The Internet of Vehicles From a Socio-Technical Perspective

A Multidisciplinary Analysis of the Next-Generation Vehicular Communication Network

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by

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Preface

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The burden of sorrow is lightened when shared, and likewise, genuine happiness blossoms through the act of sharing. In this context, I would like to thank my friends at TU Delft, who made this time unforgettable for my life. The shared experiences as well as the struggles we experienced together, will connect us forever. Noa, your cheerful nature was a light at the end of the tunnel of this work. For that, I thank you from the bottom of my heart.

Lastly, I thank my family. Thank you to my mother, who supported my academic journey despite not having the chance to achieve her academic aspirations. For your love and devotion, I am so incredibly grateful. You are the definition of a role model and an unbelievably strong person for me. I would also like to thank my sister, who paved the academic way for me. I am grateful for your dedication to excellence, inspiring me to do better every day. I share this journey with both of you, Mom and Bianca.

Lukas Balzasch
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Executive Summary

Yearly, 20.000 fatalities are recorded in road accidents on European roads alone. This situation is far more severe (1.3 million humans) when the global scope of road accidents is considered. Thus, Policy-makers are initiating policy programs to overcome this challenge by enhancing safety and maximizing the associated positive economic impact. The EU committed to minimizing fatalities by 50% by 2030 and to be net zero long-term by 2050.

To achieve this, vehicular communication networks (VCN) can play a crucial role. It is anticipated that the connectivity and communication of vehicles with their environment contribute to these goals by enabling safety functionalities or improving the traffic flow. Hereby, it is crucial to understand that this communication requires an infrastructure that assists the vehicles and ensures data transmission and operation. However, due to the European size and heterogeneity of the member states, realizing a vehicular communication network on a large scale requires increased coordination and collaboration efforts. Currently, no vehicular communication network has been introduced working EU-wide. Hence, this resembles a potential for future road improvement. To realize this, decision-makers must understand the complex properties and system interrelationships of such a large-scale infrastructure project so that a common VCN can be designed to ensure interoperability and robust functionalities across the EU. This work contributes to the aforementioned challenge by addressing the following research question:

What are fundamental socio-technical factors to consider in a future European vehicular communication network design?

A mixed approach that combines Peffer´s design science research framework and system engineering methodology is used to synthesize the contributions. By this, a vehicular communication network mission, stakeholder, and system analysis are presented in this work. Further novel and scientific sound requirements and stakeholder insights are synthesized by systematically reviewing 57 articles and interviewing 15 experts from the institutional, scientific, and industry domains. In this context, a stakeholder classification for vehicular communication networks, a 4-layer stakeholder complexity model, and a system requirement structure from a system perspective are proposed to contribute to the VCN understanding and future design attempts. Further, the reflection of the socio-technical interrelations between the technical and social VCN subsystems are subjects of this work.

The conclusion is that the reflection on socio-technical system properties plays a critical role in vehicular communication network design. Further, a future vehicular communication network consists of a magnitude of stakeholders with high interest and power; thus, designers must understand the characteristic of their co-evolutionary cooperative development. Hence, a multidisciplinary understanding and approach are critical for designers. Furthermore, the geographical segregation of designing and decision-making in a future vehicular communication network is identified, and certain goals/issues should be addressed in the respective layer. Another major conclusion is that the VCN discussion is determined more by social and socio-technical conditions, such as stakeholder cooperation/coordination and interoperability, than by technical feasibility.
These findings result in three main research contributions, which are summarized as follows:

- A 4-layer stakeholder complexity model contributing to the understanding of VCN development is contributed.
- An approach of integrating the socio-technical system perspective on the complex, large-scale infrastructure VCN project is contributed. This focuses on the processes and requirements between social and technical subsystems, addressing the integration of heterogeneous stakeholder interests.
- A comparison is made between scientific focus, stakeholder needs and objectives, and expert insights, highlighting the mismatch and alignment of requirements. This contributes valuable insights for adjustment and further research in the VCN community.

Further methodological contributions can be concluded:

- The design science research approach is aligned with systems engineering iso standards and methodology.
- The design science research framework is used as an approach to address the complexity of VCN systems. This novel perspective helps VCN stakeholders design solutions for their field problems.

