UNICORN

Unveiling Innovation Potential of Circular Approaches in Automotive Electronics and Beyond

Net environmental impact assessment of emerging mobility service systems

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Short description of the content of the deliverable

This deliverable describes the definition and impact evaluation of the UC5 of the UNICORN project. The deliverable provides insights into what the expected net impact improvements would be of a sustainable mobility system compared to the current system.

Disclaimer

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List of acronyms

ADAS	Advanced Driver Assistance Systems
CA	Circularity Assessment
CCI	Circular Cars Initiative
EF	Environmental Footprint
EGDC	European Green Digital Coalition
EV	Electrical Vehicle
FE	Functional Electronics
GEN 1	Generation 1 scenario
GEN 2	Generation 2 scenario
ICE	Internal Combustion Engine
IMU	Inertial Measurement Units
LCA	Life Cycle Analysis
MaaS	Mobility-as-a-Service
OE-A	Organic and Printed Electronics Association
OEM	Original Equipment Manufacturer
PEF	Product Environmental Footprint
REF	Reference scenario
RIA	Research & Innovation Activities
RII	Resource Intensity Index
SAE	Society of Automotive Engineers
UC	Use case
VaaS	Vehicle-as-a-Service

Executive summary

The objective of this study is to provides insights into the functioning of a circular car within a sustainable, circular mobility system and in particular to assess the expected environmental impact improvements of such a system compared to the current mobility model.
This report applies the Net Environmental Impact Methodology as outlined by the public UNICORN deliverable (D4.1. This methodology is based on the European Green Digital Coalition's Net Carbon Impact Assessment methodology and is used to provide insights into the impact improvements related to the transition to a circular mobility system.

Corresponding to the industrial use cases in UNICORN, three levels of increasing circularity are defined for this study. This definition is established through a combination of literature research and stakeholder input gathered during a workshop held with industry representatives. The levels were set in such a way as to align with the lifetime optimisation and utilisation improvement pathways of the Circular Cars Initiative (CCI), and these were translated into focus areas of 'Car sharing and Mobility-as-a-Service (MaaS)' and 'Safety & Automation'. The defined circularity levels in this report are:

- REF – The current car ownership model – Level 1 circularity (CCI)
- GEN1 – A Vehicle-as-a-Service (VaaS) model – Level 2 circularity (CCI)
- GEN 2 – An advanced Mobility-as-a-Service (MaaS) model – Level 4 circularity (CCI)

Each of these levels is defined in more detail in this report to create clear scenarios that are compared. Boundary diagrams are constructed for the systems to clarify the life cycle steps that are considered in the evaluation. Key variables influencing the scenarios were quantified using literature data. Potential effects of the GEN1 (VaaS) and GEN2 (MaaS) scenarios—enabled by the integration of functional electronic (FE) sensors—were identified and quantified for a city of 500,000 inhabitants. The identified potential effects have been classified as either first-, second- or higher-order effects, in accordance with the requirements of the Net Environmental Impact methodology. The scenarios described in this report directly serve as the basis for the net environmental impact determination of the circularity levels, with the aim of quantifying the environmental benefits resulting from changes in the mobility system.

The results demonstrate that the mobility shift, facilitated by FE sensor implementation, substantially reduces the environmental impacts associated with the mobility for a city of 500,000 people. The implementation of FE sensors in vehicles in both VaaS and MaaS, results in a large decrease in net impact for only a small initial impact associated with the production of the FE sensors themselves. The impact reduction resulting from the implementation of FE sensors is system-based; MaaS and VaaS systems favour decentralisation of ownership, thereby increasing material efficiency by increasing the use rate of cars and therefore decreasing the total number of vehicles required. In this case, therefore, the FE sensors act as enablers to generate this mobility system change, which results in the impact reduction.

1 Introduction

1.1 UNICORN project

To strengthen the European Union's (EU) global competitiveness and resilience, the European Commission's updated Industrial Strategy[1] calls for accelerating the green and digital (twin) transitions of key European ecosystems. In that perspective and funded under the call 'HORIZON-CL4-2021 Digital and emerging technologies for competitiveness and fit for the Green Deal', and more specifically the topic 'Functional electronics for green and circular economy'. The UNICORN project aims to support the development of functional electronics for accelerating the transition of the automotive industry to a circular economy. It foresees functional electronics as an enabler and catalyst of Europe's mobility twin transition.

At the convergence of unconventional nano-electronics, flexible, organic & printed electronics and electronic smart systems, the term 'Functional Electronics' (FE) was introduced as part of the EU-funded project 5E[2] in 2020. A FE solution is defined as a system that integrates advanced functionalities with physical components, extending beyond traditional electronics to deliver specific services to users. It encompasses the ever-increasing capability to integrate key digital technologies with cognitive functions, shifting from purely physical integration to functional integration[3].

The UNICORN project has been set up to support fundamental systemic changes throughout the automotive electronics value chain. It aims to demonstrate the capability to design and develop innovative green and circular technologies for automotive electronics, based on Research & Innovation Activities (RIA) on four electronic systems taken from industrial Use Cases (UC 1-4) for a battery casing, a dashboard, a seat/door system and a tire. These FE solutions (1) encompass lightweight, low impact and/or biobased materials for (flexible) substrates, films, encapsulation, inks, solvents, adhesives and flat cabling and interconnects; (2) validate resource/energy efficient, net shape, additive, printing, encapsulating and (reversible) bonding manufacturing processes for circuitry, sensors, gauges, antennas, interconnects; and (3) implement design for material circularity via reversible design, modularity, form factors to increase disassembly and recovery of valuable materials. These RIAs of UC1-4 have their main focus on embedding eco-design principles in their development and ensuring net beneficial effect on climate change mitigation (Green (functional) electronics), but the 5E project vision paper also stressed the importance of exploring the potential of FE in enabling Circular Economy technologies & strategies ((Functional) Electronics for green)[4]. This is performed in the scope of this report as a Use Case 5 (UC5) included in the UNICORN project. Within the scope of the UNICORN project, the environmental impact of all the UCs (and their different generations) is determined using a net impact measurement methodology that was developed as a public deliverable in the scope of the project.[5] This methodology is based on the 'Net carbon impact assessment methodology for ICT Solutions' developed by the European Green Digital Coalition (EGDC)[6]. This methodology is applied to evaluate the impact of UC5 in this document. The current version of this document sets the boundary

[1] European Commission (2020) Updating the 2020 New Industrial Strategy: Building a stronger single market for Europe's recovery https://commission.europa.eu/document/9ab0244c-6ca3-4b11-bef9-422c7eb34f39_en
[2] Federating European Electronics Ecosystems for Competitive Electronics Industries - 5E | Project | Fact sheet | H2020 | CORDIS | European Commission https://cordis.europa.eu/project/id/825113
[3] Further definition is provided in section 4.1

[4] Jérôme Gavillet, Kévin Le Blevennec, Emmanuelle Pauliac-Vaujour, Elise Saoutieff, Bernard Stree, et al.. Vision paper on the role and impact of functional electronics on the transition towards a circular economy. 2020. ffhal-03185801f

[5] Deckers, Jana, Karolien Peeters, Stefanie De Smet, and Pieter Willot. 2025. "Methodology for Net Impact Measurement of Functional Electronics Integration". D4.1 of Horizon Europe UNICORN Project, Grant number: 101070169

[6] EGDC (2024) Net-Carbon Impact Assessment Methodology https://www.greendigitalcoalition.eu/net-carbon-impact-assessment-methodology-for-ict-solutions/

conditions for this assessment, it defines the reference scenario and the solution scenarios and identifies the first, second and higher order effects of the implementation of the solutions.

1.2 Aim and purpose of the study (UC5)

The aim and purpose of this study, corresponding to the Use Case 5 of the UNICORN project, is to provide insights into how a circular car would function in a sustainable, circular mobility system and what the expected impact improvements would be of this system compared to the current system. The study will focus on actions fitting in the '(Functional) electronics for green' approach, focusing on how FE can contribute to Circular Economy systems and strategies, and not prioritising the environmental impact of the production of the FE (Green (Functional) electronics). The definition of what this circular mobility system would look like should be based on existing frameworks but should also include direct industry input to ensure alignment with industry focus and vision for the future. Furthermore, the definition must include how FE can contribute to achieving this system.

The circular mobility system should focus on improving the efficiency of mobility in terms of resource usage. This study further aims to include the potential for FE in supporting this efficiency improvement ((Functional) Electronics for green). The scope of the study and the integration of FE in a circular car has been co-created through market and industry input on what the most important drivers are to increase mobility efficiency and how the integration of FE can support this.

1.3 Approach

To provide insights into the potential impact improvements of the transition to a circular mobility system, this report applies the environmental impact methodology that was developed in the scope of Deliverable 4.1 of the UNICORN project.[7] The study identifies the first, second and higher order effects of the implementation of the solutions.

This environmental impact methodology provides a general approach that assesses the environmental impact of a defined context in a broad sense, taking into account lifecycle and circularity data together with a net environmental impact assessment in a uniform way. This methodology is applied to all UCs 1-5 in the UNICORN project to provide a common foundation for the impact calculations, where this report presents the results of the application to the UC5. Due to the different nature of the UCs 1-4 and UC5, the focus of the UC5 is less oriented towards the lifecycle and circularity assessment part in comparison with the UC1-4 evaluations, and with increased focus on the net environmental impact assessment part that specifically includes systemic, higher order effects to shed light on the impact of systemic mobility changes that are included in the UC5.

[7] Net Environmental Impact Methodology available online at: https://project-unicorn.eu/resources/

2 Definition of the study scope

This study aims to clarify the value of a circular mobility system and the role that FE can play in this. The process of defining the scope of this study combines insights from literature with an applied approach that captures industry input, connecting the theoretical insights and vision with direct, practical insights to define a broadly accepted scope.

2.1 Literature framework

To provide insights into how a circular car can function in a sustainable, circular mobility system, the definition started from the vision of a 'circular car' that was defined in the Circular Cars Initiative (CCI). The CCI was formed by the World Economic Forum and the World Business Council for Sustainable Development with the overarching goal to achieve an automobility system that is convenient, affordable, and targets a 50% reduction in absolute carbon emissions by 2030. The CCI is a private/public collaboration that represents an orchestrated industry effort to rethink the automotive value chains and business models using a systemic approach. In two reports, different transformation pathways with corresponding circularity levels are proposed[8,9]:

- Energy decarbonisation
- Material circularity
- Lifetime optimisation
- Utilisation improvement

The transformation pathways of energy decarbonisation and material circularity are directly connected with the materials and products used ('Green (functional) electronics') and are the primary focus of the other use cases of the UNICORN project UC 1-4. The transformation pathways, lifetime optimisation and utilisation improvement are represented in this study and focus primarily on '(Functional) Electronics for green' strategies.

The CCI further defines different levels of circularity ranging from 0 to 5:

- Level 0 - No circularity – Make-use-waste mentality
- Level 1 - Low circularity – Silo optimisation
- Level 2 – Moderate circularity – Product improvement
- Level 3 – High circularity – Aligned incentives and lifecycle optimisation
- Level 4 – Full circularity – Full circular value chain in as-a-service models
- Level 5 – Net positivity in system - Ecosystem optimisation

The descriptions in these levels show a shift from a distributed, individually tailored optimisation model in a standard car ownership model of levels 0-1, to making a stepwise transition into a connected ecosystem with a focus on service offerings instead of vehicle ownership (levels 4-5).

2.2 Industry input

From the existing literature frameworks, a workshop was structured to collect industry input with the purpose of further scoping this study. This workshop was conducted together with organic and FE industry experts, mainly associated with brand owners and original equipment manufacturers (OEM) from the automotive industry and was held following a member meeting of the Organic and Printed Electronics Association (OE-A) in Echternach, Luxembourg, on September 20, 2023.

The industry participants were asked to prioritise essential focus areas for the future of mobility. Three clear focus areas were then identified:

[8] Raising Ambitions: A new roadmap for the automotive circular economy, 2020, World Economic Forum

[9] Driving Ambitions: The Business Case for Circular Economy in the Car Industry, 2022, World Economic Forum

- Electrification
- Car sharing and Mobility-as-a-Service (MaaS)
- Safety & Automation

The workshop elaborated more on each of these future focus areas and aimed to identify further insights into the relevance and opportunities, but also on the boundary conditions and barriers. It was also defined whether these focus areas are expected to be driven by technological innovations or by societal behaviour, and finally, a link was made to the different transformation pathways of the CCI.

The focus areas on electrification and safety & automation were deemed by the industry audience to be innovations that were mostly technology-driven, and progress on these areas is achievable mostly through technical innovations from within the industry.

'Electrification' was identified as directly related to the energy decarbonisation pathway, as the shift from fossil fuels to (green) electricity decouples the usage of the car with the consumption of fossil fuels, and the vehicles do not emit CO_2 while driving. Boundary conditions were mostly related to the charging infrastructure development, which needs to match the transition speed towards electric vehicles and to the availability of green electricity to use for charging the vehicles. Also, the convenience that is typically associated with an automobile was identified as a boundary condition for a successful transition, with a focus on fast charging and an action radius comparable with internal combustion engine (ICE) vehicles. Identified barriers were the availability of raw materials, especially for the production of batteries and their recyclability. The industry feedback positions the future mobility on 'Electrification' almost exclusively in the category of 'Green (functional) electronics' through association with the energy decarbonisation pathway and is therefore not a specific focus for the UC5.

The future focus area of 'Safety & Automation' was considered of the utmost importance for industry. Safety is considered a must-have, and it is a critical requirement in all other developments towards circularity. Automation is seen as an important area that will allow improved safety, and there are considerable opportunities identified in this area for FE. An important requirement to progress in the area of automation is related to interactions and communication between vehicles, road users and objects. Sensors that could be made from FE serve as an essential source of information to allow more advanced automation features to become a reality. Furthermore, the focus area of 'Safety & Automation' was associated with improved maintenance resulting from better monitoring and improved lifetime due to lower amounts of accidents. Progress on the focus area of 'Safety & Automation' was also linked to and beneficial for the focus area of 'Car sharing and MaaS'. This connection was ascribed to their contributions towards shifting the end-user mindset of looking at the need for mobility being delivered as a service, rather than something that is provided by a self-owned vehicle. The links between the focus area of 'Safety & Automation' and the transformation pathways were not as straightforward as for 'Electrification', and they were initially difficult to pinpoint for the workshop participants. A subsequent deep dive exercise performed during the workshop did identify important links between the focus area of 'Safety & Automation' and the 'Lifetime optimisation' pathway. A clear purpose for FE to contribute to a sustainable future mobility was also identified through this focus area. These results position the future mobility focus on 'Safety & Automation' in the category of '(Functional) Electronics for green' and should therefore be included in the scope of UC5.

'Car sharing and MaaS' was defined as a focus area that is mainly behaviour-driven. Industry does not perceive progress on this focus area as being solely driven through industrial innovation but states the transition towards a system with shared mobility and MaaS is for a large part, driven by actions and demands of the end-user. Most of the identified boundary conditions and barriers that were identified during the workshop were directly related to consumer behaviour and included aspects such as convenience, availability, consumer mindset and others. Other barriers were related to questions related to (the functioning of) the business model, such as population density or a fragmentation between different service offering platforms, indicating that the business model for MaaS models is not yet fully mature. Many of the identified opportunities were related to the efficiency of mobility (rethinking the need for mobility, resource efficiency, fewer parking spots required etc) or even showed an explicit connection to the focus area of 'Safety & Automation' (fully automated service, freeing up time as a passenger etc). Also in this area, there were opportunities identified for FE to play a role. New sensors using FE can generate useful data streams (e.g. on vehicle usage, occupation, …) that can be analysed to optimise and direct the MaaS business model. The industry members directly associated the focus area of 'Car sharing and MaaS' with the transformation pathway of 'Utilisation improvement'. These results position the future mobility focus on 'Car sharing and MaaS' in the category of '(Functional) Electronics for green' and should therefore be included in the scope of UC5.

2.3 Defined scope

The combination of the transformation pathways that were defined in the CCI, with the industry priority focus areas that were defined and evaluated during the workshop, serves as the basis for defining the scope of UC5.

Actions towards 'Functional electronics for green' are the main focus of the UC5, and this category is associated with the transformation pathways 'Lifetime optimisation' and 'Utilisation improvement' included in the CCI. The industry input defined 'Safety & Automation' and 'Car sharing and Mobility-as-a-service' as priority focus areas that are associated with these transformation pathways. The scope of UC5 has therefore been defined to have a strong connection with these focus areas, while at the same time including the potential of FE for these focus areas.

Within the context of the UNICORN project's UCs, future innovations and novel technologies are introduced from an initial reference (REF) level - representing the current state-of-the-art, to an intermediary, generation 1 (GEN1) stage and then to a final stage (GEN2). For the definition of the scope of UC5, these 3 levels are coupled to the circularity levels defined in the CCI that are most relevant in the scope of the project:

- REF – The current car ownership model – Level 1 circularity
- GEN1 – A Vehicle-as-a-Service (VaaS) model – Level 2 circularity
- GEN 2 – An advanced Mobility-as-a-Service (MaaS) model – Level 4 circularity

Within the context of UNICORN, we specifically look at the role of the automobile and the contributions of FE in the transition towards a MaaS model. The environmental impact of the systems that represent these 3 levels can be defined through the net impact measurement methodology that has been developed in the scope of the UNICORN project. The application of this methodology is performed in the following chapter, which focuses on the definition of the reference situation, the solution scenarios and the identification of the first, second and higher order effects. This information will enable more precise calculations of the net impact of various mobility models in the future.

3 Methodology for net impact measurement of FE integration for UC5: Application and Interpretation

This chapter follows the Methodology for net impact measurement of FE integration that was published as the public Deliverable 4.1 (D4.1).
This methodology outlines a comprehensive approach to assess different environmental and circularity aspects of the integration of FE into various applications. The methodology aims to capture both positive and negative effects, including all direct and indirect effects of the integration, comparing scenarios with and without FE integration.
The methodology enables UNICORN consortium partners and other stakeholders in the FE sector to evaluate and enhance the environmental and circularity performance of their innovations and solutions. The application of the methodology in this study aims to identify the contributions of alternative mobility models and the implementation of FE to achieve a net positive impact. This is achieved by effectively reducing environmental burdens through consideration of multiple environmental aspects and trade-offs between carbon footprint, material circularity and other impacts.

