and support the partners in addressing an important enabler for sustainable transport.

An example of the joint project generation and undertaking

To illustrate how projects are generated and interact with each other, we can walk through the example of our industrial-PhD project on "Autonomous Driving and Motion Sickness". Directly after the Centre's financing was approved in April 2017, the Leadership Team initiated a project generation process involving all the partners. This process started by distributing an ideas template, with partners invited to discuss within their own internal groups and sketch out multiple research ideas. These ideas were to identify the "main research question", the "cross-functional conflicts" involved, and how they would "contribute to the Centre's vision". All the ideas were assembled in late August 2017 and then distributed to all the partners to reflect on what connections they saw between ideas, and to identify which ideas, that had originated elsewhere, might also be of interest to them. This reflection within partner organisations then fed into a joint project generation workshop on 15th of September 2017. The workshop involved not only partner representatives (e.g., those on the Board or CCG) but also others within their wider organisation. One idea discussed between the partners at this workshop originated from internal discussions at Volvo Cars in relation to enablers for autonomous vehicles. As a result of discussions at the workshop primarily between Volvo Cars, AB Volvo and KTH Vehicle Dynamics, the idea was expanded to include how motion sickness would be critical for the behaviour of autonomous vehicles. Like the other research ideas, this idea was discussed further internally within the partners and at the Eco2 CCG meeting on 29th September and selected to continue be jointly formulated in a PhD-project description, which the Board took a decision to approve. Ilhan Yunus was then recruited as an industry PhD (i.e., employed at Volvo Cars and PhD student at KTH). This project has allowed those involved to grow their multidisciplinary understanding of motion sickness and vehicle dynamics. This development was helped by the strategic recruitment of Georgios Papaioannou as a postdoc in the "Energy efficient driving: Tyre wear estimation and optimization" project. Georgios's prior knowledge about motion sickness complemented existing vehicle dynamics competence within the project grouping. This was also supported by the recruitment of another PhD Henrik Hvitfeldt in the "Motion cueing in driving simulators" which again brings complementary activities to Ilhan's project. This means that there is a strong grouping in these three projects, with PhDs, the postdoc, the KTH supervisors, and the industry supervisors interacting. The project is also part of the Alignment and so gains from interaction at project cluster meetings and other Eco2 events. The other projects in Eco2's portfolio have also followed a similar generation process and benefit from inclusion in the Centre's environment.

These formal Eco2 organisational groupings not only structure the work but also create informal knowledge spill-overs between the members and lead to an emergent environment where the sum is greater than its constituent parts. This can be best seen when the CMG, CCG and RG (along with other supervisors and interested centre members) meet on a quarterly basis to update on the research project clusters and discuss other topics of interest. One of these quarterly events is a Spring Workshop, which usually includes wider topics. For example, the Spring Workshop in May 2019 included a workshop on "The Sustainable Development Goals and their relation to transportation/vehicles" – showing Eco2 to be ahead of the game for our Vinnova handler who had just been tasked with getting the centres to implement something like this. These types of dynamic and provocative discussions are typical of Eco2 and, on a

separate occasion, have led to a CCG representative from an industry partner to refer affectionately to Eco2's "unconventional meetings". Over the years, we have successfully maintained good dialogue between the partners and built up a trust that is key to identifying, defining, and running joint project with joint resource allocation that are "Eco2 in nature" and push boundaries of the groups involved – as another CCG representative said when describing the Centre to some colleagues who were unfamiliar with it: "Eco2 is a real centre!".

Constructing competence development and knowledge transfer

While Eco2's research results are important and significant in terms of our pursuit of our vision, building competence within the partners is equally important. Here, this centres around understanding the challenges of industry and the wider societal needs and actively building competence development into our activities. Again, this starts with organisational structures within the centre, but includes other specific aspects. For example, our distributed leadership model creates a leadership mentoring for new members, and we have had activities such as a book club looking at gender equality issues where we read "The Masculinity Code: The 7 Virtues of Leadership" by Ulrika Sedell and Jonas Nyman, which explicitly addresses the interrelationship between management methods and diversity and equality. These contribute to fostering an inclusive environment, which is a prerequisite for Eco2's partnership.