The results have implications for designing stakeholders in a VCN. Based on the analysis, it is recommended that policymakers identify and extend common objectives with the industry to establish public-private business cases. Further, vehicle manufacturers should participate and embrace the transition to a vehicular communication network by cooperating strongly with stakeholders. In addition, implementing the relevant technologies to communicate with the heterogeneous infrastructure is suggested to shape future infrastructure connectivity development. Lastly, the lack of socio-technical reflection in scientific literature is identified. Hence, scholars should elaborate on the interactions and interrelationships between the social and technical subsystems in future work.

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List of abbreviations and acronyms

Abbreviation	Defintion
5G	Fifth-generation technology standard for broadband cellular networks
EECC	European Electronic Communications Code
EU	European Union
GDPR	General Data Protection Regulation
IEC	International Electrotechnical Commission
INT	Interview
IoV	Internet of Vehicles
ISO	International Organization for Standardization
ITS	Intelligent transportation system
ITU	International Telecommunication Union
OEM	Original Equipment Manufacturer
OBJ	Objective
SIoV	Social internet of vehicles
STS	Socio-technical system
UN	United Nations
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
V2x	Vehicle to everything
VANET	Vehicular ad hoc network
VCN	Vehicular Communication network
WiFi	Synonym for WLAN

1
Introduction

This Chapter introduces the research problem of the work. Further, the scientific relevance of the problem is highlighted and a research question is derived in Chapter 1.2. Thereafter, the research problem is decomposed into its sub-components in Chapter 1.3 and Chapter 1.4 presents the sub-research questions. Lastly, the link to the master program is depicted, and a thesis outline is provided in Chapter 1.5 and 1.6.

1.1. Research Problem Introduction

Mobility itself can be classified as a fundamental human right (United Nations, 1948). Nowadays, the European Union (EU) achieved a motorization rate above 50% of its inhabitants, resulting in greater mobility than ever before (European Commission, 2020b). However, the increased amount of actors on the road comes at the cost of traffic congestion and road safety. On EU roads alone, about 100,000 accidents can be recorded, of which about 20,000 include fatalities. Extended globally, 20-50 Million people suffer annually from road traffic injuries whereby 1.2 million people die, accounting for 3% costs of most countries' gross domestic product (World Health Organization, 2022).

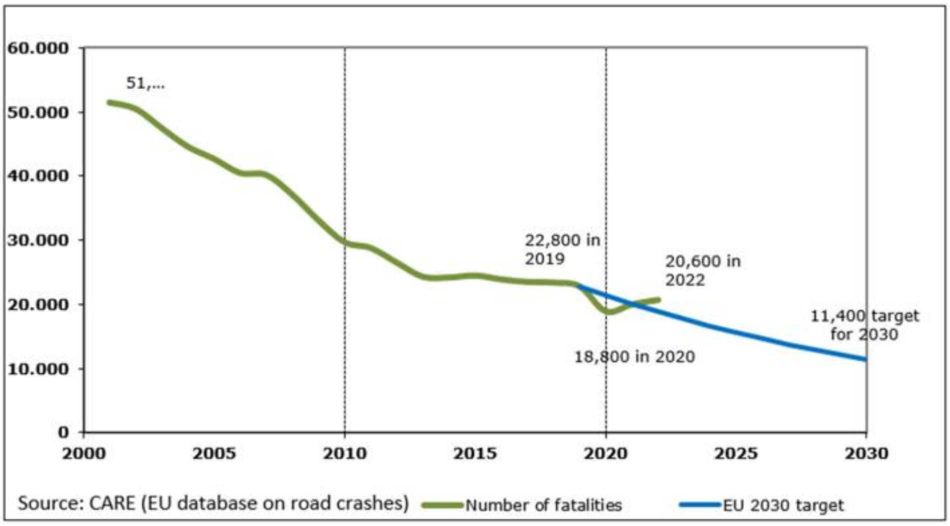

Figure 1.1: Road Fatalities in the EU (CARE, 2023)

Institutions notice this substantial impact on society. Therefore, the EU committed to minimize fatalities by 50% by 2030 and to be net zero long-term by 2050 in their EU Road Safety Policy Framework 2021-2030 (European Commission for Mobility and Transport, 2020). In order to reach these goals indicated in Figure 1.1, current standards, technologies, limitations, trends, and implications must be analyzed to guide the development of target-oriented technologies and policies effectively. However, this is challenging, as the road network and its decisions are complex. Thus, system thinking is required to tackle interventions.