The methodology leverages existing methodologies and standards such as the EGDC's Net Carbon Impact Assessment, the ISO 14044, and Product Environmental Footprint (PEF) for Life Cycle Analysis (LCA), and ISO 59020 standard for Circularity Assessment (CA) to the specific context of FE. Figure 1 illustrates that the Net Impact Assessment is supported by relevant elements of an LCA and CA.

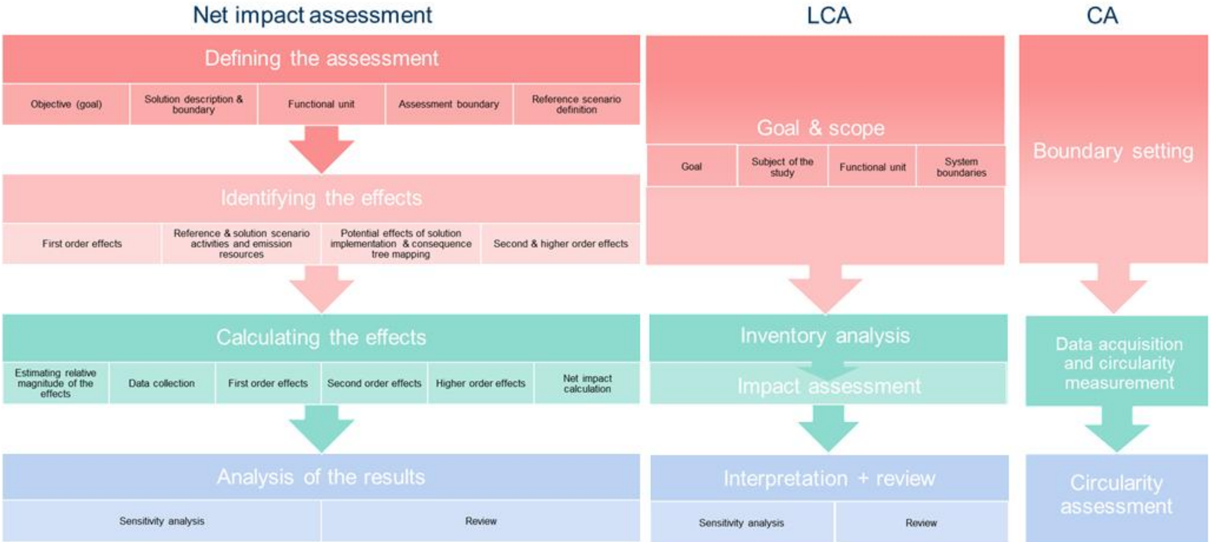

Figure 1: Overview of the different assessment steps of a net impact assessment (modified from EGDC's Net Carbon Impact Assessment steps), Deliverable 4.1 of the UNICORN project (2024)

3.1 Defining the assessment

3.1.1 Assessment objective (Goal)

The reason for carrying out this assessment is to determine the high-level impact improvements arising from a transition towards a sustainable, circular mobility system, from the perspective of an automobile. The process of defining what this circular mobility system would look like has been performed through a combination of literature and industry input (see Chapter 2). It includes the role of FE in this transition with a focus on the improvement of the efficiency of mobility in terms of resource usage and lifetime optimisation. The central focus of the assessment is the automobile, in which the FE will be installed. However, the solution scenarios (GEN1 and GEN2) will induce a modal shift, and consequently, other modes of transportation (e.g. public transportation) are also considered in the impact assessment as substitutes to car travel.

The results of the study are intended to provide more specific insights into the sustainability and circularity improvements and contributions of a ‘Functional Electronics for Green’ approach, which focuses on high circularity ambitions of the pathways “Utilisation improvement” and “Lifetime optimisation”. The results from this assessment aim to provide recommendations for system validation by project partners, to be applied beyond the materials, products and systems included in the UNICORN project, and the project itself.

The assessment will explore the potential implications of introducing FE into automobiles in the context of a MaaS system. This deliverable has a dissemination level Sensitive (SEN) and is not meant for open publication. The results of the assessment are primarily intended as guidance for future (strategic & product) development on FE by the UNICORN project partners.

3.1.2 Solution description & boundary diagram

3.1.2.1 GEN1 - VaaS

GEN1 describes a first-generation system where a vehicle is used in a shared manner. The system is operated by a central organisation that offers the Vehicle-as-a-Service (VaaS) model to consumers, which can make a reservation for a specific vehicle when they need it. This corresponds to a Level 2 system in the CCI. GEN 1 is based on VaaS systems that are currently active on the market, such as Poppy, Cambio (BE), MILES Mobility (DE & BE), and Free2move (cities throughout the EU). In this scenario, these shared vehicles are used by end-users to meet their mobility needs in combination with the use of other transportation means.

A user can reserve a vehicle for a certain period and is charged accordingly for the usage of the vehicle, with a fraction of the cost related to the time the vehicle has been reserved, and a fraction of the cost related to the kilometres driven. This is typically complemented with a subscription cost to the system. The consumer can either drive the vehicle during the reserved period, but the car can also be parked during this time, making it unavailable for other subscribers in the system.

In the scope of GEN1, a system is considered where the vehicle can be left in any available parking space in the city, from where it is available for pick-up by the next user. The location of all vehicles in the system is monitored centrally through the location device that is standardly present in a modern vehicle (used for GPS purposes). Users will be appointed the vehicle closest to their location that suits their requirements (e.g. in terms of size). The reservation of the vehicle and selection of the users’ preferences will be done through an app. This is therefore associated with an additional energy requirement

In GEN1, these vehicles are equipped with hardware sensors, which are absent in the reference situation of private car ownership. These additional sensors consist of FE devices that will support the monitoring of the vehicles in the VaaS system and focus on predictive maintenance. These sensors are used in the engine, brakes, suspension, tires, batteries, fluids, etc. FE have the potential to be used for many of these applications. The continuous monitoring of the status of car parts can improve the maintenance effectiveness and decrease the chances of vehicle failures, which might otherwise be challenging in a car not managed and monitored by a single user. These sensors are diverse in requirements and function, and it is outside of scope of this deliverable to define the exact type of sensors required. To be able to perform the environmental impact assessment, including these additional sensors, the average environmental impact of the sensors included in as defined in the UNICORN project, was used as a proxy for the impact of the predictive maintenance sensors included in the GEN1 assessment. The included FE sensors are sensors integrated in a battery casing, in a dashboard module , a seat belt reminder (SBR) system and a tyre pressure monitor.

The boundary diagram in Figure 2 includes all the activities that are considered within the scope of the assessment. The production of the electrical vehicle (EV) represents the production of an EV as included in the REF (see Section 3.1.5). The production of the FE sensors included in the GEN1 vehicle is considered an additional step in the life cycle. During the use phase, the impact of charging the EV (electricity use) is considered, as well as driving the EV and the impact of the time that the vehicle is not being driven and occupies a parking space (EV parked). It also considers the impact of the necessary services, such as maintenance and the use of the operating system of the car booking application. To correctly model the impact of a VaaS system, the impact of its implementation on the use of alternative mobility means is also taken into account within the boundaries of the model, as the shift in the mobility system is expected to influence the distribution rate between these mobility means.

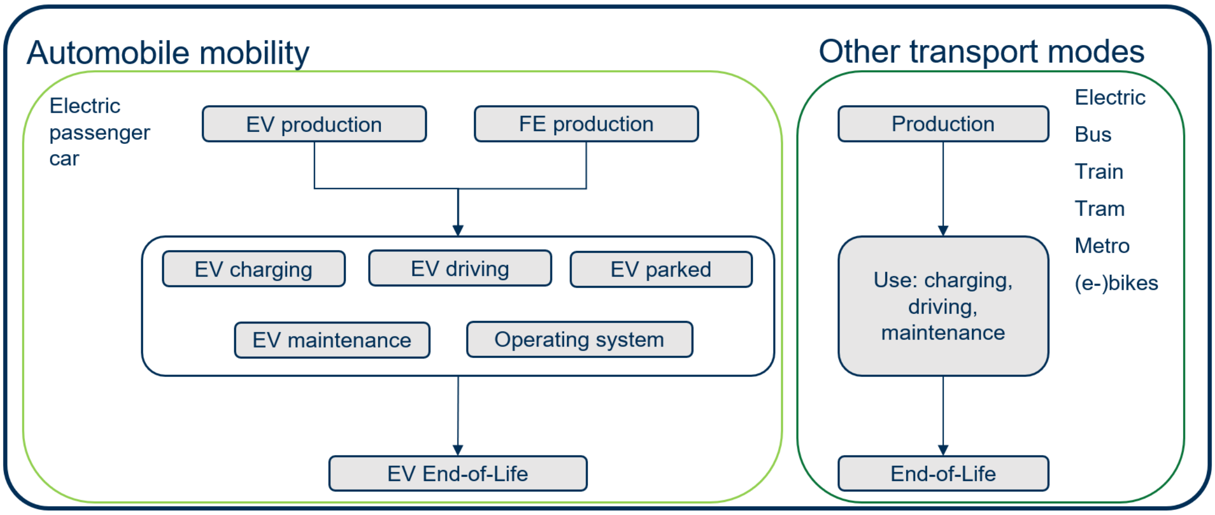

Figure 2: GEN1 - VaaS system boundary diagram.

3.1.2.2 GEN2 - MaaS

In GEN2 we consider an advanced Mobility-as-a-Service (MaaS) model that focuses on providing mobility rather than providing a vehicle for transportation. This corresponds to a Level 4 system of the CCI. Multiple definitions of what a MaaS model entails exist in literature, but in the scope of this study, it is defined as *a* system that *"replaces privately owned vehicles with personalised mobility packages, offering access to various modes of transportation as needed, leveraging the capabilities of modern information and communication technologies"*[10]. MaaS is a user-focused and intelligent mobility distribution model that consolidates offerings from multiple mobility service providers into a single platform, managed by a dedicated MaaS provider, and delivers these services to users through a unified digital interface[11].

The mobility system is set up in such a way as to provide an advanced mobility service to the end-user. Users will be able to schedule a transportation need at any time through the MaaS system. The system will propose the best way to make this trip, relying on a mix of different available transport modes. This can be approached in terms of time, cost and/or environmental efficiency, allowing the user to choose their preferred option. These transportation options are not limited to (automated) car mobility, but include all different transportation means, such as public transportation or bicycle and e-scooter options.

For the transportation steps in the MaaS system carried out using automobiles, this advanced mobility system leverages new data streams that become available through the inclusion of additional FE-based sensors in the vehicle. The purposes of these sensors in the light of the MaaS system are divided into two categories:

1. Sensors that collect and feed data to enable automated driving, making the MaaS system available for everyone (e.g. also people who do not have a driver's license). This level of automation would require a level 5 on the Society of Automotive Engineers

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[10] Nikitas, A., Kougias, I., Alyavina, E., & Njoya Tchouamou, E. (2017). How Can Autonomous and Connected Vehicles, Electromobility, BRT, Hyperloop, Shared Use Mobility and Mobility-As-A-Service Shape Transport Futures for the Context of Smart Cities? *Urban Science, 1(4),* 36. https://doi.org/10.3390/urbansci1040036

[11] Kamargianni, M., & Matyas M. (2017). The Business Ecosystem of Mobility as a Service. *96th Transportation Research Board (TRB) Annual Meeting*, Washington DC, 8-12 January 2017.

(SAE) scale, a common scale used for automated driving[12]. The level of passenger car automation is comparable to a robotaxi at this level. There are multiple types of sensors needed for automated driving, not all of which will be feasible to replace with FE sensors. The primary sensor types that are used are cameras, radar, LiDAR and Ultrasonic sensors, GPS, and Inertial Measurement Units (IMU). Similar to the predictive maintenance sensors of GEN1, the sensors are diverse in requirements and function, and the average environmental impact of the sensors included in UC1-4 is used as a proxy in the assessment. An industry example that supports this selection identifies that the collected data from a tire sensor can identify road conditions and potholes and communicate this to other vehicles to allow adaptation to these circumstances and accommodate unforeseen circumstances.

2. Sensors that focus on predictive maintenance. These sensors are included for identical purposes as GEN1 with the same proxy.

The boundary diagram in Figure 3 includes all the activities that are considered within the boundaries of the assessment. The same life cycle stages are considered as in GEN1, but the impact will be different for most of the considered life cycle stages due to the different mobility system applied. The mobility offering system, aiming at the optimisation of mobility, is shared between automotive transport and other transport modes.

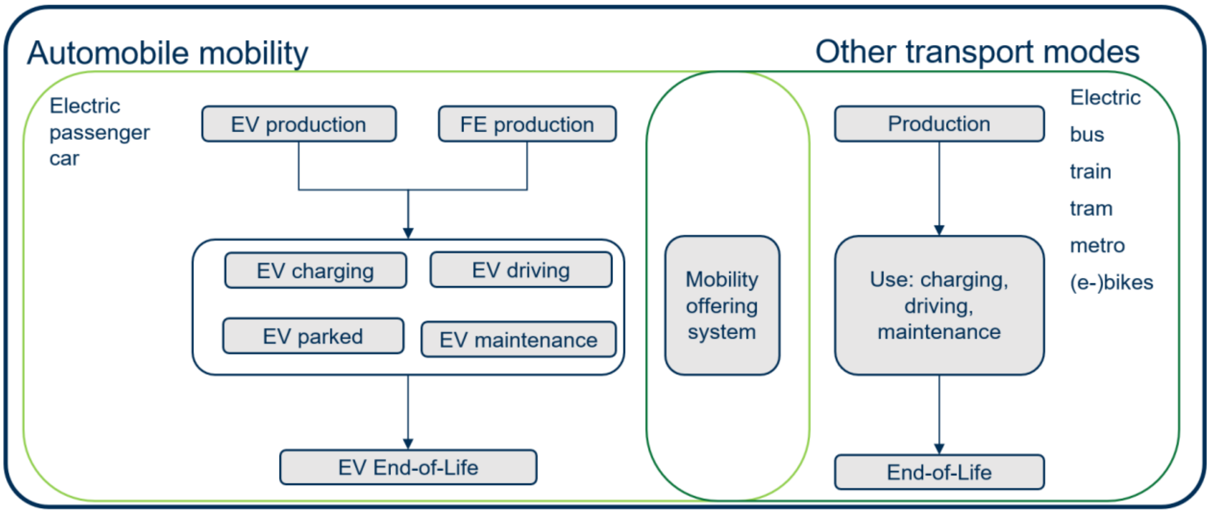

Figure 3: GEN2 - MaaS System boundary diagram.

3.1.3 Functional unit

The functional unit is the quantified performance of the product system to be evaluated and is used as a reference unit in the assessment. The functional unit qualitatively and quantitatively describes the function(s) and duration of the system in scope. It is also the reference for which the life cycle inventory data (input and output data) will be collected. The functional unit thus represents the quantified performance of a product system and serves as a reference unit in an LCA study.

An appropriate functional unit should answer the questions ‘what?’, ‘how much?’, ‘how well?’, and ‘for how long?’.

- The function(s)/service(s) provided: “what?”
    - Meeting the mobility needs of people measured in kilometres they need to travel (passenger kilometres or pkm).
- The extent of the function or service: “how much?”

[12] Synopsys Editorial Staff. (2025, February 15). The 6 levels of vehicle autonomy explained. *Synopsys Automotive*. https://www.synopsys.com/blogs/chip-design/autonomous-driving-levels.html

    - The mobility needs of a city of 500,000 inhabitants.
- The expected level of quality: “how well?”
    - The performance of the mobility should be provided with acceptable efficiency under comfortable circumstances within existing social (e.g. inclusiveness of the mobility offer) and safety norms.
- The duration/lifetime of the product: “how long?”
    - The mobility need over a period of 1 year.

<u>In this study, the following functional unit is applied:</u>

The impact of 1 passenger kilometre (pkm) from the total impact of the mobility needs of a city of 500,000 inhabitants during a period of 1 year.

3.1.4 Assessment boundary

3.1.4.1 Environmental aspects

This environmental assessment uses the predefined impact categories and characterisation factors of the Environmental Footprint (EF) 3.1 method developed by the European Commission in the framework of the PEF[13]. These impact categories are considered for the LCA’s in the scope of this study in order to assess the environmental impact of the different solutions. PEF also proposes a single score, which is an aggregated measure that combines multiple environmental impact categories into a single, dimensionless value, expressed in Pt (points). This value is obtained through normalisation and weighting. Normalisation depicts the results of the different environmental impact categories into a common scale, enabling comparison and allowing aggregation by means of a weighting step. The reference values, or normalisation factors, represent the total impact of a reference activity in a reference region for a certain impact category (e.g. climate change, eutrophication, etc.) in a reference year[14]. In the weighting step, indicator results are aggregated across impact categories using numerical factors based on value choices. The resulting weighted scores are summed up to obtain a single impact score.[15] The EF method uses standardised weighting factors developed by the European Commission.

The calculation of the single score is an integral part of the net environmental impact assessment in this report.

3.1.4.2 Circularity performance

The CA indicators are considered in accordance with the ISO 59020 standard, "Circular Economy - Measuring and Assessing Circularity Performance"[16]. A circularity indicator is a measure, either quantitative or qualitative, of an aspect of circularity.

In line with ISO 59020, the mandatory core circularity indicators are assessed. The established assessment objective and (differences between) the solutions calculated in terms of the described functional unit, do not include variations in terms of the mandatory circularity

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[13] European Commission, Directorate-General for Environment, *Recommendation on the use of Environmental Footprint methods, 2021. https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en*

[14] Sala S., Crenna E., Secchi M., Pant, R., Global normalisation factors for the Environmental Footprint and Life Cycle Assessment, EUR (28984), Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-77213-9, doi:10.2760/88930, JRC109878

[15] Sala S., Cerutti A.K., Pant R., Development of a weighting approach for the Environmental Footprint, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79- 68042-7, EUR 28562, doi:10.2760/945290

[16] ISO standard on Circular economy – Measuring and assessing circularity performance, 2024. https://www.iso.org/standard/80650.html.

indicators. The circularity performance of the systems in scope (REF, GEN1 and GEN2) are therefore identical for all mandatory core circularity indicators of the ISO standard. Resultantly, these indicators are not further included in the assessment. The optional ‘Resource outflows’ indicator ‘A.3.2 Average lifetime of product or material relative to industry average’ is an indicator of the time that an output resource (e.g. product) will remain in use compared to an industry average for the resource. This indicator is directly linked to the Lifetime Optimisation transformation pathway of the CCI that is in focus of the study and will therefore be considered within the scope of the assessment. This indicator is calculated using the formula:

$$R_{LP(X)} = \frac{t_{LP(X)}}{t_{IALP(X)}}$$

Where:

$R_{LP(X)}$ is the lifetime ratio of a product or material (X).