The ambitious research agenda of Eco2 also pushes individuals to develop multidisciplinary competences and create a life-long learning environment. This is true both for project supervisors (at academic and industry partners) but also for our researchers who often are coming from very disciplinary-oriented education programmes. The multidisciplinary competences these early-career researchers develop can have long-term impacts with the Centre's partners, perhaps best illustrated by the fact that previous Eco2 Scania industry PhDs, Lars Jerpdal and Rickard Österlöf, are now supervising current Eco2 PhDs, Sara Eliasson and Jukka Hyttinen – a reinforcement of competence development. It also shows how we have used industrial PhDs (doctoral students who are employed at a company) to forge strong connects between our academic and industry partners. Similarly, mobility exchanges such as KTH Assoc. Prof. Lars Drugge working part-time at Volvo Cars; former Volvo Cars employee Per-Olof Sturesson's recruitment as a part-time researcher at ECO2; Josef-Peter Schöggl's part-time employment between our partner at CD Lab in Graz and ECO2 are examples of how such exchanges contribute to building competence at the host and transferring knowledge between partners.

The SME projects have been very effective, not only enabling the SME partners to undertake competence development work that benefits or extends their business activities, but also leading to innovative dialogue with the larger industrial partners. So, for example, Yovinn have built up new AI competence within Eco2 supported by KTH researchers and applied on a project at Volvo Cars. Modular Management have also developed their scenario planning competences through Eco2 projects involving extensive dialogue with Alstom and AB Volvo. Most significantly, Eco2's longest SME partner Creo Dynamics have, over the years, built competences in active flow control, road noise control, aeroacoustics and smart structure, and recruited former Eco2 students, which was a significant contribution to their successful purchase by Faurecia (see Section 4).

The wider impacts that result from this competence development and knowledge transfer are discussed more in Section 4, but the dynamic in the projects and between the partners in Eco2 clearly constitutes an innovation environment.

3.2. Initiatives to change the wider environment

Communicating about ECO2

In recent years we have continued to develop our communication beyond the consortium through traditional channels to the scientific community; engagement in other academic / industry forums and networks; as well as reaching out to other interested parties and the general public via traditional media and social media channels. These efforts are organised into our Communication Plan and Publications Plan which is shared and discussed with all members of the Centre. In addition to scientific publications (see Section 2 for more details), this has led to, for example, increased use of LinkedIn, ResearchGate and

the centre's website as important channels to communicate about our work. We have also had, for example, work on the effect of the COVID-19 pandemic-related restrictions on noise levels in central Stockholm receive coverage in the industry newspapers, leading to subsequent articles in all the major Swedish news media outlets. These efforts amplify the results of the centre's activities and complement efforts to communicate through traditional dissemination channels.

At the host university

Eco2 is based at KTH Royal Institute of Technology and there constitutes a core centre in both KTH's Transport Platform and the Strategic Research Area TRENoP (Transport Research Environment with Novel Perspectives). There are many inter-personnel connections between these initiatives with, for example, Eco2 Leadership Team member Peter Göransson being director of the Transport Platform, and the director of the TRENoP, Mikael Nybacka, also being a member of Eco2 Coordination Group.

Eco2's knowledge generation and competence development are connecting into the education programmes at KTH. The most direct example of this is the centre's own Eco2logy PhD course, which builds on the Eco2 fundamentals and research, and attracts PhDs from within Eco2, external PhDs, industry employees and teachers from our wider network.

ECO2logy has also served as a starting point for ECO2 members to establish similar courses at master's level in 2020. This notably includes the two new courses *Challenge-based Railway Systems Design* (7.5 credits) due to start in the autumn of 2022, and *Sustainable Vehicle Design* (7.5 credits) that started in autumn 2021. Both courses have a strong sustainable development dimension and are closely aligned to the ECO2 vision. The organisation and holding of these courses will not only mean that the centre's research and activities can have an earlier influence on students at KTH, it will also act as focal points for building competence within the centre.