Moreover, the situation in Europe is aggravated by the increased number of individual stakeholders (countries but also industry), which often have diverging interests complicating the alignment of policy-making and technology harmonization. In addition, the emergence of new technologies and disruptive events can cause further uncertainty hampering policy-making and investments in road infrastructure.

To address these challenges and objectives of future mobility, vehicular connectivity and communication is a promising approach. The Automotive Edge Computing Consortium (AECC) (2020) estimated that connected cars will generate 10 exabytes per month by 2025. This data can allow applications such as autonomous driving or emergency warnings helping to improve the road system. However, neither does the current infrastructure support this data flood nor is a fully in-vehicular data computation beneficial due to efficiency concerns. Moreover, this amount of data is potentiated by the expected growth of connected vehicles shown in Figure 1.2. Therefore, vehicle communication solutions capable of unlocking this potential by scaling and adapting to these growing technical requirements of future technologies are required.
In the past, the EU attempted to introduce ITS-G5, a WiFi-based short-range communication network for vehicles enhancing connectivity to improve safety on the road. However, the large-scale introduction failed due to industry acceptance and inconsistencies among the European states. Nevertheless, the advantages of such communication remain, and increasing cellular coverage through 5G along with technical progress intensifies the institutional discussion of vehicular communication networks (VCN).

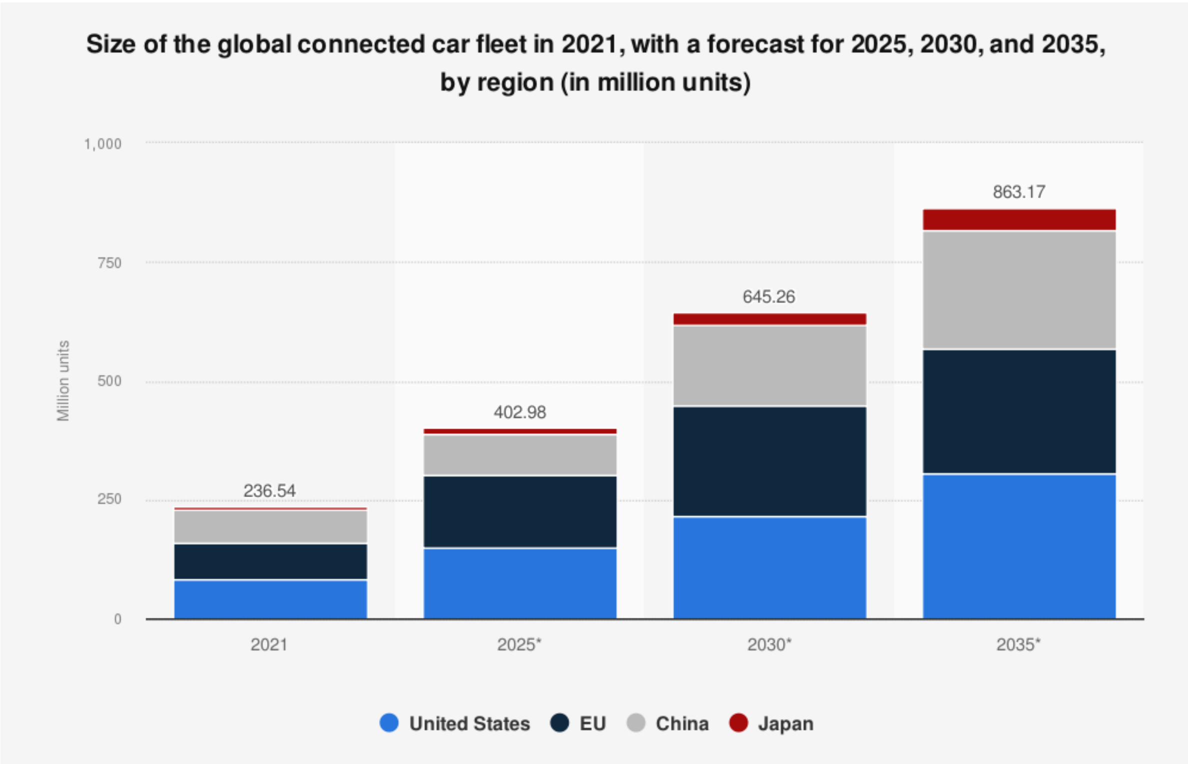

Figure 1.2: Size of the global connected car fleet estimation (Statista, 2021)