$t_{LP(X)}$ is the lifetime of a product or material (X) in years.

$t_{IALP(X)}$ is the industry average lifetime of a product or material (X) in years.

It is important to consider that this indicator is calculated on an individual product basis (lifetime of one vehicle), and not on a system level. The lifetime of vehicles needed to operate the alternative transportation means is not included in this calculation. Since the study focuses on a comparison at system level, it is also required to consider the broader context of the functional unit and the different generations considered in the circularity performance, in which the usage and ownership of the vehicle differ fundamentally.

From a system perspective, an additional indicator can be of relevance to complement insights from the Average Lifetime indicator with an indicator that focuses on the intensity of resource use between different considered scenarios. The economic indicator A.6.3. ‘Resource intensity index’ (RII) is a well-used and demonstrated indicator for higher system levels. It is the ratio of the change rate of resource consumption to the change rate of gross domestic product (GDP) over a period of time. It provides a quantitative measure of economic growth versus total resource use. The calculation of the RII indicator is performed using the formula:

$$I_{RII} = \frac{(E)}{F}$$

Where:

I_{RII} is the RII, expressed as a ratio

E is the rate of variation of resource inflow consumption (mass) per unit time, calculated as:

$$E = \frac{Resource\ inflow_{GEN\ X} - Resource\ inflow_{REF}}{Resource\ inflow_{REF}}$$

F is the rate of variation of GDP per unit time. Within the scope of this study, the economics of the different systems is not considered, and resultantly it is not feasible to estimate the effect of the mobility system on the GDP. Within the scope of this project, a circularity indicator that focuses specifically on the intensity of resource use related to the usage of automobiles, expressed in material input mass required to meet the mobility demand, would be a more representative measure of the circularity properties of the system. There is, however, no such specific indicator defined in the ISO standard, although indicators related to the intensity of resource use are referenced as indicators that “can also be used or can be developed in the future” without specifying a formula to be used for their calculation. As such, in the scope of this assessment, the RII for automobiles in the system is used, with the assumption that the rate of variation of GDP per unit time remains constant throughout the different systems, and the factor F is assumed to be 1.

As such, within the scope of this document, the RII is used as an indicator that provides insight into the efficient usage of resources.

3.1.4.3 Temporal boundary

The time boundary for the mobility systems is defined as one year of operation. The net impact assessment methodology prescribes the use of an ex-post approach, which evaluates the actual impact of implemented solutions. Accordingly, evaluations will be conducted as if the solutions were implemented today. However, the solution scenarios are developed from an ex-ante perspective. Indeed, they represent scenarios that have not yet been implemented at a city-wide scale. This approach makes the assessment valuable for strategic decision-making and for gaining insights into potential activities. However, the results should not be used for public reporting of net environmental impacts due to significant uncertainties.

3.1.4.4 Geographical boundary

The assessment is done for a city of 500,000 inhabitants located in Europe.

3.1.4.5 Implementation context

The solutions of GEN1 and GEN2 will be implemented in a typical mobility context representative of a large city. This context consists of a wide range of different mobility modes that are available for citizens, such as public transportation (e.g. bus, train, tram ...) or individual transport means (e.g. cars, (e-)bikes). The used electricity mix to power this mobility remains equal, and also the types and models of each mobility solution are fixed, except for the number of sensors implemented in cars in the different generations. It is assumed in the scope of this assessment that every means of motorised transportation is powered by electricity. There is no diversity considered between different types of models within the same method of mobility. This means that a general impact is considered for an EV, which represents the average impact of the different EV models that are available on the market. The demand for maritime and air mobility is out of scope. Additionally, distances covered on foot are not included in the analysis.

The considered levels in the scope of this assessment (REF, GEN1 & GEN2) differ in the way the access to these mobility options is organised, but the underlying mobility need (context) to which the models are implemented remains identical. This means that the demand for mobility is considered equal between the different levels, but the distribution between the different means of mobility will evolve.

3.1.5 Reference scenario definition

The reference scenario (REF) is the benchmark model on mobility and represents the currently dominant mobility system, corresponding to a Level 1 system in the CCI. The reference scenario considers a mobility system based on private car ownership in combination with other transport models (bicycle, public transport, etc.). The car considered in the reference scenario is an EV that is owned and used by a consumer or family. The vehicle is assumed to be equipped with the currently standard technology, including sensors that contribute to passenger safety, ergonomics, comfort, assisted driving and user experience. These sensors are used throughout the car interior for applications such as driver monitoring, climate control, gesture control or biometric sensors for personalisation. These sensors are currently used for the detection of the presence of a passenger and connect this to an alarm reminding the passengers to use their seatbelts.

When the vehicle is not being driven by the owner(s), it is parked either at the user's home or in a parking location. Service of the vehicle is performed on a kilometres-driven based maintenance program, accompanied by repairs in a reactive manner, identifying failures through standard warning systems. Maintenance is performed through a network of maintenance shops and supports lifetime extension. The parameters of usage of the vehicle in the reference scenario are based on literature data and aim to represent the average use of a typical vehicle in a car ownership model:

- A typical popular EV is selected as the reference vehicle. The EVs with the highest EU sales numbers in the first half of 2024[17] are considered. These vehicles correspond to the category of **large type vehicles** in the vehicle database of Sacchi et al..[18] This category of large type vehicles is therefore used as a representation of the average EV in the mobility system.
- An average **total mobility need** per person is defined as 10,700 km per year (all mobility modes). [19] The mobility demand of a city of 500,000 inhabitants during a period of 1 year, as defined in the functional unit, is 5.35×10^9 pkm (10,700 km * 500,000 inhabitants).
- An **average distribution between the different modes** of transportation is considered for each citizen and listed in Table 1. The values provided by the European Commission in 19, were normalised to account for the removal of air and sea travel, which were outside the scope of this analysis.
- The **average occupancy rate** of the EV during driving is defined to be 1.4 passengers, in line with available EU car occupancy data.[20]
- The vehicle is **driven** for 1h per day.[21,22]
- The **service life** of the vehicle is defined as 150,000 km.[18]

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[17] Inside EVs - These were the best-selling EVs in Europe for 2024's First Half., 2024 https://insideevs.com/news/727873/best-selling-ev-europe-h1-2024/

[18] Sacchi, Romain, and Christian Bauer. 2023. "Life-Cycle Inventories for on-Road Vehicles." Paul Scherrer Institut, Villigen, Switzerland. https://doi.org/10.5281/zenodo.5156043.

[19] European Commission: Directorate-General for Mobility and Transport, *EU transport in figures – Statistical pocketbook 2023*, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2832/319371

[20] EUROSTAT. 2021. "Passenger mobility statistics", 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Passenger_mobility_statistics

[21] Katona, Géza & Juhasz, Janos. (2020). The History of the Transport System Development and Future with Sharing and Autonomous Systems. Communications - Scientific letters of the University of Zilina. 22. 25-34. 10.26552/com.C.2020.1.25-34.

[22] Joint Research Centre: Institute for Energy and Transport, Zubaryeva, C., Pasaoglu, G., Fiorello, D., Alemanno, A. et al., Driving and parking patterns of European car drivers – A mobility survey, Publications Office, 2012, https://data.europa.eu/doi/10.2790/70746

- There are 571 **EVs owned per 1,000 persons**.[23]
- The **average km driven** per year for one vehicle is calculated from the input parameters as 11,111 km.
- The average lifespan of an automobile is estimated at 13.5 years, as described by Sacchi et al.[18]
- The EV is charged using **electricity from the European electrical grid**, with the corresponding distribution between the different sources (fossil, nuclear & renewable energy sources)[24].
- A **maintenance frequency** of once every 10,000 km is considered, corresponding to 1.1 maintenance events per vehicle per year.
- The **end-of-life treatment** of the EV is considered according to current practices in Europe and as implemented in the life cycle assessment database used for the calculations.

Table 1: Baseline modal split in passenger transport (EU, 2023)[19]

Transport mode	Usage %[25]
Passenger cars	83%
Powered two-wheelers	2%
Buses and coaches	7%
Trains	6%
Trams and metros	1%

[23] EUROSTAT. 2023. "Passenger cars in the EU". 2023. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Passenger_cars_in_the_EU 2023 data

[24] Wernet, Gregor, Christian Bauer, Bernhard Steubing, Jürgen Reinhard, Emilia Moreno-Ruiz, and Bo Weidema. 2016. "The Ecoinvent Database Version 3 (Part I): Overview and Methodology." The International Journal of Life Cycle Assessment 21 (9): 1218–30. https://doi.org/10.1007/s11367-016-1087-8.

[25] Numbers do not add up to 100% due to rounding.

3.2 Identifying the effects

The effects of implementing GEN1 and GEN2 systems compared to the reference scenario are identified by following the 5-step process outlined in the EGDC methodology: (1) Identify activities and emission sources for both the reference and FE solution scenarios, (2) Identify potential effects associated with implementing the solution, (3) Map these effects using a consequence tree, (4) Identify first-order effects, (5) Identify second and higher-order effects.

3.2.1 Identification of activities and emission sources for the scenarios

Starting from the defined assessment boundaries, implementation context and boundary diagrams for GEN1 and GEN2, activities that contribute to the overall environmental impact of the scenarios are presented in Table 2. An overview of the values used to model the different scenarios is presented in the following sections and is provided in Annexe 1.

Table 2: Identified activities under the reference scenario and the solution scenarios (GEN1 and GEN2)

Reference scenario: Mobility demand of a city of 500,000 inhabitants with privately owned cars	GEN1: Mobility demand of a city of 500,000 inhabitants through a VaaS system	GEN2: Mobility demand of a city of 500,000 inhabitants through a MaaS setup
Production of cars	Production of cars	Production of cars
Production of other mobility means: bicycle, bus, tram, train, metro	Production of other mobility means: bicycle, bus, tram, train, metro	Production of other mobility means: bicycle, bus, tram, train, metro
N/A	Production of predictive maintenance sensors	Production of automation & predictive maintenance sensors
N/A	Implementation of a car booking system	Implementation of a ride optimisation (and booking) system
N/A	N/A	Energy needs for automated driving
Use of electrically powered transport modes to meet the mobility demand	Use of electrically powered transport modes to meet the mobility demand	Use of electrically powered transport modes to meet the mobility demand
Use of road infrastructure during driving and parking	Use of road infrastructure during driving and parking	Use of road infrastructure during driving and parking
N/A	Use of the software system to monitor the VaaS system	Use of the software system to monitor the MaaS system
Maintenance transportation modes	Maintenance transportation modes	Maintenance transportation modes
End-of-life transportation modes	End-of-life transportation modes	End-of-life transportation modes

3.2.2 Identification of potential effects associated with implementing the solution

3.2.2.1 GEN 1 - VaaS

- From the perspective of the end-user, the ease of access to an automobile changes compared to the REF scenario with private car ownership. The convenience for the end-user decreases since the vehicle needs to be reserved for specific use slots instead of being constantly available. This report, therefore, considers a **shift in the proportional use of the different modes of transport** away from passenger cars and towards alternatives, which is also reported by car-sharing systems in Belgium.[26] A total shift away from passenger cars of 15% is considered. For short trips, this shift is made towards powered two-wheelers (+5%) because of the high availability and efficiency of this transportation mode. For longer trips, this shift is made towards the different public transportation means such as buses and coaches (+4%), trains (+4%), trams and metros (+2%). The resulting modal split under this scenario is summarised in Table 3.
- Because the VaaS system fills the need for mobility in a similar manner as the reference scenario, the **average occupancy rate of the EV during driving is not changed** from the reference scenario and remains 1.4 passengers.
- Operators of the VaaS model have a commercial incentive to decrease idle vehicle time. This report considers that each vehicle in a VaaS model is reserved for 30% of the time and is available for reservation for the remaining 70%. During the day and especially in rush hour traffic, it is expected that a high number of vehicles will be reserved, while at night, a lower reservation rate is expected. Furthermore, this report considers that during the reserved hours, a vehicle is driven 30% of the time on average. The vehicle is reserved for a purpose beyond the drive itself, and as a result, will stay idle during the execution of that purpose. For example, if an end-user wants to use the vehicle for commuting, the vehicle could be reserved for 10 h, but only driven for 2 h, where the remaining 8 h the car will be parked at or near the workplace. From these assumptions, **the time the vehicle is driven in the VaaS system has increased** to 2.16 h per day.
- **The service life** of the vehicle is considered to increase by 50% to 225,000 km due to higher usage efficiency and improved status monitoring through the inclusion of additional FE sensors.[19]
- **The number of vehicles needed to meet the mobility demand is lower** due to increased use efficiency and decreased demand. Nevertheless, a sufficient number of vehicles remains necessary to meet the peak demand needs, where 25% of all persons are mobile during rush hours.[27] This percentage is representative of survey data gathered annually in Flanders over a period of 5 years. The latest reported results from 2019 showed that 75% of respondents needed transport during the day, with an average transportation time of 71 minutes per day. The report does not clarify the exact time travelled during rush hour; therefore, an overestimation is considered where these 71 minutes are fully allocated to the rush hours (a total of 4 h per day). The number of vehicles per 1,000 persons drops to 217.
- The **average km driven per year** for one vehicle is calculated from the input parameters and increases to 24,000 km. **Maintenance** is performed every 10,000 km, corresponding to 2.4 maintenance events per vehicle per year, where the additional sensors improve the status monitoring of its parts, leading to efficient maintenance and improved service lifetime.
- An additional environmental impact is considered through the **operation of the vehicle reservation system**. This includes the additional energy requirements of the app usage for booking a vehicle. The booking for each trip would require an average data amount of

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[26] https://www.autodelen.net/wp-content/uploads/2023/03/Impact-report-Car-sharing-in-Belgium-in-2022.pdf

[27] Report of the 5th research on mobility behaviour in Flanders (2020) OVG 5.5. https://www.vlaanderen.be/mobiliteit-en-openbare-werken/onderzoek-verplaatsingsgedrag-vlaanderen-ovg/onderzoek-verplaatsingsgedrag-vlaanderen-5-2015-2020#rapporten

5.6MB[28], associated with an increased energy consumption per kilometre, which is considered.

- The **production impact of FE sensors** to allow the operations of the system (i.e. sensors for predictive maintenance) induces an impact. Additional FE sensors are included in the vehicle to leverage benefits related to predictive maintenance. Modern EVs already include a significant number of sensors for basic operation, safety, and diagnostics, which can also be used for predictive maintenance purposes; these sensors are not additional and therefore not considered here.[29] Furthermore, detecting and analysing more complex patterns across multiple sensor inputs simultaneously can also provide additional value without requiring additional sensors.[30] However, given the large number of vehicle parts that are subject to maintenance and failure, effective monitoring & maintenance prediction will require data collection through sensing for most of these parts. Considering the major failure points in an EV (battery, motor, drive control, tires, wiring, etc.)[31,32] and the need for potential redundancy, an estimated 35 additional sensors are considered to achieve a comprehensive predictive maintenance level, covering the critical subsystems (see Table 5).

Parameters not mentioned in the listed effects are considered to remain unchanged compared to the REF scenario.

Table 3: Assumed modal split in passenger transport for GEN1

Transport mode	Usage %
Passenger cars	68%
Powered two-wheelers	7%
Buses and coaches	12%
Trains	10%
Trams and metros	3%

[28] Data provided by iTTi in the context of 2024 ESA project 'Case studies on the environmental and sustainability impact of selected ESA activities with LCA', REEP LCA Case study #5, ESA contract No 4000144946/24/F/CP

[29] Murphy, C. (2025, May 29). *Choosing the most suitable predictive maintenance sensor*. Analog Devices. https://www.analog.com/en/resources/technical-articles/choosing-the-most-suitable-predictive-maintenance-sensor.html

[30] B. C, et. al. (2025). Predictive maintenance of electric vehicles using machine learning. In *International Journal of Research Publication and Reviews* (Vol. 6, Issue 5, pp. 4406–4408) [Journal-article]. International Journal of Research Publication and Reviews. https://ijrpr.com/uploads/V6ISSUE5/IJRPR45169.pdf

[31] Zhang, Y., & Guo, D. (2022). Design of pure electric vehicle training platform and development of fault diagnosis system. *Architecture Engineering and Science*, *3*(2), 148. https://doi.org/10.32629/aes.v3i2.898

[32] Moussa, A., & Aoulmi, Z. (2025). Improving electric vehicle maintenance by advanced prediction of failure modes using machine learning classifications. *Eksploatacja I Niezawodnosc - Maintenance and Reliability*. https://doi.org/10.17531/ein/201372

3.2.2.2 GEN 2 - MaaS

- The mobility system in GEN2 is managed centrally and offers the most suitable (combination of) transport mode(s) based on defined mobility needs. Consumers will not be able to select their means of transportation themselves, but the system makes an optimised suggestion calculated in terms of total efficiency and cost. This is expected to result in a further shift between the available transport modes. **The usage of passenger cars is expected to drop** further to 50% and is considered to directly shift to public transport, with buses and coaches showing the largest increase due to their route flexibility (+9%). The transport modes of trains and trams & metros are both attributed with an increase of 5%. The usage of powered two-wheelers is taken to be the same as for GEN1 as it is considered that this transportation mode will remain important for short trips, although additional use is also not expected through the GEN2 mobility system. Table 4 provides an overview of the modal split that is used.
- **Additional mileage** can be induced due to pick-up of end-users: 20% additional car kilometres are considered per person to take this into account (deadheading).
- The central monitoring system will optimise the transport and **increase the average occupancy rate** of a car to 2.8 passengers.[33]
- The **number of vehicles that is needed to meet the mobility demand is lower** due to the increased occupancy rate and decreased demand. The number of vehicles required in the system is driven by the peak demand during rush hours, where 25% of all persons are considered to be mobile during rush hours, identical to GEN 1.[27] The calculated number of **vehicles per 1,000 persons drops to 53.**
- Operators of the MaaS model have a commercial incentive to maximise transportation efficiency. The time the vehicle is driven (usage efficiency) is expected to be further increased over GEN2. The number of vehicles in the system is defined by the peak demand during rush hours, and the **time the vehicle is driven in the MaaS system** is calculated as **6.8 hours per day**.
- **The service life** of the vehicle is considered to increase by 100% to 300,000 km compared to the reference scenario due to higher usage efficiency and improved status monitoring through the inclusion of additional FE sensors.[19]
- Due to the high usage efficiency, the average **distance driven per year** for one vehicle has increased to **75,333 km**.
- **A maintenance frequency** is performed every 10,000 km, corresponding to 7.5 maintenance events per vehicle per year, where the additional sensors improve the status monitoring of its parts, leading to efficient maintenance and improved service lifetime.
- Similar to GEN 1, the additional energy requirement for the utilisation of an app for booking a vehicle was considered in GEN 2, with this value being the same for both scenarios.
- Full automation of the electric vehicle fundamentally relies on data processing, algorithms and AI actions. As a result, **additional software and processing requirements** are also included in the model through increased computational and energy demand associated with calculating route optimisations, inter-vehicle communications, additional sensor use and data processing. To account for this additional energy demand, the electricity consumption per kilometre travelled by the EV was increased to 0.361 kWh/km. This value was based on an average of the results from a multiphysics energy analysis model and a case study conducted on an autonomous electric vehicle taxi in New York City in 2019.[34] This represents a **57% increase in energy consumption relative to the baseline scenario**

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[33] European Commission. Directorate General for the Environment. 2018. Environmental Potential of the Collaborative Economy: Final Report and Annexes. LU: Publications Office. https://data.europa.eu/doi/10.2779/518554.