Eco2 also feeds into other courses and the programmes at KTH with Eco2 members teaching in many other courses such as the PhD course *Integrated Transport Systems*, and being responsible for programmes such as the 5-year Programme in Vehicle Engineering, MSc Railway Engineering and MSc Vehicle Engineering. This is beneficial as Eco2-developed competence contributes to the inclusions of sustainability, and knowledge about how it connects to vehicle design, into the KTH education.

Leading the way

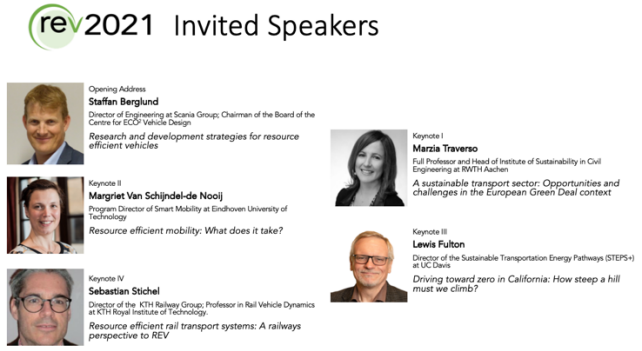
Eco2 is establishing itself as an important node in a wider international network. For example, we have established agreements with Christian-Doppler-Laboratory for Sustainable Product Management enabling a Circular Economy, Graz, Austria and Centre of Excellence of Inverse Modelling and Imaging, Kupio, Finland whose expertise complement ours[13].

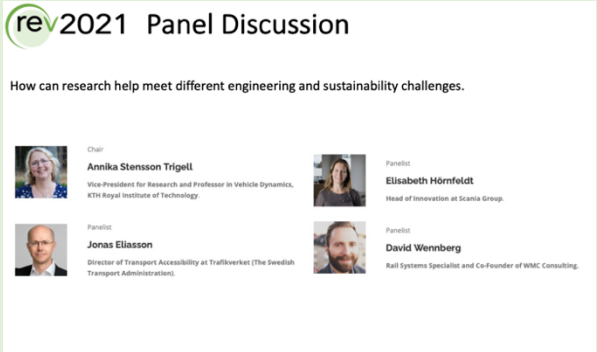
A significant achievement for the centre during the past five years in terms of pursuing our research agenda, engaging with an international network, was our establishment of the Resource Efficient Vehicles conference. This is to be continued through a *reVehicles* international committee – including an Eco2 participant – with the follow-to the first conference to be held in Graz, Austria in 2024. The conference is a conduit for Eco2 to interact and share with a much wider audience. This is a clear example of Eco2 leading the way internationally.

[13] A similar agreement is likely to follow with Gustave Eiffel University.

***rev2021* – Resource Efficient Vehicles conference**

Having identified a need for a multidisciplinary conference in this area, Eco2 began planning this event in late 2019. The reaction to these plans was very positive and we quickly recruited an international Scientific Committee. The conference took place online (as a result of the challenges of the pandemic) in June 2021, brought together over 120 participants from relevant areas of academia, industry and public agencies, including participants from 12 countries. Held over three days, it included 40 paper presentations during 13 sessions, five keynote presentations, four workshops and an expert panel discussion.





The conference showed that the subject of resource efficient vehicles has a wide appeal and is useful for uniting efforts towards sustainable transport; that Eco2's multidisciplinary topics could translate into interesting discussions during the conference sessions; and that as keynote speakers, Margriet Van Schijndel-de Nooij put it: "a de-silofication is needed" – something that the conference directly contributes to. More information, including papers and presentation recordings, can be found at www.rev2021.org.

4. The centre's utilization of knowledge and impact on partners and society

4.1. Following up on our work

Following recommendations from the Follow-Up process in 2020, we have explicitly formulated Research Objectives (see Section 2), which complement the wider perspective of our existing Intended Results for this competence centre. To track our progress towards our Research Objectives we have also created three new Key Performance Indicators (KPIs) which directly map to these objectives, which qualitatively and quantitatively list evidence in a log of how we are meeting each objective. For example, entries for Research Objective 3 can be:

[2018-09-06] Workshop in the Future Mobility Scenarios SME project with Modular Management and KTH at Bombardier. The workshop focussed on global and regional specific trends which could influence train configurations. The workshop was a step towards creating a model to transform train configurations in a resilient way for different scenarios.