Despite the technical origin of a communications network, the development/implementation of such a solution on the infrastructure is more than just a technical challenge. Both institutional aspects, such as regulations or subsidies, as well as social considerations, including ethical usage of generated data and social acceptance of the stakeholders, have to be additionally taken into account. In addition, unexpected interdependencies of these factors and the emergence of disruption cannot be ruled out. Hence, an approach that integrates these layers into the design is needed. Therefore, the socio-technical systems perspective combining institutional, infrastructural, ethical, technical, industry, and human behavior layers can benefit the development of such intervention.

To contribute to future mobility challenges, this work aims at providing an interdisciplinary view that copes with the complexity of vehicular communication networks and future developments. This view intends to improve system understanding and guide VCN design efforts to meet the EU´s Vision of the next-generation transport infrastructure objectives. Hence, this work contribution is to provide a socio-technical on the VCN concept.

1.2. Scientific Relevance

As described above, future requirements, such as the amount of data, challenge the current vehicular communication network. In addition, the EU has seen an annual increase in vehicles on its roads which potentiates the road network´s problems (Eurostat, 2023). This challenges the EU targets of traffic reduction and accident fatalities. Duivenvoorden (2010) and Retallack and Ostendorf (2020) identified that an increased amount of vehicles on the road resulted in more incidents reported. Analogously, the rate of traffic congestion rises with the number of accidents. Thus, the number of vehicles correlates with the aforementioned problems. Therefore, decision-makers are confronted with the issue of combining growth with institutional goals.

An approach to deal with these problems is to enhance technological capabilities. As vehicles are increasingly equipped with sensing options, advanced computational functionalities such as autonomous driving can be realized. Hence, scholars such as Mishra et al. (2023) or Wan et al. (2021) are focusing on technological advancements. However, due to the application´s excessive use of resources and the vehicle´s limitation of onboard energy, solutions are needed to address this trade-off.

Future vehicular communication networks could contribute to the challenge by assisting this trade-off. For this, significant efforts from institutional and technical perspectives must be made to realize such an endeavor. Concepts such as the Internet of Vehicles (IoV) have been proposed in the literature but remain conceptual, with a prime focus on technical functionality. Hence, important institutional and social aspects are underexplored. Table 2.4 summarizes the main technical concerns mentioned by the authors from the literature review.

Please note that Silva and Iqbal (2019) provides ethical rules for the SIoV context resembling a part of the social subsystem. Hereby, the SIoV refers to a communication function for the social networks of neighboring connected vehicles and not the entire VCN. Therefore, applicability is questionable. In addition, Iqbal (2018) analyzes the technical aspects of the IoV regarding ethical design rules, thus, partly addressing the socio-technical aspects of a system perspective. However, to the best of our knowledge, no reflection on a multidisciplinary view incorporating institutional elements and the relationship to the technological subsystem are addressed in scientific literature, thus, leaving important aspects out as VCNs are socio-technical systems.

Therefore, a knowledge foundation addressing this is needed to help decision-makers and designers determine a design for the next-generation vehicular communication networks that cope with future developments and contribute to the EU mobility objectives. To address this issue, the following research question is derived:

Research Question: What are fundamental socio-technical factors to consider in a future European vehicular communication network design?

1.3. Problem Decomposition

The research question aims at contributing to the introduced problem above. Since the problem is a complex issue in a socio-technical system, the question is decomposed. This is summarised in Figure 1.3 and intends to show the individual components and sub-problems of the research question. The following paragraphs introduce the three subcomponents.