[34] Zhang, C., Yang, F., Ke, X., Liu, Z., & Yuan, C. (2019). Predictive modeling of energy consumption and greenhouse gas emissions from autonomous electric vehicle operations. *Applied Energy*, *254*, 113597. https://doi.org/10.1016/j.apenergy.2019.113597

- The **production impact of FE sensors** to allow the operations of the system (i.e. sensors for predictive maintenance and automation) induces an impact. The number of sensors for predictive maintenance was taken to be the same as in the GEN 1. It is considered that the MaaS system does not require additional sensors for predictive maintenance purposes compared to the GEN1 system. For the automation requirements of this model, however, additional sensors were considered on top of the existing sensors used for automation. To estimate the additional number of sensors required for automation, it is important to consider that an average new car sold in the EU is already equipped with some form of Advanced Driver Assistance Systems (ADAS)[35]. It is safe to estimate that an average new vehicle sold on the European market would be equipped with at least SAE (Society of Automotive Engineers) level 1 automation[36]. According to a 2025 IDTechEx report on autonomous vehicle sensors, level 1 automation requires cameras and LiDAR, amounting to a total of approximately 4 sensors per vehicle[37]. In GEN 2, a fully autonomous vehicle is considered, which corresponds to an SAE level 5, or a "robotaxi" system. A 2023 IDTechEx report highlights the need for 38 sensors for SAE level 5, due to additional cameras, LiDAR, and Radar (Table 5)[38]. This, therefore, corresponds to an **additional 34 sensors that are considered for GEN2**. Parameters not mentioned in the listed effects are considered to remain unchanged compared to the REF scenario.

Table 4: Assumed modal split in passenger transport for GEN2

Transport mode	Usage %
Passenger cars	50%
Powered two-wheelers	7%
Buses and coaches	20%
Trains	15%
Trams and metros	8%

Table 5: Types & number of additional sensors compared to the REF scenario assumed in GEN 1 & 2.

Sensor Category	GEN 1 - VaaS	GEN 2 - MaaS
Predictive maintenance	35	35
Automated driving	0	34
Total	**35**	**69**

[35] *Autopromotec Blog - By 2030, 54% of all cars in Europe will be equipped with Adas systems*. (2021). https://www.autopromotec.com/en/autopromotec-adas-2021/a607

[36] Synopsys Editorial Staff. (2025, February 15). The 6 levels of vehicle autonomy explained. *Synopsys Automotive*. https://www.synopsys.com/blogs/chip-design/autonomous-driving-levels.html

[37] Jeffs, J. (2023). Autonomous vehicles will drive automotive sensor market growth. *IDTechEx*. https://www.idtechex.com/en/research-article/autonomous-vehicles-will-drive-automotive-sensor-market-growth/29971

[38] *LTS GDS. (2025). Autonomous Vehicle Trends: What's Next for Autonomous Driving. https://www.gdsonline.tech/autonomous-vehicle-trends-whats-next/*

3.2.3 Mapping of the identified effects in a consequence tree

3.2.3.1 GEN 1 - VaaS

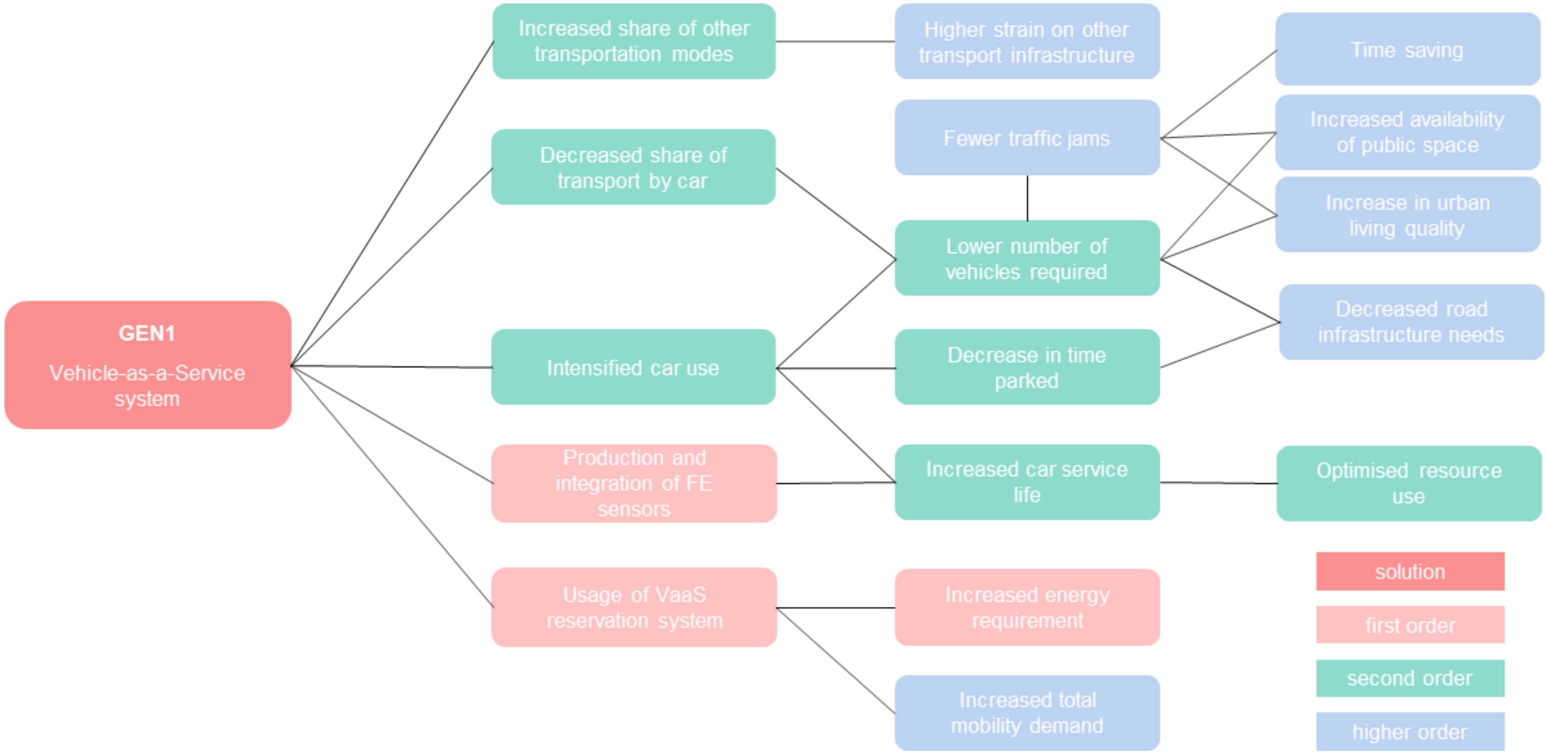

Figure 4: VaaS (GEN1) consequence tree

3.2.3.2 GEN 2 - MaaS

Figure 5: MaaS (GEN2) consequence tree

3.2.4 Identify first order effects

First order effects are the life cycle impacts resulting directly from the components of the solution and its implementation. These effects pertain to the direct impacts associated with the life cycle of the solution, which may include various components that require thorough assessment.

3.2.4.1 GEN1 - VaaS

Environmental impact of the production and integration of the FE sensors for predictive maintenance

The production of the sensors has an impact in terms of aspects like the raw material extraction and production. The full details of these impacts are characterised in the (confidential) environmental impact evaluations executed in the scope of project UNICORN. The impact calculations that are relevant in this deliverable have been included in the calculations of Chapter 4.

Environmental impact of the usage of the VaaS reservation software solution and the increased energy requirement.

To reserve the passenger car in a VaaS system, a booking system, for instance, operated via an app, is necessary. The major impacts associated with this software requirement of the VaaS system are included through the resulting energy required to operate this system.

3.2.4.2 GEN2 - MaaS

Environmental impact of the production and integration of the FE sensors for predictive maintenance and for automated driving.

The production of the sensors would have an impact in terms of aspects like the raw material extraction and production. The full details of these impacts are characterised in the (confidential) environmental impact evaluations executed in the scope of project UNICORN. The impact calculations that are relevant in this deliverable have been included in the calculations of chapter 4.

Environmental impact of the usage of the MaaS booking software solution and the increased energy requirement.

To schedule the mobility means for every request, the user makes a travel schedule through the MaaS system, a booking system, for instance, operated via an app. The major impacts associated with this software requirement of the MaaS system would be the resulting energy use.

Environmental impact of automated driving and subsequent increase in energy consumption.

To autonomise a vehicle, not only are sensors required, but so is a subsequent increase in computational capacity from the vehicle. This increased software component translates into an increased energy requirement per kilometre driven.

3.2.5 Identify second order effects

Second order effects are the indirect impacts that arise from changes to the reference activities due to the deployment and use of the solution. These effects stem from the modification or replacement of the reference activities or from additional activities initiated by the implementation of the solution. The resulting changes in GHG emissions are considered second-order effects, which can be either positive (emission reductions) or negative (increased emissions due to additional or modified activities).

3.2.5.1 GEN1 - VaaS

Increased share of other transportation modes

Because VaaS shifts the cost model from ownership (with high fixed costs) to usage-based or subscription models, it disincentivises unnecessary car use and decreases the immediate availability benefit of an automobile over public transport. This change in incentives makes people more likely to choose public transport, biking, or walking when those modes are more efficient or cheaper for a given trip.

Decreased share of transport by car

With VaaS, vehicle usage becomes more deliberate. Without the immediate availability and sunk costs of car ownership, people make more cost-conscious travel decisions, often choosing alternative modes for short, congested, or expensive trips, resulting in a lower overall share of trips by car.

Intensified car use (of individual cars)

Operators of the VaaS model have a commercial incentive to decrease vehicle idle time. Vehicles are actively managed to be in use as often as possible, serving multiple users throughout the day. Instead of sitting idle like private cars, VaaS vehicles operate more consistently, leading to intensified use. (See also Section 3.2.2.1)

Lower number of vehicles required (to meet mobility demand)

As a consequence of the increased share of alternative transport means and the increased per-vehicle use due to the lower idling times and the sharing system.

Decreased time spent parked for the vehicle

In a VaaS system, shared vehicles are in motion more often and serve multiple users' mobility needs continuously, and they therefore spend less time parked.

Increased service life of the vehicle

Due to the use of predictive maintenance sensors, which optimise repair requirements, combined with the increased use of individual vehicles due to the lower idling times.[33]

Optimised resource use

Results from the additional use rate of vehicles, as occupancy rates increase and the idle time of passenger cars decreases due to more frequent use of individual vehicles. This results in resources being used to manufacture and maintain the passenger cars being used more optimally.

3.2.5.2 GEN2 - MaaS

Increased share of other transportation modes

The MaaS system offers seamless access to multiple transport options (e.g., public transit, bike-share, e-scooters, carpooling, ride-hailing), making transportation via car only one of the options that are continuously evaluated and presented at the same level as the user.

Increased occupancy rate

Shared mobility options (e.g., carpooling, ridesharing) are inherent within MaaS ecosystems. Algorithms match passengers with similar routes, leading to fewer vehicles transporting more people.

Intensified car use (of individual cars)

The MaaS system allows vehicles to be used a factor of 9 times higher, rather than remaining parked or idle for most of the day, as with privately owned vehicles. (See also Section 3.2.2.2)

Decreased share of transport by car

A consequence of the MaaS system is that vehicle usage becomes more deliberate and tailored when it is best suited. The MaaS system provides mobility in the most optimal way, and as a result, there is no general preference for car transport over alternative transportation means. This results in a lower overall share of trips by car.

Additional mileage for on-location pick-up of passengers

Vehicles must travel to where passengers are located, resulting in additional miles being driven without passengers (deadheading). (See also Section 3.2.2.2)

Fewer vehicles on the road simultaneously

Because of the decreased share of transport by car and the increase in car occupancy associated with the MaaS model, a reduction in the number of cars on the road is expected at any given time.

Lower number of vehicles required (to meet mobility demand)

The number of vehicles required to meet the mobility demand is driven by multiple factors. The increased vehicle utilisation across multiple users minimises fleet size while maintaining service levels. The increased share of alternative transport modes and higher occupancy rates further contribute to this factor.

Optimised usage of resources to meet mobility needs

MaaS systems use real-time data and demand forecasting to allocate vehicles more efficiently, reducing idle time and underutilised capacity in transportation networks.

Increased car service lifetime in kilometres driven

Thanks to predictive maintenance sensors that optimise repair scheduling, and the increased use of individual vehicles in a shorter period due to higher occupancy rates and reduced idling time, vehicles stay functional and relevant for a longer driving range.

Decreased parking time for the vehicle

In a MaaS system, shared vehicles are in motion more frequently to serve multiple users. As a result, they spend less time parked, reducing the overall demand for parking infrastructure.

Fewer traffic jams

Functional use of vehicles through MaaS (including fewer unnecessary trips) reduces the total number of vehicles on the road. Fewer vehicles mean less congestion, especially during peak hours.

Optimised resource use

As a result of the additional use rate of vehicles, which is a consequence of the increase in occupancy rate, and a decrease in idle time. This results in resources being used to manufacture and maintain the passenger cars more optimally.

3.2.6 Identify higher order effects

Higher order effects are indirect impacts that arise as a consequence of second order effects, often following behavioural or structural changes such as shifts in consumption patterns, lifestyles, and value systems. These effects can be either positive or negative, and they encompass, but are not limited to, rebound effects. Higher order effects occur as causal chains of actions stemming from second order effects, with increasing uncertainty as these chains extend further. The distinction between second order and higher order effects can sometimes be unclear, as both types of effects are interlinked. The accurate categorisation of effects is less critical than ensuring all impacts are identified and assessed.

3.2.6.1 GEN1 - VaaS

Higher strain on other transport infrastructure

As private car use decreases, users increasingly rely on alternative transport modes (e.g., public transport, cycling, walking). This mode shift places additional demand and, therefore, strain on this infrastructure.

Fewer traffic jams

More rational use of vehicles through VaaS (including fewer unnecessary trips) reduces the total number of vehicles on the road. Fewer vehicles mean less congestion, especially during peak hours.

Time saving

Reduced traffic would reduce the amount of time spent on the road, leading to time savings while travelling.

Increased availability of public space

Due to the decrease in the number of cars on the road and the subsequent decrease in the need for road infrastructure, this would allow for more public spaces, replacing currently existing spaces devoted to cars.

Increase in urban living quality

Fewer vehicles on the road lead to reduced congestion, noise, and light pollution. Additionally, less infrastructure devoted to cars allows cities to allocate more space to public areas and housing.

Decreased road infrastructure needs

Due to the lower number of cars on the road and the lower number of parking spots, the amount of road infrastructure needed decreases.

3.2.6.2 GEN2 - MaaS

Time spent on switching transport modes

With the travel schedule being made by the app algorithm, a journey could consist on average of more than one transport mode, which could in some cases result in an additional time spent switching transport modes.

Higher strain on other transport infrastructure

As more people shift from private cars to public and shared modes, infrastructure such as bike lanes, sidewalks, and public transport systems may experience increased demand, potentially leading to overcrowding, maintenance issues, or capacity limitations.

Optimised driving system (and energy use)

The full automation of the vehicle fleet allows for optimised driving, as vehicles can communicate, anticipate obstacles, and adjust routes more efficiently than human drivers. This leads to smoother acceleration, less braking, and more efficient use of regenerative braking, significantly reducing energy consumption.

Increased total mobility from convenience

The immediate and continuous availability of transportation means tailored to the required destination could result in an overall increased mobility of people, increasing the demand and impact of transport.

Decreased road infrastructure needs

With fewer private vehicles and higher vehicle occupancy rates, the overall burden on road infrastructure decreases. This reduces the need for expansion or intensive maintenance of roads and parking facilities, especially in urban areas.

Increase in urban living quality

The introduction of MaaS systems aided by autonomous vehicles reduces the likelihood of road accidents. Furthermore, fewer vehicles on the road lead to reduced congestion, noise, and light pollution. Additionally, less infrastructure devoted to cars allows cities to allocate more space to public areas and housing.

Increased availability of public space

Fewer vehicles reduce parking demand. As a result, parking lots, garages, and on-street parking can be repurposed into parks, bike lanes, or community spaces, expanding publicly accessible urban areas.

Time saving

Reduced congestion, app-based route optimisation, and faster multimodal transfers result in shorter travel times for users. Shared and public options that use dedicated lanes also contribute to quicker trips.

Energy saving

Increased efficiency of transportation and reduction of congestion allow for a more optimal transportation system with a lower energy need to meet the demand.

4 Calculating effects

4.1 Identify relevant effects

This step involves identifying relevant effects from the consequence tree that are considered to create a relevant change in impact. All the effects identified in the consequence trees from GEN 1 (see Figure 4) and GEN 2 (Figure 5) are considered relevant at the initial stage, and the contribution of the usage of the VaaS reservation system (GEN 1) and MaaS booking system (GEN 2) is investigated. Higher-order effects are assessed qualitatively.

4.2 Data collection

The assumptions for the different scenarios (reference scenario, GEN 1 and GEN 2) are outlined in sections 3.1.5 and 3.2.2. Further explanation on the conversion of input data for the different scenarios to activity data for the analysis is provided in Annexe 1.

For the calculation of the environmental impact, this exercise makes use of secondary data except for the production of the sensors. For the production of the sensors, data have been collected in the different use cases of the UNICORN project and are reported in the confidential deliverable D4.2 – Environmental and circularity performance of UC1-4[39]. The emission factors and their source are provided in 4.2.1.. When necessary, further explanation of the modelling is provided below the table.