[2020-11-17] New article from Lifecycle Energy Optimisation project by Bouchouireb et al on EoL modelling in the LCEO framework. The results show that the inclusion of an EOL model in the LCEO methodology impacts the design of vehicle structures and links subsystem space allocation and material use intensity to vehicle production system level energy efficiency leading to a transformation of the system level impacts.

Each such entry in the log allows a mapping towards the research objectives. This information is directly useful for centre members and leaders to see progress. Additionally, it has the added benefit of identifying information that can be communicated to a wider audience, for example, in a LinkedIn post. As the Research Objectives and this KPI framework are new, the plan is to roll it out in full in autumn 2022.

Our Research Objectives focus on the research content of our work, but the true added value of a competence centre goes beyond this. We are developing knowledge to deal with interdependent complex problems, multidisciplinary competences, and have an innovation environment, where we expand beyond the assembled core competences. This cannot be achieved outside the centre. As a result, we continue to also use our Six Intended Results and existing five Centre KPIs to inform our leadership. These have been documented in our Annual Reports since 2017 and continue to prove valuable. For example, tracking the gender balance in our organisational groupings has led to direct discussion at Board meetings about representatives and recruitment strategies; tracking the citations has served as input to a centre-wide reflection on publication and impact, which was formalised with a workshop on the topic in December 2021, and also feeding into our Publication Strategy; and tracking participation at Centre events has allowed us to see how moving online during the pandemic actually increased the participation. Such examples show the use of such data in running the Centre and give us a context to discuss our wider Intended Results as a centre and the values we want, such as a gender balance.

4.2. Impact on partners and utilization of knowledge

Eco2 is benefitting our partners, wider network and ultimately society. Within the Centre this is primarily in terms of generating new knowledge and developing competence for the members of the Centre. These primary impacts are built upon having a dynamic, inclusive, innovative, and emergent environment that also constitute secondary impacts. Furthermore, the Centre is increasingly having an impact on the wider network. Some examples of these impacts are highlighted here.

Like other areas of Swedish industry, the vehicle industry is finding it increasingly difficult to recruit the skills needed to compete on the world market. The Swedish government identified this as one of four main challenges for Swedish industry with every fifth recruitment failing completely. They identified that the quality and relevance of education is often too low and the transition from old to new jobs needs to be facilitated. In this capacity, Eco2 has a very large impact on the industrial partners with many former PhD students working at our industry partners and significantly more coming through course and programmes at KTH that are heavily shaped by Eco2 thinking. As discussed in Section 3, this includes channelling industry needs into the education, creating multidisciplinary skillsets and including wider sustainability challenges.

These types of impacts of Eco2 are illustrated below, in relation to Scania, with perhaps the most noteworthy feature being former Eco2 PhDs (pre-2017) continuing to work at Scania, leading vehicle development work and supervising the two current Scania-Eco2 industrial PhDs. This shows a now multi-generational aspect to Eco2's impact that again would be difficult to replicate outside of the Centre's setting. It is also worth noting the role of Eco2 in connecting our network partner at the "Christian Doppler Laboratory for Sustainable Product Management enabling a Circular Economy" in Graz through our shared postdoc with Scania's Sustainability Group – a quite clear and concrete example of Eco2 helping our industrial partners with sustainability challenges.

Impacts at Scania

"Scania's expectations of Eco2 have been fulfilled in terms of increased knowledge base, impact on product development, and partnership with KTH and others. Increased knowledge base means that competent engineers and researchers are one of the most important factors for Scania's future competitiveness, as well as for the Swedish vehicle industry. Over the years five Scania employees have gained their PhD degrees as part of Eco2, and several researchers have also been recruited to Scania from the Centre. With the two on-going industrial PhD projects, the Centre directly contributes to Scania's strategic recruitment of skilled engineers and researchers with doctoral degree. In terms of the impact on Scania's product development process, these former and current PhDs implement their own research into the development of new vehicles at Scania. For example, current PhD Jukka Hyttinen is delivering valuable results and knowledge, and implementing his research within a design group and helping other Scania designers with his new knowledge. In terms of strategic partnership, the Centre is a catalyst to develop competence and two-way transfer of knowledge. The focus on multidisciplinary collaboration has been a trigger for Scania internally to gather for multidisciplinary workshops

entirely dedicated to research. For example, we have had helpful workshops together with KTH researchers and Eco2/Graz postdoc to get help with implementing a sustainable product development checklist method at Scania.