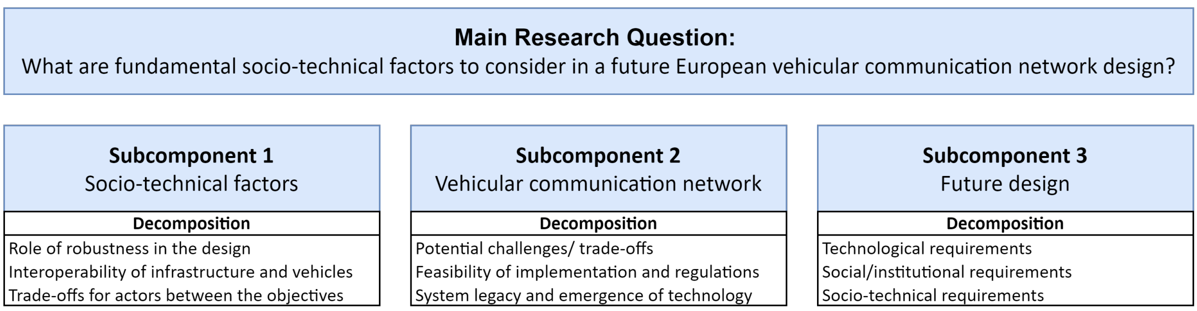

Figure 1.3: Problem decomposition of the research question

Vehicular communication network To contribute to a future design of a vehicular communication network, the current and anticipated solutions must be analyzed. It is crucial to critically reflect on their trade-offs and challenges to understand the validity of an approach. Further, technical and complex artifacts within the vehicular communication network must be evaluated on meaningfulness and feasibility for the technical and social subsystem. These indications can provide insights into the fundamental questions about the value investment rate and value for society. In addition, identifying the system´s path dependency on prior decisions, especially of the geographical context, can contribute to a more holistic understanding. Lastly, the emergence of new technologies might affect the development of networks; thus, incorporating openness to uncertainty should be considered.

Future design Since vehicular communication networks are socio-technical systems, the points above must be considered from a system perspective. For this, relevant requirements for future systems can be elicited from the abovementioned sub-component. Hereby, the problem splits itself into the social/institutional, technical, and socio-technical points of view, whereby the latter is particularly relevant to the identified knowledge gap. These requirements will result from understanding the interactions or interdependencies of the technical and social subsystems. Specific attention should be paid to aligning the institutional side with industry voices. As the EU has set targets for intelligent transportation and is investing in research of specific technologies, strong implications for VCN design choices are derivable. Hereby, challenging aspects such as heterogeneity of the actors (e.g., vehicles or institutions) and technology (e.g., infrastructure hardware or communication type) must be incorporated to ensure an open system. Further, the technical challenges and constraints must be considered to ensure the continuity of the concept. Here the technical challenges identified in the scientific relevance chapter can be analyzed. Critical things to tackle are handover and seamless switching of a vehicle's connection to a new provider or edge, latency optimization, and bandwidth congestion.

Socio-technical factors The last component of the question highlights the characteristic of the problem. A potential solution must address the deeply inherited socio-technical properties of a vehicular communication network. For this, the focus is set on the interoperability property of a VCN as it resembles a key challenge that connects the social and technical systems. Further, the role of robustness in VCNs must be explored as it resembles another fundamental component of the system. VCNs are highly dynamic due to their high mobility and are also part of critical infrastructure that ensures security/safety for humans. Hence, robustness and interoperability are the keys to coping with these challenges. Therefore, as is so often the case with complex systems, these properties must be seen as a central element for all sub-components as it defines the ability of the VCN to continue functioning correctly over a wide range of conditions (Gribble, 2001). Furthermore, these attributes are selected as they play a significant role in the interactions between the social and technological subsystems of a VCN, hence, represent a socio-technical system perspective.

1.4. Research Questions

In alignment with the Peffers et al. (2007) Framework and the problem decomposition, sub-questions are formulated based on the main research question. A detailed description of the questions is presented in Chapter 3.2.

SQ1: What is the complexity in which a future European vehicular communication network will be developed?

This research question aims at analyzing the stakeholder complexity to understand the impact of this social system on the VCN design. This understanding provides the basis for analyzing the technical system and identifying the interactions between these subsystems.

SQ2: What are the system requirements of a robust and interoperable vehicular communication network, considering the socio-technical aspects?