4.2.1 Identifying activities and emission factors (LCI data sources)

Table 6: Identifying activities, emission factors and sources

Activity	Emission Factor	Source Emission Factor	Remark
Production of passenger cars, including battery production and end-of-life treatment	0.14 kgCO_2eq/km	Passenger car, battery electric, NMC-622 battery, large, 2021 {RER}| Cut-off, U[40]	This includes the production of the car, battery and end-of-life treatment. The emissions factor was normalised to 1 km using the assumption of 200000 km driven over the lifespan[40]
Electric passenger car use – Electricity	0.33 kgCO_2eq/kWh	1 kWh Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, U[24]	0.243 kWh/km[40] electricity use
Electric passenger car use – road and brake ware emissions	0.02 kgCO_2eq/km	Calculated using an adapted version of 1 km Transport, passenger car, battery electric, NMC-622 battery, label-certified	Includes road infrastructure, road maintenance, brake and road ware emissions (Car maintenance, electricity use and car

[39] Deckers J., De Smet S., 2025, Environmental and circularity performance of UC 1- 4. Confidential deliverable of the UNICORN project, Grant number: 101070169.

[40] Sacchi, Romain, and Christian Bauer. 2023. "Life-Cycle Inventories for on-Road Vehicles." Paul Scherrer Institut, Villigen, Switzerland Note This study/report was prepared under contract to the Federal Office for the Environment (FOEN). The contractor bears sole responsibility for the content. https://doi.org/10.5281/zenodo.5156043

		electricity, large, 2021 {CH}| Cut-off, U[40]	production were removed from the record 'Transport, passenger car, battery electric, NMC-622 battery, label-certified electricity, large, 2021 {CH}| Cut-off, U' to calculate the emission factor
Passenger car maintenance	112.67 kgCO2eq/piece	1 piece Passenger car maintenance {RER}| maintenance, passenger car | Cut-off, U[24]	The record (one piece) assumes 1 maintenance event takes place every year for 10 years. Maintenance per km was calculated by dividing the emission factor per piece by 9 (assuming no maintenance in the last year), then normalised based on the average annual use of 15,000 km relative to the estimated 10,000km between maintenance events.
Production, use and end-of-life powered two-wheelers	0.03 kgCO_2eq/pkm	1 personkm Transport, passenger, bicycle, electric {GLO}| market for transport, passenger, bicycle, electric | Cut-off, U[24]	
Production, use and end-of-life buses and coaches	0.04 kgCO_2eq/pkm	1 personkm Transport, passenger bus, battery electric - overnight charging, NCA battery, label-certified electricity, 13m single deck urban bus, 2020 {CH}| Cut-off, U[40]	
Production, use and end-of-life trains	0.07 kgCO_2eq/pkm	1 personkm Transport, passenger, train, fleet average {GLO}| market for transport, passenger, train, fleet average | Cut-off, U[24]	
Production, use and end-of-life trams and metros	0.08 kgCO_2eq/pkm	1 personkm Transport, passenger, tram, electric {GLO}| market for	

		transport, passenger, tram, electric | Cut-off, U[24]	
Booking system energy use	0.03 $kgCO_2eq/kWh$	1 kWh Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, U[24]	See section 4.2.1.2 for the calculation of booking system energy use. This is multiplied by the emission value sourced from ecoinvent.
Automation energy use	0.03 $kgCO_2eq/kWh$	1 kWh Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, U[24]	See section 3.2.2.2 for an explanation of the automation energy requirement and sections 4.2.1.3 and 4.2.1.4
FE sensors (Automation and Predictive maintenance)	0.08 $kgCO_2eq/p$	Average of Gen2 | printed sensors, SBR GEN2 | complete module | with cable, SBR GEN2 | complete module | without cable, Gen2 | Tire sensor from UC4[41]	See section 4.2.1.1

4.2.1.1 Environmental impact of the production of the FE sensors for predictive maintenance and automation

To calculate the impact of the FE sensors, an average value of all the sensor results from UC4.2 was used, with the impact assumed to be representative for all types of possible sensors used, both for automation and predictive maintenance[41]. The same impact data was therefore used for both sensor types. This value was then multiplied by the required number of sensors for each category (34 for predictive maintenance, and an additional 35 for automation in GEN 2) in each scenario. This value was then multiplied by the total number of EVs necessary, giving the total number of FE sensors required for each scenario.

4.2.1.2 Environmental impact of automation

The environmental impact associated with passenger car automation in GEN2 is associated with a significant additional energy use through additional processing and computing requirements. According to literature, this value was averaged to be 0.361 kWh/km based on the results from a multiphysics energy analysis model and a case study conducted on an autonomous electric vehicle taxi in New York City in 2019[34]. Considering the already accounted for 0.243 kWh/km from the baseline and GEN scenario associated with EV usage, an additional 0.118 kWh/km was used to account for the additional energy usage of automation.

4.2.1.3 Environmental impact of the usage of the VaaS reservation software solution

To account for the booking of the vehicle through an app, only the associated energy consumption was considered. It was assumed that booking for each trip would require an average of 5.6 MB. Using a conversion factor of 0.003 kWh/MB, resulting in a per-trip energy consumption of 0.0168 kWh[28]. Based on the 10,700 km travel demand per person, the average

[41] Deckers, Jana, Karolien Peeters, Stefanie De Smet, and Pieter Willot. 2024. “Methodology for Net Impact Measurement of Functional Electronics Integration. D4.1 of Horizon Europe UNICORN Project.

daily distance travelled per person is 29.3 km. This value is close to that of the 2022 EU survey for short-distance trips of 27km. The results of the survey also find an average number of 2.7 trips per day[42]. This results in an average trip distance of 10.87 km and an energy consumption of 0.00155 kWh per kilometre associated with the app's usage.

4.2.1.4 Environmental impact of the usage of the MaaS reservation software solution

The energy consumption from ordering vehicles through the app was also considered, using the same values as in GEN1. This results in a total energy consumption per kilometre of 0.363 kWh when accounting for the energy use of the car, the automation system and the reservation app.

4.2.2 Data quality and availability assessment

The main data issues are related to the assumptions made to build the scenarios and the availability of data to do so. These limitations are discussed in Chapter 5.2. Regarding the data quality and availability of emission factors used to calculate the environmental profile, the datasets are considered representative for the EU in 2024. For passenger car mobility, the dataset used reflects electric vehicles only; combustion engine vehicles were not included, even though they still represent a significant portion of the EU fleet. Similarly, buses, trams and bicycles are all assumed to be electrically powered, with no changes across the different scenarios. The datasets used to calculate emission factors for bicycles, buses and trams are considered representative of electrified transport in the EU. For train transport, a market-average fleet has been used.

The dataset used to calculate the emission factor for electricity is representative for the EU market in 2024.

4.2.3 Qualitative evaluations of the higher-order effects

The complexity of the higher-order effects identified does not allow for an accurate quantification of their impact, mainly because of the lack of representative data and the synergistic nature of these effects. For this reason, higher order effects associated with both GEN1 and GEN2 were excluded from the net impact quantification but are assessed qualitatively. These effects are listed in Table 7.

Table 7: Overview of identified effects that are assessed qualitatively

Scenario	Effect
VaaS (GEN 1) & MaaS (GEN 2)	Fewer traffic jams Increased availability of public spaces Decreased road infrastructure needs Increased overall mobility demand Higher strain on other transport infrastructures
Additional qualitative effects for MaaS (GEN 2)	Optimised driving system Energy Savings

[42] DG Move *et al.* (2022) *Vols 978-92-76-55029–7*, *Study on New Mobility Patterns in European Cities, Task A: EU Wide Passenger Mobility Survey*.

Fewer traffic jams (GEN 1 & 2)

Transitioning to a VaaS system would reduce the total number of vehicles while increasing public transport use. Fewer cars on the road would decrease traffic congestion, leading to shorter trip times and more reliable transit. Reduced congestion would also lower air and noise pollution in high-traffic areas. In addition, maintaining a more consistent speed would improve energy efficiency. Overall, congestion reduction is likely to have a relatively large positive impact in both GEN 1 and GEN 2. The lower vehicle numbers in GEN 2 would likely result in the least traffic and, therefore, the largest decrease in associated impacts. However, predicting the exact relative decrease in traffic between REF, GEN 1, and GEN 2 is prone to a significant level of uncertainty.

Increased availability of public spaces & decreased road infrastructure needs (GEN 1 & 2)

Decreasing the amount of parking spaces or reducing road capacity would likely have an important impact on the environment, as these spaces can be repurposed for parks, pedestrian areas, or cycling infrastructure, which in turn supports mode shift away from cars. Both GEN 1 and GEN 2 can contribute to this shift, though GEN 2, by significantly decreasing the number of vehicles, would once again have the highest gains from this effect. Moreover, the magnitude of the benefit depends on how authorities choose to redevelop these spaces. With things like green spaces and active transport infrastructure producing clear knock-on environmental benefits.

Increased overall mobility demand due to system convenience (GEN 1 & 2)

A potential rebound effect from greater convenience in the mobility system offered in both GEN 1 and 2 is an associated increase in total mobility demand. If the parameters of the current model hold, this would mean an increase in all of the transport modes. This would, in turn, increase the impact magnitude for each input relative to the current results as the total mobility demanded for a city of 500,000 increases in GEN 1 and GEN 2 relative to REF. Moreover, this rebound effect would likely be highest with GEN 2 due to its high level of convenience, in which case the total impact of GEN 2 could be much higher than the current results of the quantitative analysis

Higher strain on other transport infrastructures (GEN 1 & 2)

This shifting of travel patterns resulting from the implementation of VaaS and MaaS, which results in the modal split changes, would add strain on the existing rail, bus, and cycling networks, particularly in mixed systems which encourage intermodal connections. This can manifest as bottlenecks at hubs and increased wear on public transport assets due to the larger number of users, especially without equivalent investment in capacity or maintenance. This effect would have major impacts, like reducing the lifespan of transport infrastructure; the overall impact from "other transport means'' would likely be higher than in the current qualitative results. As the modal split shift towards public transport is even stronger in GEN 2, this scenario would have the largest associated impact from this effect; however, it is difficult to gauge the magnitude of this change.

Energy Savings through optimised driving system (GEN 2)

Benefit from advanced automation, and predictive routing enables highly optimised driving patterns. Despite this initially causing a first-order effect, which increases energy consumption. When considering higher order effects implementation of an automated system could fluidify traffic and optimise the driving regime to reduce energy consumption. Smoother acceleration, better speed control, efficient path planning, and optimised regenerative braking could significantly reduce vehicle energy use.

5 Net impact calculation

5.1 LCA & Net environmental impact calculation

As requested by the Methodology for net impact measurement of functional electronics integration[5], based on the EGDC net-carbon impact assessment methodology[6], the calculation' results are presented in the format of a Waterfall graph, which compares the reference scenario to a solution scenario (see section 5.1.1 and 5.1.2). Net climate change impact results are provided. Along with the single score results, which aggregate the results of the assessment in a single score expressed in Points (Pt) using normalisation and weighting (see section 3.1.4.1).

Further analyses of the different scenarios are made in section 5.1.3.

5.1.1 Net impact of Vehicle as a Service solution (GEN 1 - VaaS)

Figure 6 depicts the waterfall graph showing the net carbon impact associated with the VaaS system (GEN1). This demonstrates a very low first-order impact magnitude, as this value is so low relative to the other effects that it is not visible on the graph. This is explained by the fact that the VaaS solution only has two first-order effects: the energy use associated with the booking system and the predictive maintenance sensors, both of which have a low impact per person-kilometre. This same relationship is present in Figure 7, which depicts the waterfall graph for the net impact of the single score, an aggregate value used to represent aggregated impacts for all environmental impact categories. From these graphs, it can be observed that there is an impact savings created from second-order effects, reducing the impact of the VaaS system to 29% relative to the reference situation, from 0.18471 $kgCO_2$/pkm to 1.3091 $kgCO_2$/pkm in terms of GHG emissions. While a reduction of 35% is observed for single score, from 3.54E-5 Pt/pkm in the reference scenario to 2.29 E-5 for the VaaS.

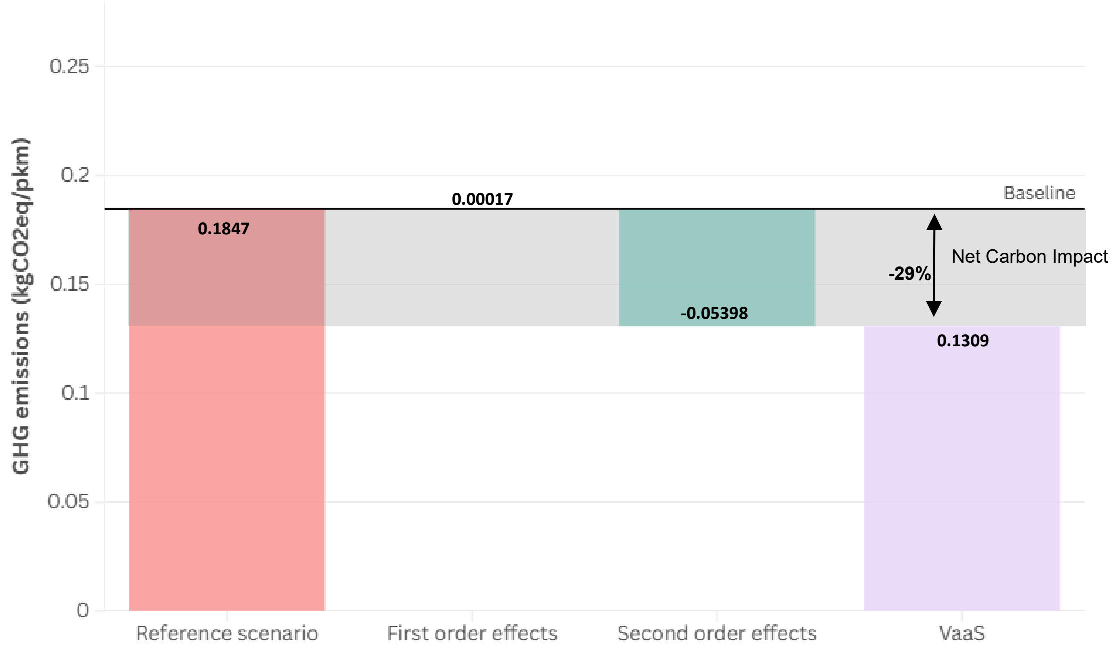

Figure 6: Net Impact of Assessment of VaaS (GEN 1) GHG Emissions

Figure 7: Net Impact of Assessment of VaaS (GEN 1) Single Score

5.1.2 Net impact of Mobility as a Service solution (GEN 2 - MaaS)

The net impact result for the MaaS (GEN 2), is presented in Figure 8 & Figure 9 for GHG emissions and single score, respectively. In this case, the first-order effects' impact is higher compared to the VaaS system in GEN 1. The first-order impact is attributed to the MaaS solutions' additional sensors for automation, and additional energy usage devoted to automation, the latter contributes to this impact more significantly. Also in the MaaS scenario, the results demonstrate a large impact reduction associated with second-order effects, resulting in a net impact reduction of 49% terms of GHG emissions, from 0.18471 kgCO_2eq/pkm to 0.09469 kgCO_2eq/pkm and a reduction of 56% for single score from 3.53E-5 Pt/pkm to 1.57E-5 Pt/pkm.