The growing importance of a more sustainable vehicle development is of special interest to Scania. This topic now involves senior research staff at Scania working in close collaboration with researchers at both the academia and other companies within the centre. For example, in 2019, four members of the Energy Economy and Sustainability R&D group attended the ECO2logy: Ecology and Economy in Vehicle Design course. At that time, the topic of sustainability was still in its beginning at Scania, and out of the four participants only two were working full-time with sustainability while one was working partially, and one was the group's manager. In the backdrop, groundwork was being done for the first external LCA and the first Science-Based Target (SBT) calculations. Looking back, the Eco2 course contributed towards building competence in sustainability and in starting a discussion around the company's ambitions in this area. Now in 2022, after becoming the first heavy-duty vehicle company to have approved SBT and having presented our third-party verified BEV LCA at the Eco2 conference rev2021, it feels like the circle has been completed.

We expect an even greater impact from Eco2 on Scania in the years to come." – Scania, March 2022

The Scania impact description also highlights how the centre's multidisciplinary approach and sustainability connections have helped them in areas of "growing importance".

Similar sentiments about Eco2 impacts are stated by other partners such as *"ECO2 has given us the opportunity to focus on, and increase our knowledge in, development of autonomous driving with respect to motion sickness and development of energy efficient vehicles in simulators."* – Volvo Cars, January 2022. Such Eco2 impacts are important contributions to building resilience within the Swedish vehicle industry at a time of rapid change.

Getting help within Eco2 with tackling future challenges is also something that Volvo Trucks see as an impact, highlighting that *"ECO2 plays an important role as an independent platform for the Swedish vehicle industry to work together on future research and development"* – again indicating that the type of collaboration, between competing companies, that Eco2 has successfully built up over the past 15 years should not be taken for granted, and could be difficult to replicate outside the context of the centre.

The opportunities provided within Eco2, and their impacts, are even more apparent with our SME partners. Throughout Eco2's past we have engaged SMEs as partners and emphasised their participation in the knowledge generating activities as members of CCG and the Board. The Centre context means that their role is as highly flexible specialists, who can quickly exploit new knowledge to transform basic research into applied innovations, and this has been a key element in the collaboration strategy.

For example, SME partner Yovinn had little prior knowledge about artificial intelligence (AI) when they began their SME project "Tools for Identification of Eco-design Potential" together with Volvo Cars. Although the direct activity in the project was within a resource efficient vehicles context, a follow-on impact for them was that they gained AI skills that subsequently enabled them to undertake a project with a client to automatically generate designs for protective covers. So, the Centre is resulting in new business opportunities for partners.

Similarly, Modular Management who joined Eco2 in 2017, have during the last two years worked on scenario modelling SME projects. This activity started together with Bombardier (now Alstom) and came to involve Volvo AB during the last year. The projects have allowed them to take their core competence in modular design and build new competences in scenario modelling as they study how modular product architectures can meet future needs. The work has resulted in three Master theses as well as the subsequent recruitment of two new employees.

This opportunity to undertake long-term competence development in Eco2 beyond day-to-day core business and to converge these into innovative business opportunities is best illustrated in the Creo Dynamics success story below.

Eco2 and Creo Dynamics: A joint success story

Creo Dynamics have been involved in Eco2 since the start in 2006 (when they were A2 Acoustics). Over the years they have taken part in several SME projects in the centre. They have used these opportunities to work together with the larger industries. For example, their most recent project was together with Volvo Cars in 2020 and looked at using active noise control as a way to improve interior noise comfort while reducing weight. Often these projects have allowed them to host a master student whom they subsequently hired to retain the competence developed. Additionally, the projects have led to them patenting technologies. They also directly hired a former Eco2 PhD student. So Eco2 has helped them to build competence and grow their business. Ultimately, this has contributed to French automotive supplier Faurecia buying a 70% stake in the company, with Creo Dynamics becoming an innovation hub in the form of a separate business unit within Faurecia. The impact of Eco2 on Creo Dynamics is summarised in their own presentation slide in Figure 4.