As stakeholder complexity is understood, the second research question analyzes vehicular communication networks' current and future requirements. For this, the technical subsystems must be explored in the context of the social system's implications to synthesize the socio-technical context. Hereby, the question intends to identify design challenges and relationships concerning the robustness and interoperability properties of the network to support further work and decision-makers.

SQ3: How feasible are the complexity abstraction and system requirements regarding granularity, understandability, and correctness?

As the socio-technical system perspective is established, its validity and feasibility must be evaluated. Thus, sub-question three intends to demonstrate and evaluate the designed artifact of sub-question one/two and, subsequently, how they assist the design of vehicular communication networks. By this evaluation, insights for designers of a VCN can be generated.

1.5. Systems Perspective and Link to CoSEM Program

Introducing a VCN resembles an integration of a socio-technical system in the complex road infrastructure system. Thus, it represents a system of systems which is why a multidisciplinary approach is crucial when designing a specific component. This includes the institutional side represented by policy-making within the EU and member states and the technical communication components and limitations. In addition to that, the interrelationships and interactions within these subsystems play a crucial role. These socio-technical components of a VCN take place in various temporal, spatial, and institutional scopes. Hence, the system perspective must be incorporated into the design to ensure the consideration of the system legacy and interconnections. Not only the design resembles a complex challenge, but also the operation and the ethical implications of the VCN. Human behavior impacts the system's operation by demanding and using the network within a few moments through their usage and vehicle type. This implies a high system dynamic caused by the human component, which must be represented in the infrastructure scalability and efficiency design and subsequently requirements (Bréhon–Grataloup et al., 2022). Lastly, VCNs have an ethical layer that further complicates the design as system failure causes fatal situations (Musa et al., 2022). Hereby, responsibility allocation, safety regulations, and privacy concerns are part of the challenge and must be incorporated into the design.

Therefore, this thesis topic fits into the Complex Systems Engineering and Management (CoSEM) study program as it deals with the VCN's complexity and elaborates on the technical requirements, social requirements, and socio-technical interactions of a future VCN.

1.6. Thesis Outline and Scope

This work is divided into nine chapters. Chapter 2 lays the theoretical foundations to understand this work by providing background information about socio-technical systems, vehicular communication networks, and systems engineering. Further, the literature reviews of this thesis are presented. Chapter 3 introduces the methodology of this thesis consisting of a research approach and research framework. Thereafter Chapter 4 defines the VCN problem space by analyzing the objectives of the EU and the Government of the Netherlands. Chapter 5.2 shows the results of a stakeholder analysis. Based on these findings, a system analysis is performed in Chapter 6. In Chapter 7, the findings of this work are evaluated. Chapter 8 discusses the outcome of this work, including the implications of the research questions, societal relevance, and limitations. Lastly, Chapter 9 summarizes this work's contributions, provides stakeholder recommendations, and gives a future outlook.
This thesis's institutional and geographical scope is set to the EU, with the case study of the Netherlands as an example. Furthermore, vehicular communication networks are reflected from the highway infrastructure perspective.

2
Background

To understand the problem´s complexity that this work is addressing relevant concepts must be understood. Hereby, this chapter follows the top-down approach by providing the abstract concept of socio-technical systems in Chapter 2.1 and specifying this concept down to vehicular communication network in Chapter 2.2. Thereafter, systems engineering is introduced in Chapter 2.3 resembling the bottom layer of this work. Based on the understanding of the concept, a literature review of vehicular communication networks is conducted in Chapter 2.4. Lastly, the academic knowledge gap of this work is formulated in Chapter 2.5 with regard to the literature review.

2.1. Socio-technical Systems

The term socio-technical systems (STS) refers to systems incorporating technical artifacts in a social context. This means that technologies are placed and intertwined in a broader context of policies, regulations, economics, human-decision making, and ethics rather than viewed isolated. Moreover, numerous dynamic entities with changing interests and influence exert their power over the system, leading to the creation and evolution of multiple layers across distinct time periods. A complex artifact emerges within the STS from these interconnections of perspectives and path-dependent development.