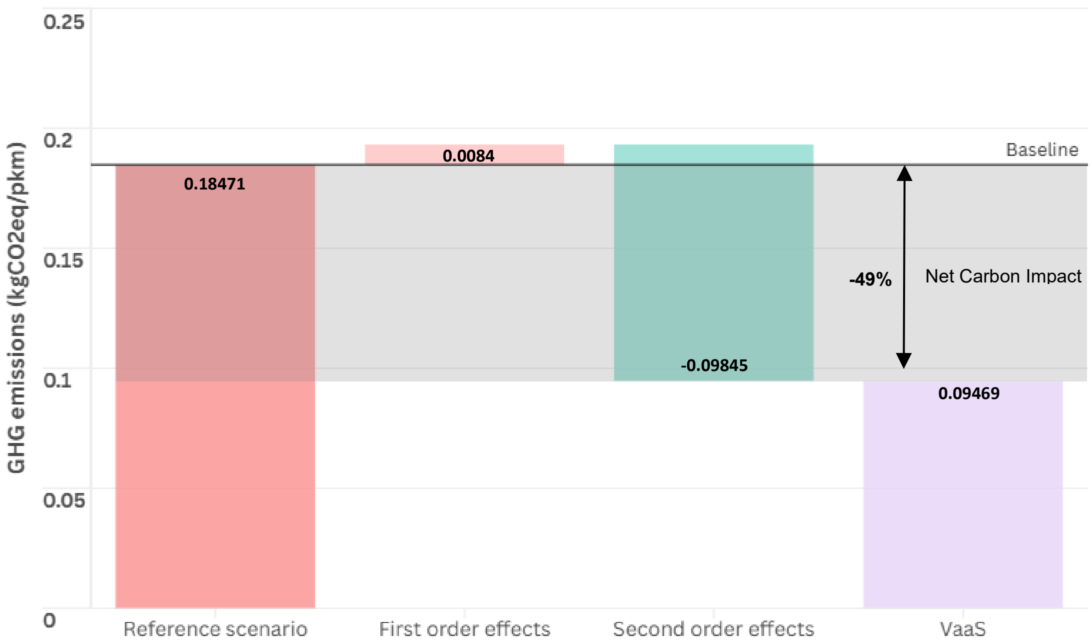

Figure 8: Net Impact of Assessment of MaaS (GEN 2) GHG Emissions

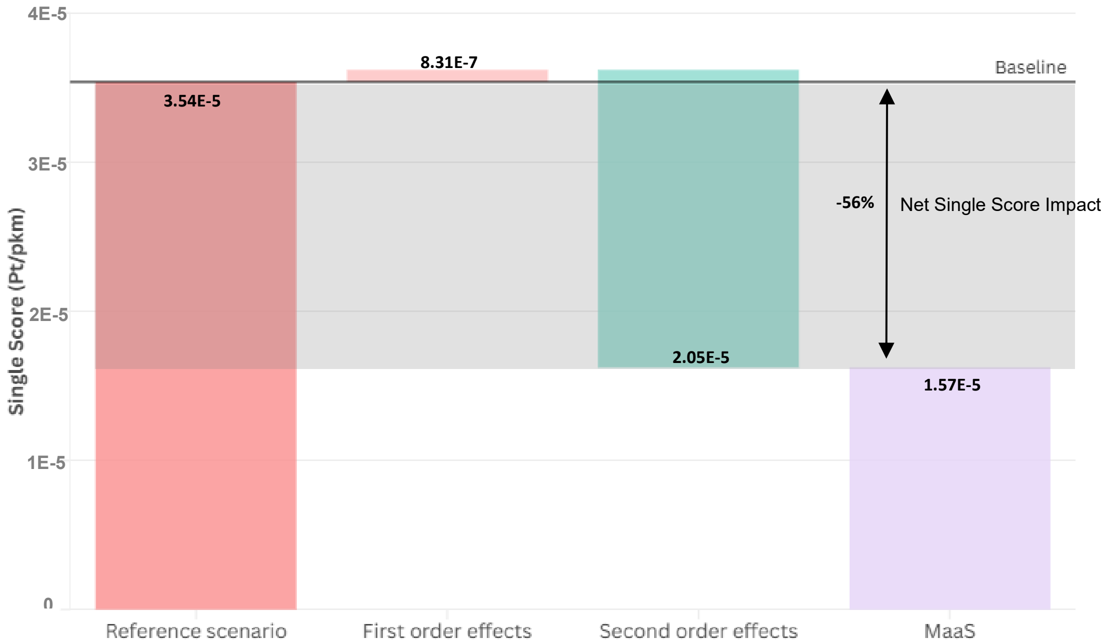

Figure 9: Net Impact of Assessment of MaaS (GEN 2) Single Score

5.1.3 Further analysis of reference situation, VaaS and MaaS solution

From the results presented in

56%

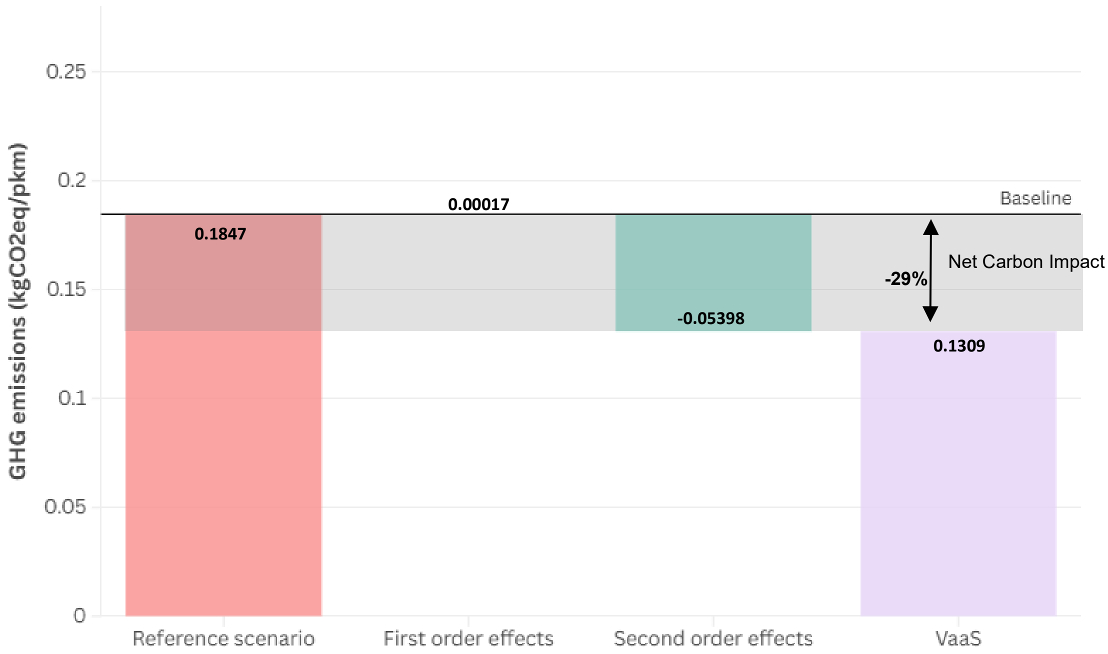

Figure 6 through Figure 9, it can be determined that both the VaaS and MaaS scenarios result in lower net impacts relative to the reference situation, with the MaaS having the lowest net impact, with this relationship being evident in Figure 10, where the MaaS has a 27% lower net impact than that of the VaaS.

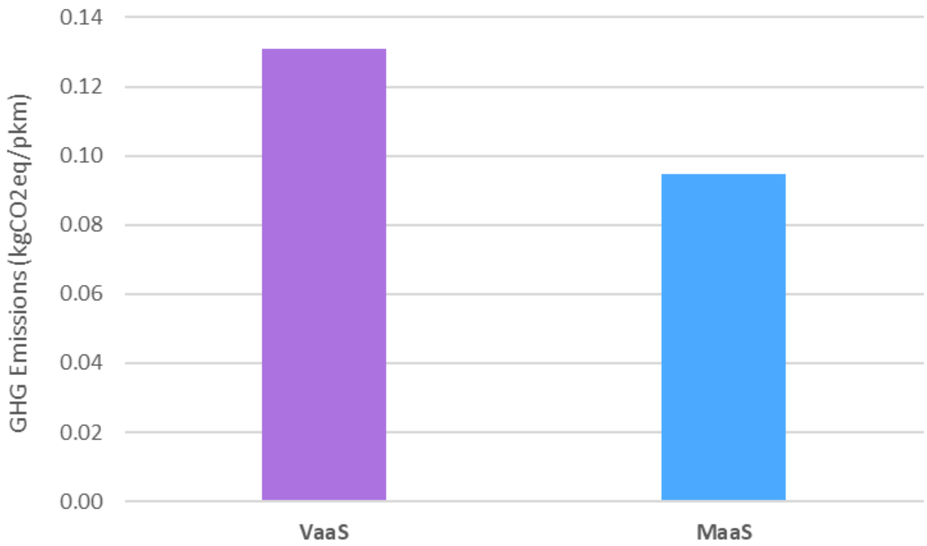

Figure 10: Net GHG Emissions Associated with VaaS & MaaS

A deeper understanding of the individual drivers behind these results can be derived from Figure 11, which depicts the GHG emissions associated with each first-order impact for both VaaS and MaaS solutions. This demonstrates the relatively low impact contribution from both the booking system and the production of sensors, explaining the low impact of first-order effects for VaaS seen in

Figure 6 and Figure 7. Moreover, the figure shows the relatively higher impact associated with the energy requirement for automation, explaining the higher impact of the first-order effect for the MaaS solution portrayed in Figure 8 and Figure 9.

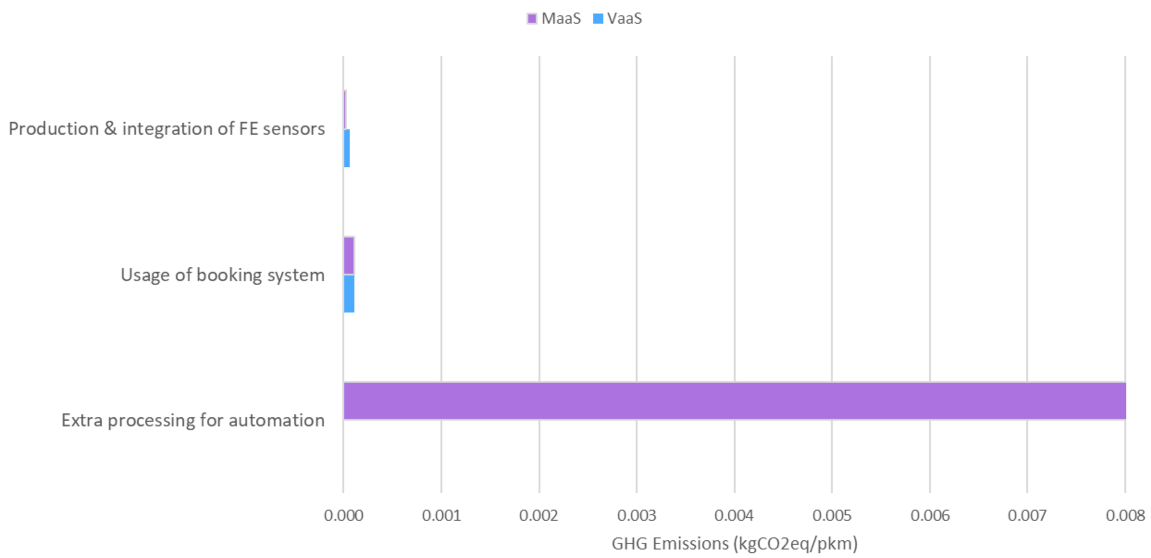

Figure 11: Impact Magnitude of GHG Emissions of First Order Effects for VaaS & MaaS

The lower net impact associated with MaaS relative to VaaS can further be explained by the results seen in

Figure 12. This shows that the VaaS and Maas solutions have a lower impact on all effects associated with cars, as both these scenarios result in lower car usage and require a lower number of personal vehicles. However, the figure also shows a higher impact associated with other transport means for both solution scenarios. This is explained by the higher use of other transport means other than cars in both these scenarios, with the MaaS system having the highest modal split away from cars, resulting in this scenario having the highest impact for this effect. Nevertheless, the total GHG emissions associated with GEN 2 remain the lowest overall all followed by the VaaS solution, with this relation holding true for all other investigated impact categories.

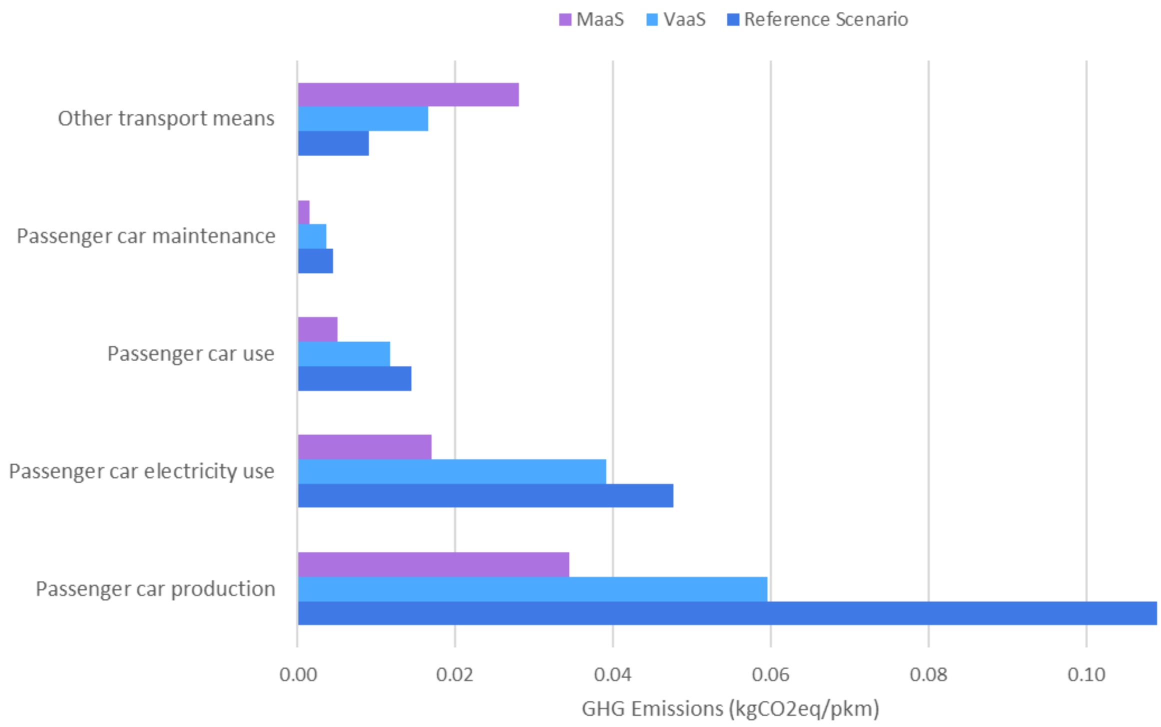

Figure 12: Impact Magnitude of GHG Emissions of Second Order Effects for VaaS & MaaS

The effects contributing to the impact of each scenario are further demonstrated in Figure 13, showing a hotspot analysis for each scenario in terms of GHG emissions. This further solidifies the interpretation from the earlier graphs, with MaaS having the lowest emission, followed by VaaS and the reference solution scenario. It once again shows that passenger car production, use and electricity have the highest impact of all effects for VaaS and the reference situation, with maintenance and other transport means use being smaller contributors. For MaaS, however, the major contributors are shown to be other transport means and passenger car use, with smaller impacts associated with car production, electricity use and automation.

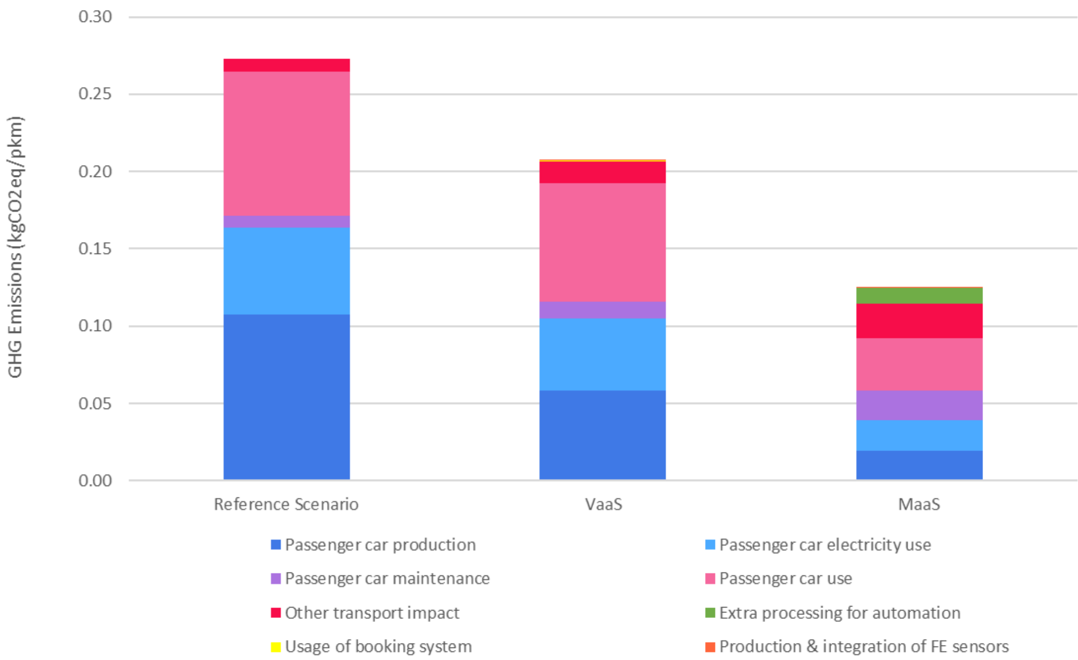

Figure 13: Hotspot Analysis of GHG Emissions for REF, VaaS & MaaS

Figure 14 depicts the relative difference in impact magnitude for each impact category relative to the reference situation. This once again demonstrates that MaaS has the lowest impact of all scenarios consistently over the different impact categories, followed by VaaS. For MaaS, the largest decreases, ranging between 59% and 61%, are observed in *"Resource use, minerals and metals," "Water use," "Ecotoxicity, freshwater",* and *"Human toxicity, cancer and non-cancer",* while the reduction in GHG emissions is slightly smaller at 49%. The smallest changes occur in *"Eutrophication, terrestrial", "Land use", "Eutrophication, marine",* and *"Photochemical ozone formation".* For the VaaS solution, the largest decreases, between 38% and 40%, are found in *"Resource use, minerals and metals", "Water use", "Human toxicity, cancer and non-cancer",* and *"Ecotoxicity, freshwater"*, compared to a 29% decrease in GHG emissions. The smallest changes occur in *"Land use", "Ionising radiation", "Resource use, fossils"*, and *"Eutrophication, terrestrial"*.

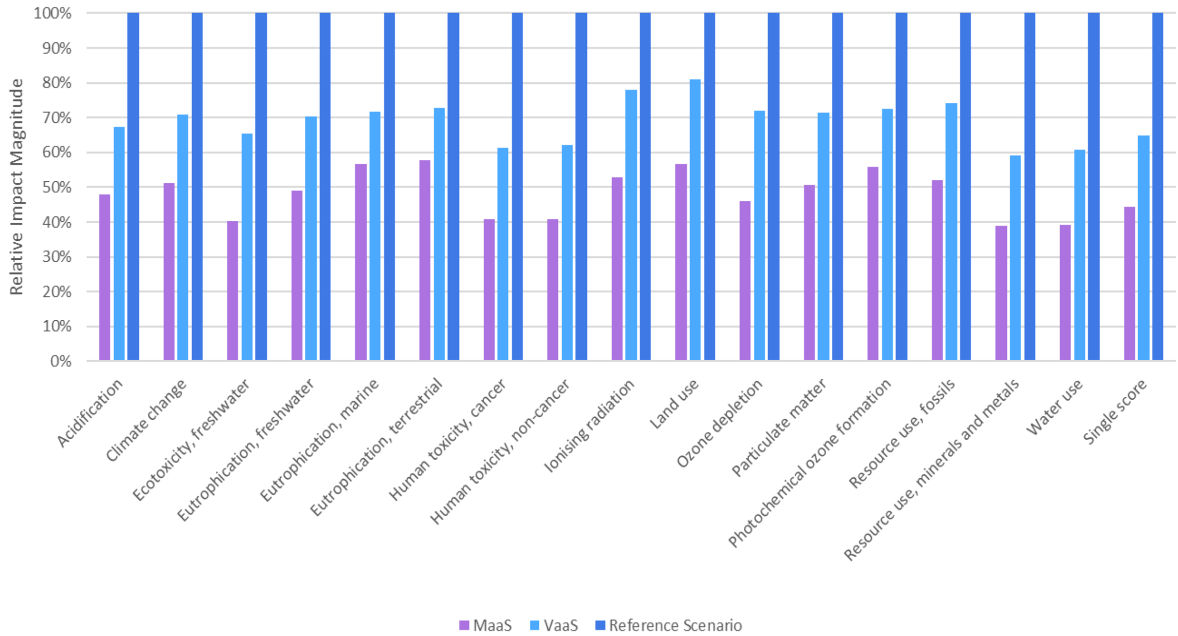

Figure 14: Relative impact magnitude of each scenario for all impact categories

5.2 Uncertainty and sensitivity analysis

5.2.1 Errors and Uncertainties

The model used for this analysis attempted to represent the average situation for each scenario in Europe to achieve the goal of the study. The lack of available data and the complexity of predicting outcomes in the implementation of radically different systems from what exists today posed challenges. To accurately portray the conditions in each system, generalisations needed to be made, resulting in uncertainties.