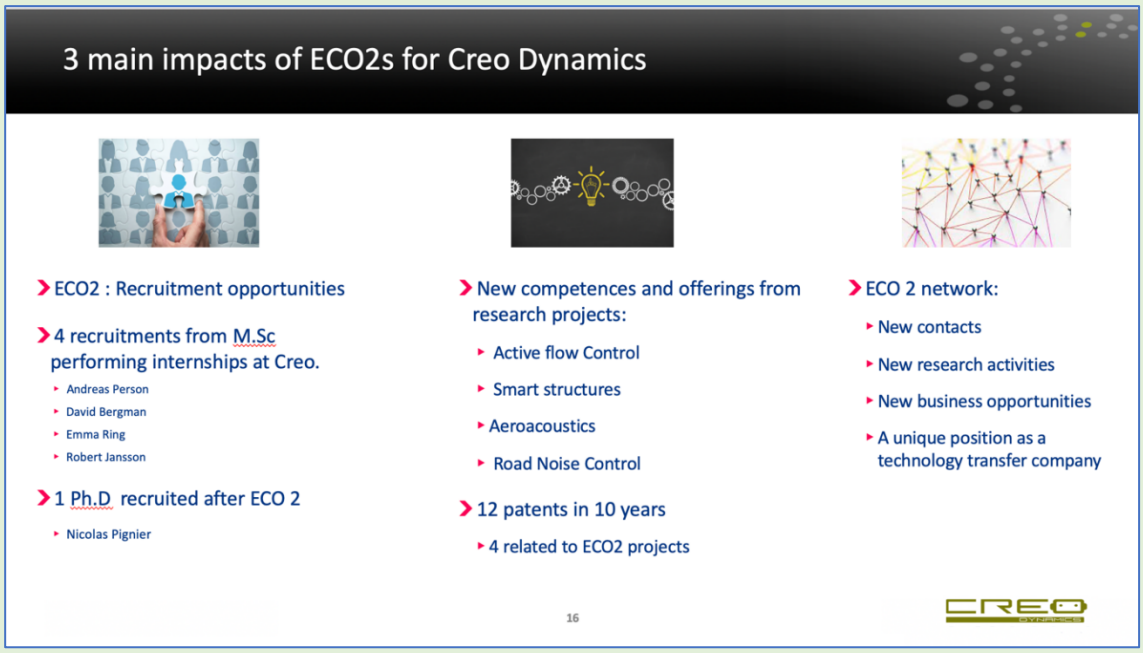


Figure 4: Slide from the presentation "Creo's involvement in ECO2: Impact of research activities on the development of an SME" presented by Christophe Mattei, Faurecia Creo Dynamics on 14 December 2021.

The opportunities in Eco2 and how they lead to innovation is also something academic partners VTI and KTH highlight, along with increased industrial relevance for their research. With European funding increasingly targeting high TRL applications there is limited scope to explore new opportunities. That the Centre has comparatively long-term funding, allows the industrial partners to have a longer-term perspective on how research results feed into their own development processes. This together with other centre values (perhaps most importantly trust) and a sense of jointly pushing the boundaries lead to what VTI refer to as "risky research" – not in the sense that it is high stakes but rather that it is research that might not be envisaged or undertaken without Eco2. So, the Centre is encouraging innovative research[14]. The effect of the centre on growing competence in academia is also illustrated by the fact that the current Eco2 director Ciarán O'Reilly and the latest member of the Leadership Team Malte Rothhämel have positions within Conceptual Vehicle Design and Vehicle System Technology – multidisciplinary subject topics that were formulated and established in large part thanks to Eco2.

Eco2 is therefore an innovation environment for its partners. As Yovinn put it *"Our Eco2 work sticks out from our other core work, and we don't know where we will arrive with it, but it's innovative. Yes, money*

[14] This even goes as far as the Centre itself being the focus of Schöggl et al upcoming journal publication on "Barriers to sustainable and circular product design – A literature review and empirical prioritisation in the European automotive industry".

is a prerequisite but it's more about the opportunity to do something that makes a difference and is cool". The sentiment expressed here is shared by all the partners in Eco2.

Eco2 is also having direct impacts on society, even if our main activities are on supply-side questions, which indirectly impact on society. Examples here are our work on night-time delivery. This was done in collaboration with Stockholm City and has seen initial noise measurement – a potential showstopper for increasing traffic efficiency by moving to off-peak hours – result in extended trials, a revision of local policy on permit-based night-time deliveries, and an expansion of this activity at an international level (EIT Urban mobility project, collaboration with the City of Munich). The initiative has since been highlighted as one of ten significant impact cases with societal relevance under KTH's strategic research areas, and resulted in several national media appearances.

5. Plan forward

The Eco2 story is that we are building and sharing knowledge about how to resolve existing and new conflicting interdependencies in vehicles, using this to develop ways to increase their resource efficiency, and integrating sustainability considerations. In doing this we are driving resource efficient vehicles research, improving vehicles, and contributing to sustainable transport and the SDGs. We have also established an innovation environment, where we are building multidisciplinary competences within the partners to deal with sustainability challenges and contributing to increasing resilience within the Swedish-based vehicle industry's ecosystem.

While vehicle design is the primary focus application, much of work is readily applicable to other systems. This is thanks to multi-functional (solution or technology independence) and multi-scalar (scale independence) approaches. For example, our work on efficient material usage and life cycle energy optimization could easily be applied to other areas and scales – indeed we have had interest in applying these to marine horticulture. So Eco2 is a "goldmine" for models and approaches to life cycle design processes which could be connected into other system-level approaches such as infrastructure and socio-economic models. However, this is not to say that Eco2 itself would expand or shift focus to these areas. Rather, it is to highlight the potential to spin-off our work into other initiatives.

For Eco2, the journey continues towards resource efficient vehicles in a sustainable society. We have been maturing for the past 15 years with each phase seeing a step forward in understanding and scope. We see this continuing in the coming five years and beyond, with continuing development of core areas to meet not only present but also future emerging challenges. Here we see further opportunities to develop multidisciplinary enablers to meet sustainable requirements through greater *alignment*. This includes, for example, how new configurations such as high-capacity transport (HCT) will require new dynamic stability models for the longer and heavier vehicles; how electric motors will pose new cooling requirements; how encapsulation can reduce noise but must maintain air flows; how the state-of-charge of batteries will affect vehicle performance losses, etc. We also see opportunities to increase the multifunctional *density* through new concepts. Some examples include the integration of multifunctional structural batteries; connecting new usage profiles with vehicles dimensioning, also taking into consideration outlying cases; vehicle packaging configurations that make better use of materials and space; etc. These enable and directly contribute to increased resource efficiency.

Of special interest is also how we plan to expand activities that lead to *transformation* of transport. It's important to distinguish here that it is not our intention to switch focus to higher system consideration (such as transport or societal planning), but rather to grow into the research gaps where vehicles connect to the wider systems.

Here we, firstly, see opportunities to continue our cross-scalar modelling (e.g., life cycle energy, etc.) tying into life cycle assessment and to expand on questions around vehicles interaction with the infrastructure, for example, how battery charging infrastructure couples to vehicle design; how charging times connect into vehicle capacity and transport speed and efficiency, etc.

We, secondly, see opportunities in continuing to connect our resource efficiency work to circular economy thinking. So, for example, to look at questions surrounding the reuse of materials over life cycles and,

also, the conflict between efficiency-motivated replacements and maximizing the reuse of components. This includes challenges around how to integrate mid-life upgrades. Our focus on functions (rather than technologies or products) is again advantageous in the context of transitioning to circular economy, with much of our work in the alignment and density clusters providing greater transport function (e.g., increased transport range), while transformation looks to identify and leverage tipping points.