For example, it was assumed that under the MaaS system, the occupancy rate would increase to double that of the VaaS and current system. This is a strong assumption since an increase in the availability of vehicles through automation would allow for a larger number of people per vehicle. Though this value is based on literature, a change in this value would strongly affect the results of this analysis.

Another key assumption with the model is the values used for the total service distance lifespan of vehicles in each scenario. Based on the existing literature, this value was set at double for the MaaS solution relative to the reference situation. This is a very significant increase, and it could very well be that there are deviations from this assumption noticed in the practical system, higher degradation of common goods[43], putting an uncertainty on the calculations of this study. Nevertheless, under a fully autonomous system, it could be assumed that the vehicle lifespan range could be enhanced due to more optimised use of vehicles and reduced road accidents.

These results are based on values for a city of 500,000 inhabitants and, therefore, potentially not representative of larger and smaller towns and cities. Moreover, the modal split used was an average European value for all travel and is therefore potentially less representative for cities. Especially those with a drastically different modal split, like in the Benelux region, where biking would make up a much greater percentage in the adopted reference scenario.

It is also important to note that a major assumption of the model is the complete participation of all inhabitants in each scenario's system. The actual uptake of each system would likely be less all-encompassing. Nevertheless, the current analytical approach likely remains representative of the impacts associated even with partial adoption.

5.2.2 Sensitivity Analysis

A sensitivity analysis can be performed on some of the model parameters to determine the importance of these assumptions on the current results.

<u>Change in the occupancy rate.</u>

As mentioned in Section 5.2.1, one key assumption in the model is that the occupancy rate in MaaS (GEN2) is double that of the reference system (REF). As seen in Figure 15 adjusting the MaaS occupancy rate to 1.4, matching the other scenarios, has a significant impact on the results. The magnitude of all passenger car-related impacts in MaaS increases, with the impact from car production surpassing that of VaaS (GEN 1). Consequently, the net impact of MaaS system also becomes higher than that of VaaS. This outcome stems from the shorter lifespan of passenger vehicles in GEN 1, driven by their high usage rate, without any increase in the number of people per trip. While the number of vehicles needed to reach rush hour capacity in MaaS remains lower than the number required to meet passenger car mobility demand in VaaS, due to an 18.2% shift in modal split, the higher usage and shorter lifespan in MaaS result in more new vehicles being needed annually compared to VaaS. This highlights an important consideration for the MaaS model; such conditions could lead to significantly faster vehicle degradation[43], resembling a "tragedy of the commons", and thus require substantially more replacements over time, resulting in a potentially higher impact, despite the lower number of total vehicles.

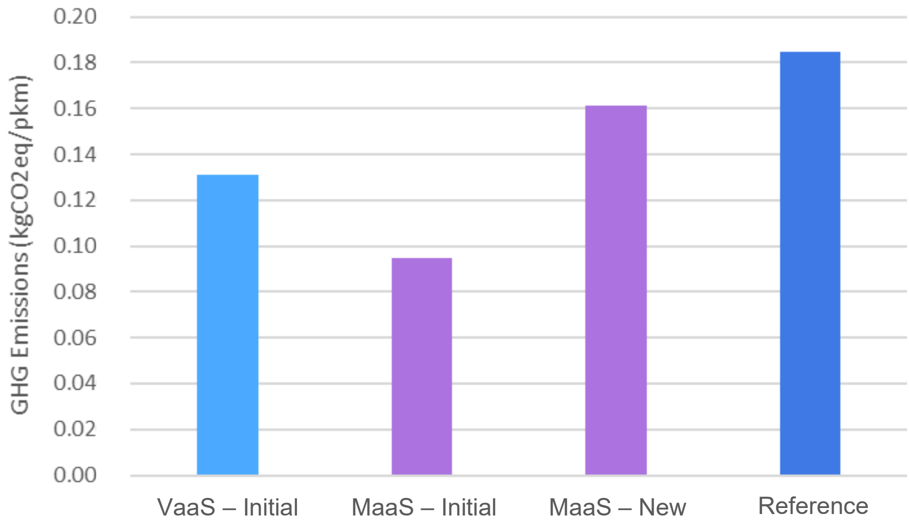

Figure 15: Net Carbon Impact of GEN 1, GEN 2 and REF With All Scenarios at 1.4 Passengers Per Vehicle

<u>Change in the service distance lifespan</u>

[43] Marciano, A., Frischmann, B. M., & Ramello, G. B. (2019). Tragedy of the Commons after 50 Years. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3451688

Another important parameter is the service lifespan of the vehicle; in the current model, it is assumed that the VaaS and MaaS vehicles have 50% and 100% of the service lifespan distance, respectively, relative to the reference scenario. Although this is based on available literature references (see Section 3.2), it is meaningful to analyse the sensitivity of this parameter and compare the effects of the actual total distance covered by the vehicles for the VaaS and MaaS systems. As seen in Figure 16, setting the service distance to that of REF for all three scenarios results in a decrease in the impact magnitude difference between each scenario for passenger car production due to an increase in the impact of both VaaS and MaaS. This results in a smaller net impact difference between VaaS and MaaS, with MaaS remaining the lowest impact scenario. Though the impact increase for MaaS is larger than that of VaaS, as the service lifespan decreases more significantly. This increase in impact is due to the resulting decrease in the lifespan of individual vehicles and, therefore, an increase in the number of new vehicles produced per year. This demonstrates that, despite a decreased service lifespan or total lifespan, assuming a greater degradation rate of vehicles for VaaS and MaaS, the implementation of MaaS and VaaS systems nevertheless results in a reduced total and net impact.

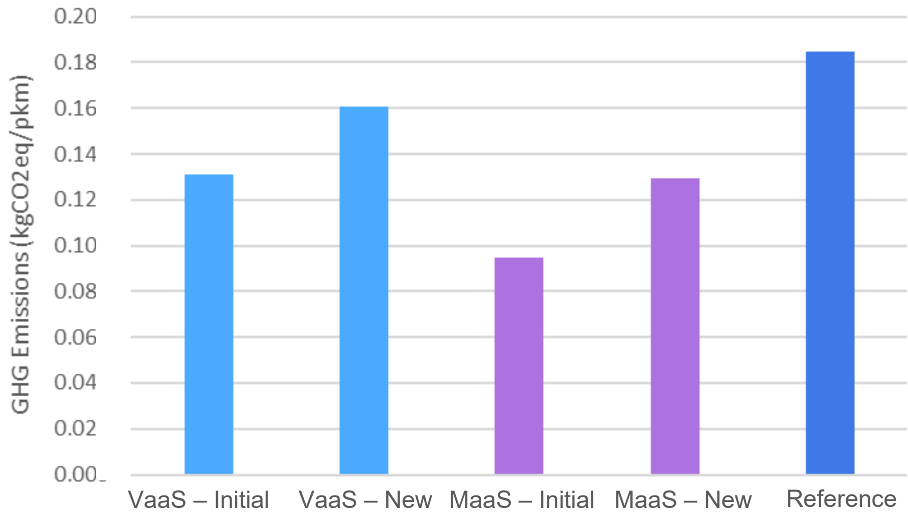

Figure 16: Net Carbon Impact of VaaS, MaaS and REF With All Scenarios at 150,000 km Service Life

<u>Change in the number of sensors</u>

Another key factor in the scope of the UNICORN project is the effect of sensors on the net and the total impact of VaaS and MaaS . To determine the sensitivity of the impact of sensors on both scenarios, an extreme case is considered in which significantly more sensors can be tested. Where automation and predictive maintenance require much greater precision and redundancy. Increasing the number of sensors 100-fold to 3400 and 3500 for automation and predictive maintenance sensors, respectively, creates an increase in net impact of 4% and 2.9% for VaaS and MaaS , respectively, as demonstrated in Figure 17. This highlights the minute impact that sensors within both systems have relative to all other effects.

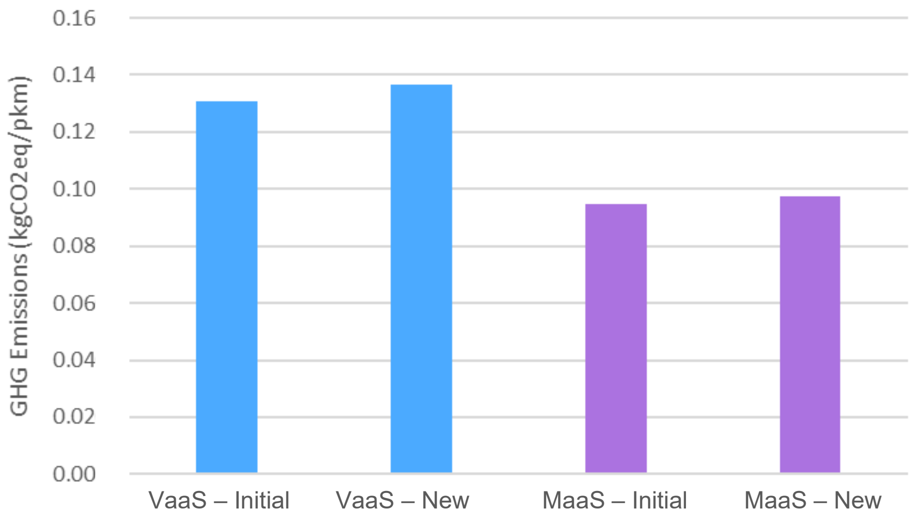

Figure 17: Net Carbon Impact of GEN 1 and GEN 2 with 100 Times More Sensors

<u>*Increase in mobility demand*</u>

As discussed in section 4.2.4, one of the higher-order effects associated with the implementation of a VaaS or MaaS is a rebound effect, causing an increase in the total mobility within the system due to increased convenience. To gauge the extent of this higher-order effect, a sensitivity analysis can be conducted to alter the mobility demand in VaaS and MaaS. In the scope of this sensitivity analysis, an increased mobility demand of12% increase from 10,700 km per person per year to 12,000 km is considered. As seen in Figure 18, an increase in total mobility relative to REF causes an increase in the impact of all effects, resulting in a 11% increase in the net impact for VaaS and 7% for MaaS. The more muted increase of MaaS can be explained by the fact that the value of cars produced does not change despite the increase in mobility demand, as the number of vehicles required during peak demand does not change and remains higher. This shows that despite an increase in total mobility, this rebound effect would likely not change the general trend of the results, as the number of vehicles needed in VaaS and MaaS remains much lower than in REF.

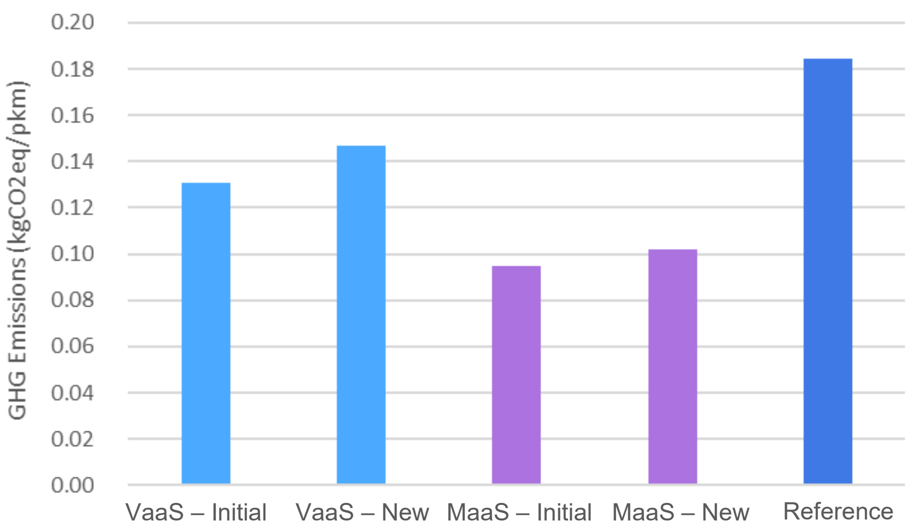

Figure 18: Net Carbon Impact of GEN 1, GEN 2 and REF Accounting for Increased Mobility Demand

6 Circularity assessment

As discussed in section 3.1.4.2, within the scope of UC5, the Resource outflows indicator ‘Average lifetime of product or material relative to industry average’ is considered, as well as the ‘Resource intensity index’ (RII) indicator. The REF scenario considers an industry average lifespan of an automobile ($t_{IALP(REF)}$) of 13.5 years as described by Sacchi et al.[18] The ecoinvent database considers an average of 150,000 km driven for a vehicle during its lifespan,[44] and with an average driving time of 1h per day,[45] the average driving speed is determined to be 30.4 km/h, which is kept constant over the different systems.

The calculation of the resource intensity index (RII, I_{RII}) reflects this lifespan of each individual automobile in the mobility system-wide usage of resources for automobile mobility. Given the assumption in the scope of this study that the rate of variation of GDP per unit time is equal to 1, the RII is defined by the rate of variation of resource inflow per unit time. To calculate this rate of variation, the amount of automobiles needed to meet the mobility demand via passenger cars over a defined time period is defined by first considering the total mobility need via passenger cars in kilometres, which is calculated to be 286,119 cars for the REF scenario (see Annex 1).

In the calculation of the rate of variation of resource inflow consumption per unit time (E) it is considered that the same amount and type of resources are required to produce a car in all scenarios.

6.1 Circularity of VaaS

In the VaaS system that is modelled in GEN1, the average lifespan changes due to different performance on the variables of the model. First, the service lifetime in kilometres driven is expected to increase to 225,000 km according to a study by the European Commission.[46] As a typical VaaS automobile serves the mobility needs of many people instead of just the owner or the owner's family, the time that the vehicle is effectively in use on the roads has increased. Within the scope of this report, it is considered that a typical VaaS vehicle has a daily average driving time of 2.16 h per vehicle. From these parameters, the lifespan of an automobile ($t_{LP(GEN1)}$) in VaaS is calculated to be 9.4 years, yielding a lifetime ratio ($R_{LP(GEN1)}$) of 0.7, showing a significant decrease in the lifespan of each individual automobile in the system.

The number of automobiles required to meet the mobility demand of the functional unit is 108,592 at any given time. Since each vehicle has a service lifetime of 9.4 years, this number of vehicles is recalculated to cover the full period of 13,5 years (the average lifetime of a REF vehicle), resulting in a total number of required vehicles of 156,373. The calculation of the resource intensity index (RII, I_{RII}) shows how the decreased lifespan of each individual automobile is reflected in the mobility system-wide usage of resources. The RII is calculated here as follows:

$$RII = \frac{Resource\ inflow_{GEN1} - Resource\ inflow_{REF}}{Resource\ inflow_{REF}} = -0.45$$

Demonstrating that the RII shows a strongly decreased resource intensity of automobiles in the VaaS mobility system compared to the REF mobility system, with 45% less resources required to provide the mobility demand via automobiles in the GEN1 system compared to the reference. Even though the lifetime of 1 vehicle decreases by 30%, the overall mobility system via automobiles requires 45% fewer resources.

Since the VaaS system has an increased usage of other mobility means, the resources required to meet this non-automobile mobility demand is expected to increase, resulting in an overall system-wide RII that is expected to be higher than -0.45.

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[44] Wernet, G., Bauer, C., Steubing, B. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 21, 1218–1230 (2016). https://doi.org/10.1007/s11367-016-1087-8

[45] Katona, Geza, and Janos Juhasz. 2020. "The History of the Transport System Development and Future with Sharing and Autonomous Systems." Communications - Scientific Letters of the University of Zilina 22 (1): 25–34. https://doi.org/10.26552/com.C.2020.1.25-34.

[46] European Commission. Directorate General for the Environment., Trinomics., VVA., Cambridge Econometrics., and Vito. 2018. Environmental Potential of the Collaborative Economy: Final Report and Annexes. LU: Publications Office. https://data.europa.eu/doi/10.2779/518554.

6.2 Circularity of MaaS

The MaaS system that is modelled in GEN2 further changes the circularity performance as measured by the average lifespan and resource intensity indicators. The service lifetime in kilometres driven of a vehicle in a MaaS system is expected to increase further to 300,000 km[33], and the time that a vehicle is effectively in use on the roads has increased further due to the core business model of a MaaS automobile, where the mobility needs of many people are served in a manner that is disconnected from a single vehicle and fully optimises the usage of each mobility means towards the need. The number of vehicles in a MaaS system is determined by the peak demand during rush hour, where 25% of all people are considered to require transportation, and it is considered that 90% of vehicles is actively transporting passengers during rush hours, and 30% during other hours. As such, a daily average driving time of 6.8 h is considered per vehicle. From these parameters, the lifespan of an automobile ($t_{LP(GEN2)}$) in MaaS is calculated to be 4.0 years, yielding a lifetime ratio ($R_{LP(GEN2)}$) of 0.30, showing a substantial decrease in the lifespan of each individual automobile in the system.

The number of automobiles required to meet the mobility demand of the functional unit at peak hours is 26,635 at any given time. Since each vehicle has a service lifetime of 4 years, the number of vehicles required to cover the full period of 13,5 years (the average lifetime of a REF vehicle) is 90,291. Also, for the MaaS system, the calculation of the resource intensity index (RII, I_{RII}) provides further insights in how this decreased lifespan of each individual automobile is reflected in the mobility system-wide usage of resources. The RII is calculated as follows

$$RII = \frac{Resource\ inflow_{GEN1} - Resource\ inflow_{REF}}{Resource\ inflow_{REF}} = -0.68$$

Demonstrating that the RII shows a strongly decreased resource intensity of automobiles in the MaaS mobility system compared to the REF mobility system, with 68% less resources required to provide the mobility demand via automobiles in the MaaS system compared to the reference. Even though the lifetime of 1 vehicle decreases by 70%, the overall mobility system via automobiles requires 68% fewer resources.

Also in this case, since the MaaS system has an increased usage of other mobility means, the resources required to meet this non-automobile mobility demand is expected to increase, resulting in an overall system-wide RII that is expected to be higher than -0.68.