Thirdly, we see opportunities to expand on current scenario modelling work and to use the platform of the Centre to continue to have a dynamic discussion about the future challenges we face. So, for example, regarding trends such as circularity, legal restrictions, changing demographics, resource availability, etc. This type of work is illustrated in the most recent SME-led project in 2022 in Figure 5. There is an opportunity here to further connect the research projects and the partners and to increase the resilience within the vehicle industry to future challenges.

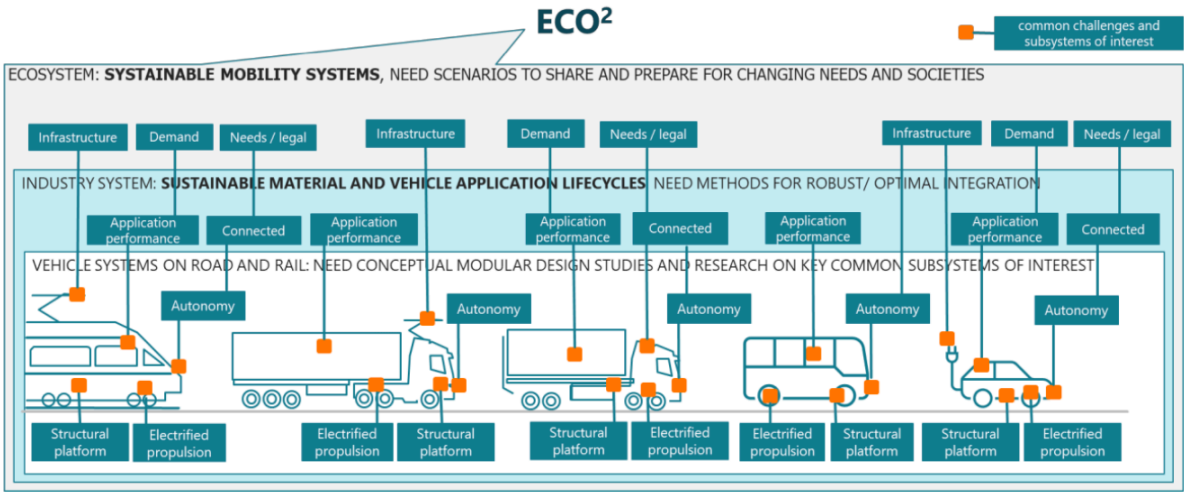


Figure 5: SME-led project on Sustainable Mobility Scenarios (picture from Modular Management).

As before, the generation of the projects will be jointly undertaken (in autumn 2022) to ensure common Eco2 projects. New core partners and SMEs will be added with the primary consideration being how they complement our existing competences. For example, we have had preliminary discussions with Region Stockholm to enhance public considerations in our work. There is scope also to expand within the existing partners with, for example, discussions are ongoing to include Volvo Cars Sustainability Centre, and to include more engagement with the road units within Trafikverket. We also anticipate that wider network will grow as our *reVehicles* conference initiative continues and *rev2024* is held.

We see this approach – of a strong Swedish-based core with a growing, looser international network – as the model to continue. We see opportunities to continue to engage in EU projects. However, given the often-high TRL-levels of such projects, we will continue to prioritise opportunities that are in line with our fundamentals (e.g., pre-competitive function focus) and core values (e.g., consensus, dialogue, gender-balance, etc.), and believe this is how we can be most effective in developing our innovation environment and in leading the way for others. We believe we can have a strong Swedish-based core and be world leading at the same time.

We expect these future developments to follow a similar "s-curve" pattern, as we have before, with each step building on the last. As an impactful centre, in what is an essential topic both domestically and globally, we believe that we have an important mission to continue. We also believe that we are successfully *driving resource efficient vehicles in a sustainable society.*

Publication Information

Ciarán O'Reilly, Peter Göransson, Romain Rumpler, Jenny Jerrelind, Susann Boij, Carlos Casanueva Perez, Malte Rothhämel, Per Wennhage. Eco2 Vehicle Design: Self-evaluation report 2022. The Centre for ECO^2 Vehicle Design, KTH Royal Institute of Technology, 2022.

Contact information

The Centre ECO2 Vehicle Design, KTH Royal Institute of Technology
Teknikringen 8, SE-100 44 Stockholm, Sweden
www.eco2vehicledesign.se