6.3 Discussion of Circularity Indicator Results

The results of the calculation of the circularity indicators within the scope of this study demonstrate the importance of the system perspective when considering circularity. Sustainable and circular design and performance are typically measured at the product level, as this is what is directly influenced by OEMs and brand owners. This strategy leads to improved circular performance at the product level and is a well-established and successful approach for sustainable innovation. The results of the calculation of the lifetime ratio and RII, however, demonstrate that these actions on the product level are not necessarily observed at the system level and that the calculation of the circularity indicators should be evaluated in a broader scope as well. While it is indeed the case that the average product lifespan in years drops significantly in the VaaS & MaaS systems, this drop in lifespan is directly related to the different system organisation, in which the vehicle is used more frequently and, as such, builds up its mileage in a shorter period of time. This shorter, more efficient lifespan of a vehicle offers additional innovation opportunities to the sector, as newly developed features will be introduced into the market at a faster pace. The average lifetime of a vehicle in the MaaS system is calculated as 4.0 years, meaning that every four years, a full vehicle fleet rotation occurs, resulting in more than 3 times more technology rotations compared to the current REF system. It can therefore be expected that in a MaaS system, the business model of the automotive industry could shift away from creating revenue solely through maximisation of the number of vehicles sold but will be more targeted to provide and valorise an increased innovation rate to the market.

Furthermore, the calculation of the RII demonstrates that the decrease in lifespan and expected innovation rate increase will not be accompanied by an increased use of resources. On the contrary, due to the alternative role of the automobile in the MaaS mobility system, in total, a 68% drop in resources required for automobiles is realised due to the significant increase in usage efficiency, occupation rate and lifetime kilometres. The alternative mobility systems establish fundamentally different business model drivers for automotive brand owners, with an economic value creation model that is to a greater extent, decoupled from resource usage and more related to advancements in technology and innovation.

7 Conclusions & Perspectives

The construction of this report has provided several interesting insights that can serve as a basis for future actions. The process of defining the scope of the study was performed through the involvement of industry, and it clearly showed the industry's commitment towards sustainable mobility. It was shown that brand owners and OEMs in the automotive industry are focusing strongly on aspects that are within their circle of control, such as the electrification of vehicles, but also on automation and safety. On the other hand, the importance of increasing mobility efficiency through car sharing and MaaS systems was widely recognised, but not at the forefront of their innovation focus since this shift was mainly considered driven by social factors and consumer behaviour, aspects that are beyond their (direct) control. However, the potential role of Functional Electronics in the focus areas of Safety & Automation and Car sharing and MaaS was broadly recognised by the consulted industry stakeholders.

The further elaboration on the identified mobility systems considered in this study, i.e. the GEN1 VaaS system and the GEN2 MaaS system, demonstrated the complexity of these systems from the perspective of brand owners and OEM, with complex consequence trees with multiple first, second and higher order effects that become increasingly more difficult to assess. Nevertheless, the assessment of the effects through literature data and calculations in the scope of this report showed significant differences in resource usage between different systems that start from the same context of answering to the mobility needs of a city of 500,000 inhabitants. The evolution from a typical vehicle ownership model to a MaaS model showed a decrease in required passenger cars and an increase in kilometres driven per vehicle. This causes the effective lifespan of automobiles to decrease to a range of around 4 years in the MaaS system, from 9.4 years in a VaaS system and 13.5 years in the reference ownership model, ensuring a fast market uptake of innovative breakthroughs to stimulate further market development. Even though the effective lifespan of an automobile dropped significantly, the overall environmental impact of the mobility system also decreased, moving from the reference scenario to a VaaS system with a 29% decrease in GHG emissions and a 35% drop in single point impact. Moreover, this reduction in impact was even more pronounced for the MaaS system, falling 49% in GHG emissions relative and 56% in single point impact relative to the reference scenario. This demonstrates that sustainability at the product level is not necessarily equal to sustainability at the system level. Furthermore, the impact calculations demonstrated that the additional impact caused by the production of sensors (first order effect) that are included in the vehicles to allow for predictive maintenance and automated driving, had no relevant contribution to the overall mobility system’s impact and their second and higher order benefits substantially outweigh the first order effects.

This study does not account for the quantitative impact of higher-order effects., Higher-order effects (e.g. rebound effects) were only considered qualitatively due to the complexities of managing uncertainties and limited data availability. Nevertheless, the qualitative assessment suggests that most of these effects would likely have only a minor influence on the final results of the quantitative analysis. One effect with potentially significant influence, increased mobility demand, was tested during the sensitivity analysis, which showed only a muted change in the overall trend. Another effect that may alter the results is the potential energy savings from autonomous driving, which could reduce the total impact of the MaaS solution on passenger car electricity use and partially offset the first-order impact of the additional energy required for automation. Another higher-order effect is increased impact on other public infrastructure; however, it is unlikely that changes in infrastructure in the solution scenarios would alter the final trend. Overall, it is therefore unlikely that incorporating higher-order effects quantitatively would have a major influence on the final trend observed in the current results.

The largest determining factor for the impact of each scenario was the number of personal vehicles on the road, as this dictates the number of cars produced each year, the frequency of maintenance events, and overall vehicle energy use. This explains why the MaaS solution has the smallest impact of all three scenarios; it has the fewest vehicles on the road, driven by the highest increase in per-car use and the greatest reduction in total car demand. For the same reason, the VaaS solution shows the second smallest impact, with the second largest increase in per-car use and reduction in total car demand. Even though the impact associated with other transport modes increases for both VaaS and Maas, this increase is smaller than the decrease in car-related impacts. This is further explained by the higher resource use per person-kilometre associated with a passenger car relative to all other means of transport (e-bike, bus, tram and train).

This higher resource efficiency per person-kilometre can also have important implications regarding criticality and critical raw materials, as EVs contain large amounts and many types of metal, many of which are critical and strategic. Reducing the number of EVs required, while keeping the same mobility in Europe through more efficient resource use, would reduce the impact of mobility on criticality.

The results of this analysis carry important economic implications. Firstly, within the sensor industry, even though the total number of cars decreases, the sharp rise in sensors per vehicle (4 in REF, 39 in VaaS, and 63 in MaaS) drives sensor sales from 84,000 in REF to 450,000 in VaaS and 480,000 in MaaS. In contrast, automakers face declining revenues from vehicle sales due to the reduced number of cars required in VaaS and MaaS. Since these vehicles are put in the market through a different system, the current car-manufacturer business model could be significantly disrupted as shared mobility and multimodal transport reduce the need for private cars. Nevertheless, total mobility demand remains, meaning there is still valuel to capture by supplying this demand. To do so, however, automakers would need to adapt towards a service-oriented business model, focusing on monetising mobility itself to gain market share in the VaaS or MaaS system. Such diversification could offset the decline in car-centric mobility and align carmakers with the shifting transport trends. Finally, a major economic consideration lies in the wider impact on national economies. Many European countries depend heavily on the automotive sector; therefore, a reduction in car sales could significantly affect the European economy. However, a solution could lie in an economic value creation model that is more related to advancements in technology and innovation or is directed to a product-as-a-service model offering the potential to compensate for this decline and sustain economic contributions from the automotive sector.

Based on the results of the sensitivity analysis, it can be observed that despite some uncertainties and assumptions in the model, the overall trend associated with the results of the analysis holds true. A change in the lifespan distance, number of sensors or an increase in the mobility demand did not change the overall trend of the results. Moreover, the results of the sensitivity analysis demonstrate that one of the most important assumptions and variables in the model is the occupancy rate. An increase in the occupancy rate decreases the number of cars used and the distance travelled by car. Making the occupancy rate equal for the MaaS and VaaS models results in a negative shift in the analysis outcome for the MaaS model.

When interpreting these results, it is important to consider how they could be affected when considering a future perspective. The results would likely change considerably if they were projected for 30 years in the future. The impact difference between each scenario would likely reduce as the European grid increases its share of renewable production, reducing the impact of passenger car energy use. Moreover, an increase in EV recycling would also likely lead to a reduction in the end-of-life impacts of passenger cars. On the other hand, the impact associated with other transport means could also be reduced.

Based on the results of the quantitative analysis, VaaS causes a 29% decrease in the net carbon impact relative to REF, while MaaS achieves a 49% decrease. However, the single score net impact reduction is significantly higher at 36% and 56% for VaaS and MaaS, respectively. This points to the fact that the resulting impact reduction from implementing both scenarios is more pronounced for other impact categories than GHG emissions. Looking into the individual impact categories' contributions to the single score, there is a significant difference in magnitude between the categories, explaining the deviation between the percent change in single score relative to GHG emissions. For VaaS, compared to the reference situation, reductions are observed in “resource use, minerals and metals,” “water use,” “human toxicity, cancer,” and “human toxicity, non-cancer,” with the decreases in these categories being more pronounced than those for GHG emissions. For MaaS, improvements are seen in “resource use, minerals and metals,” “water use,” “ecotoxicity freshwater,” “human toxicity, cancer," and "human toxicity, non-cancer," with reductions in these impacts also greater than the decrease in GHG emissions This emphasises the importance of considering a broad range of impact categories in the net impact assessment, revealing potential trade-offs between impact categories. It also shows that the largest impact reduction for both scenarios is not just emissions-based but largely resource-based, likely driven by the reduction in the materials needed, resulting from a decrease in car use and production.

The results of this analysis show that the implementation of FE sensors contribute to the enabling of mobility systems that have a significant effect on reducing the impacts associated with the mobility for a city of 500,000 people. The implementation of FE sensors in vehicles in both a VaaS and a MaaS scenario, show only a relatively small additional impact, associated with the production of the FE sensors compared to the environmental benefits of the systems compared to the current reference mobility system.

Future work could explore alternative geographic contexts, such as mobility systems in a rural area. While the current assessment uses literature sources to construct the scenarios, further validation of the underlying assumptions would enhance the robustness of the analysis.

Annex 1: Overview of scenario data and calculations of activity data for the reference and solution scenarios

General data	REF	GEN1	GEN2	unit	source REF	source GEN1	source GEN2
Inhabitants	500000	500000	500000	persons	not relevant		
Functional unit	1	1	1	pkm	not relevant		
Total mobility demand per person	10700	10700	10700	km/p/yr	European Commission, 2023		
Total mobility demand for all inhabitants	5.35E+09	5.35E+09	5350000000	km/yr	not relevant		

Modal split inland passenger transport (EU-27, 2021)	REF	GEN1	GEN 2	unit	source REF	source GEN1	source GEN2
Passenger cars	83%	68.20%	50%	%	EC, 2023, share recalculated after removing maritime and air transport	Own calculations, see deliverable	
Powered two-wheelers	2%	7.30%	7%	%			
Buses and coaches	7%	11.20%	20%	%			
Trains	6%	10.00%	15%	%			
Trams and metros	1%	3.00%	8%	%			

Scenario parameters automobile use - input paramete	REF	GEN1	GEN2	unit	source REF	source GEN1	source GEN2
Occupancy rate EV	1.4	1.4	2.8	passenger	EEA, 2020 ; Eurostat	EEA, 2020; Eurostat	EC, 2018
Daily idle hours	23.0	21.84	14.4	hours	Katona and Juhasz, 2020 and EC JRC, 2012	Calculated using information from EC, 2018	
Daily idle hours for peak demand	/	/	17.2				
Service lifetime of the vehicle	150000	225000	300000	km	Wernet, 2016 (Ecoinvent)	EC, 2018	EC, 2018
Energy Consumption from booking app	0	0.00168	0.00168	kWh/km	/		
Automated driving sensors	0	0	34	sensors/vechic	/		
Predictive maintenance sensors	0	35	35	sensors/vechic	/		
Lifespan automobile	13.5	/	/	years	Sacchi and Bauer, 2023 (value for 162000 km)		
EV Electricity consumption per km	0.243	0.243	0.243	kWh/km			
Automated driving energy requierement	0.000	0.000	0.118	kWh/km			
Maintenance frequency	10000	10000	10000	km			
Percentage of person mobile in rush hours	25%	25%	25%	%	Onderzoek Verplaatsingsgedrag Vlaanderen 5 (2015 - 2020) | Vlaanderen.be		
Additional car kilometers	0%	0%	20%	%			

Scenario parameters automobile use - calculated value	REF	GEN1	GEN2	unit	source REF	source GEN1	source GEN2
Total distance driven per year with the EV (Based on lif	11111	24000	75333	km	calculated	calculated	calculated
Number of EV's per person	0.571	0.217	0.053	number	EUROSTAT (2024)	calculated	calculated
Total number of EV's (per 500000 inhabitants) necessary to fulfil the automobile mobility demand using rush hour capacity demand	74605	61161	26635	number	calculated	calculated	calculated
Total number of EV's (per 500000 inhabitants) necessary to fulfil the automobile mobility demand	286119	108592	15066	number	calculated	calculated	calculated
New vehicles per year	21194.0	11583.17	6688	number	calculated	calculated	calculated
Total km driven with EV per year	3179103343	2606214286	1134964286	km	calculated	calculated	calculated
Number of maintenance events per year	317910	260621	113496	events	calculated	calculated	calculated
Lifespan automobile	13.5	9.4	4.0	years	(value for 162000 km)	calculated	calculated
Average driving speed	30.4	30.4	30.4	km/h	calculated	idem ref	idem ref

Explanation of Calculations

The calculations of the input values used for the quantitative analysis of the scenarios are explained in the section below. They are based on the assumptions stated in sections 3.1.5, 3.2.1 and 3.2.2 and an overview of the data is provided in the table above.

Travel demand and the number of passenger cars required

To determine the travel demand for each scenario, the total travel demand for the city was multiplied by the modal split percentage for passenger cars and divided by the occupancy rate of a vehicle. An additional 20% mileage was included in GEN2 to account for deadheading. To determine the number of vehicles for each scenario, the total passenger car travel demand was divided by the yearly travel distance of a vehicle, which was determined by dividing the service life distance by the average lifespan of a vehicle in each scenario.

Number of passenger cars required during peak demand

To ensure that the number of vehicles available in each scenario would be sufficient to service users even during peak demand, an additional check was performed to determine the level of vehicle demand during rush hour. It was assumed that 25% of citizens would be travelling during rush hour. This was based on survey values from Flanders, which stated 76.32% of citizens require mobility and are mobile for 79 minutes per day[47]. This report takes the overestimated assumption that all this time is spent during the 4 hours of peak demand, resulting in 32.9% of these citizens being in rush hour, and therefore, 25% of mobile people are expected to travel during rush hour. The required number of vehicles to meet rush hour demand was then determined by the percentage of people travelling during rush hour via passenger cars and the occupancy rate of the vehicles. The resulting values yield a lower number of peak demand vehicles required for REF and GEN 1. For the REF system, this is explained by the personal car ownership model, where all passengers who do not require transport during peak hours do not use their vehicle during this period, so there are many vehicles present in the system for which there is no demand at that point. In the GEN1 system, there is also a need for excess vehicles for non-rush hour demand, as well as cars reserved by non-peak hour passengers that are parked during these hours are not available in this system. For the GEN2 system, the required rush hour capacity for GEN 2 is larger, and this capacity is therefore considered the required number of vehicles required to operate this scenario.

Number of cars produced

The number of new vehicles produced each year was determined based on the number of passenger cars required from either of the two methods for calculating the number of necessary vehicles, and divided by the average lifespan of a passenger car for each of the scenarios.

Occupancy rate & idle time

As discussed in Section 3.2.2, the passenger occupancy rate used of 1.4 was based on Eurostat data[20] for both the REF and GEN1 scenarios, and a rate of 2.8 was used in the GEN2 scenario based on a 2018 European Commission study by Pollitt et al.[33]. Similarly, the daily

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[47] Janssens, D., Paul, R., Wets, G., & Instituut voor Mobiliteit, Universiteit Hasselt. (2020). Onderzoek Verplaatsingsgedrag Vlaanderen 5.4 (2018-2019). In *Instituut Voor Mobiliteit*. https://assets.vlaanderen.be/image/upload/v1597797625/ovg54-analyserapport_edjcow.pdf

idle hour value for REF of 23 h was based on Katona et al.[48], while the idle times associated with the GEN1 & 2 scenarios were recalculated based on a European Commission publication[39]. This was done under the assumption that in GEN 1, vehicles would only be rented 30% of the time and only be driven during 30% of the time that the vehicle is rented. This results in a utilisation time of 2.16 hours per day and therefore an idle time of 21.84 hours per day. For GEN2, the idle hours consider that 90% of vehicles are used during peak hours, lasting 4 hours, and 30% for the remaining 20 off-peak hours. This results in 9.6 hours of use, and therefore 14.4 hours of idle time. However, as the actual number of vehicles required for GEN2 was 40% higher due to necessary considerations of peak demand, the off-peak time was decreased by 40% to account for additional vehicles, increasing the idle time of individual vehicles. This results in active time amounting to 6.8 hours and, therefore, idle time being 17.2 hours.

Service life distance and average travelling speed

The service life distance of a vehicle was taken as 150,000 kilometres for the REF scenario, and considered to increase to 225,000 km for the GEN1 system and to 300,000 km for the GEN2 system based on a European Commission study on the environmental potential of the collaborative economy.[33]

The average driving speed was calculated in the REF scenario based on the time it would take to travel all the vehicle's service life kilometres while not idle, within the 13.5 years of the vehicle's lifespan. This resulted in an average speed of 30.4 km/h, which was used for all three scenarios.

Lifespan

The average lifespan of a vehicle was calculated for each scenario based on the time it would take for a vehicle to travel its service life distance. This was done by multiplying the average vehicle speed by the active hours of the vehicle to determine the number of years until it has reached its service lifespan.

Passenger Car Electricity Use

The electricity use of the passenger car was calculated independently of the car usage, as the impact source used from the ecoinvent database used a value which was only scoped to Switzerland. To have a more representative impact factor for this input, the energy use was removed from passenger car use and calculated separately. This was done by using the 0.243 kWh/km from Sacchi and Bauer (2023)[49]. This was then multiplied by the pkm usage of the passenger car, considering the occupancy rate in the car and its modal split, to determine the subsequent total energy demand in a city of 500,000.

Maintenance frequency and number of maintenance events

Maintenance frequency was based on a maintenance event occurring every 10,000 km as described in Section 3.2.2. The total travel distance per year for all vehicles was then divided by 10,000 to obtain the number of maintenance events per year. This value was then multiplied by the edited ecoinvent data, as detailed in Table 6, which was altered by dividing the original value by 9, as this input was considered over 10 years. Assuming no maintenance in the last

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[49] Sacchi, Romain, and Christian Bauer. 2023. “Life-Cycle Inventories for on-Road Vehicles.” Paul Scherrer Institut, Villigen, Switzerland Note This study/report was prepared under contract to the Federal Office for the Environment (FOEN). The contractor bears sole responsibility for the content. https://doi.org/10.5281/zenodo.5156043.

year. It was then normalised based on the average annual use of 15,000 km relative to the estimated 10,000km between maintenance events.

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