Time scale	Social subsystem	Technical subsystem
Embeddedness *Mostly emergent*	Tacit conventions and prior decisions	Tacit conventions and prior decisions
Institutional environment *Emergent/deliberate*	Division of powers; assignment of jurisdiction: legal framework: general definition of property rights	Selection of standards, technology selection architecture
Governance *Deliberate/emergent*	Ownership; form, organisation, and methods of regulation; market design (entry number of licencees, etc.	Design of specific technical artifacts, protoocls and routines to govern operational decisions
Operation and Management *Deliberate*	Regulation of prices and conditions, antitrust enforcement, social regulation	Execution of operational decisions

Figure 2.1: Design decisions and emergence in socio-technical systems from (Bauer & Herder, 2009)

An example of a highly complex socio-technical system is the road network of the European Union as indicated in Figure 2.2 (Geels et al., 2017). Hereby, the STS can be decomposed into a diverse range of technical artifacts such as traffic systems, vehicular communication networks, vehicles, and roads. These artifacts were created, implemented, and changed over the decades.
However, the road network also consists of social aspects shaping its existence, maintenance, and expansion. Each member state has a complex and unique organizational structure that decides on these aspects in accordance with the higher-level EU directives.
This results in a co-evolution of technical artifacts and a constant mutual influence of technology on institutions and vice versa (Bauer & Herder, 2009).
To assist in designing such socio-technical systems, these two layers can be analyzed (Shin, 2014). For this purpose, the following paragraphs are referenced to Bauer and Herder (2009) design decision

matrix, which categorizes the social and technical subsystems according to the time scale. This categorization was adapted from Williamson (2000) and can be seen in Figure 2.1. Hereby, the timescales are separated into Embeddedness (10^2 to 10^3 years), Institutional environment (10 to 10^2 years), Governance (1 to 10 years), and Operation and Management (Continuous adjustments) (Williamson, 2000).

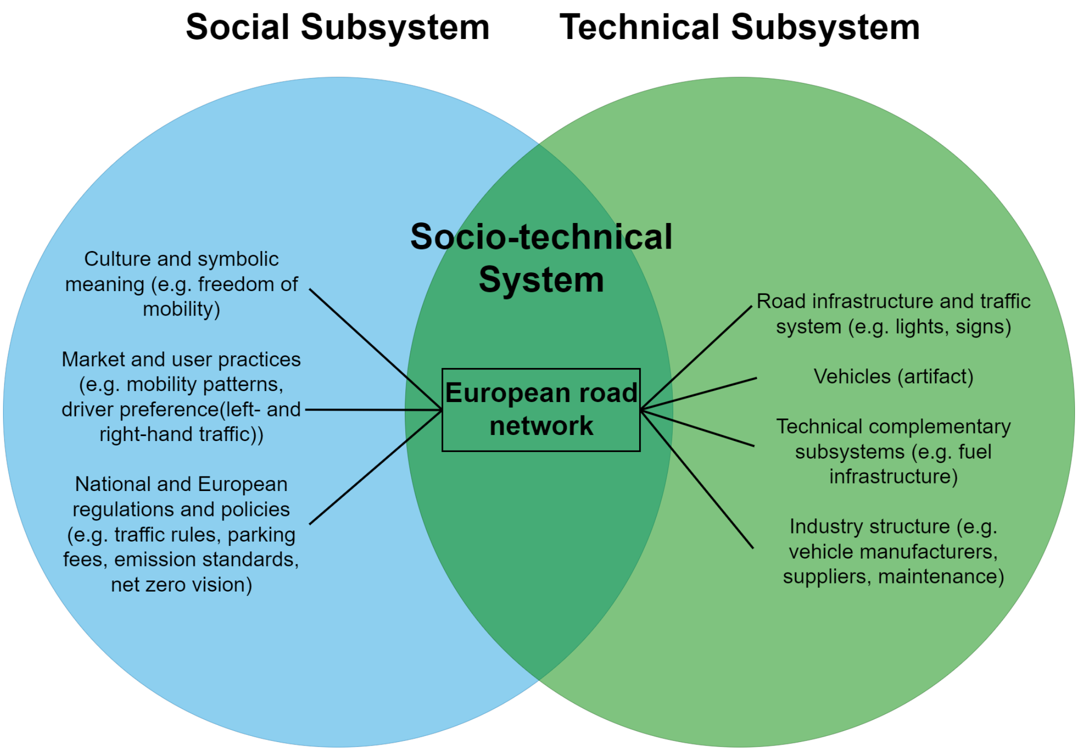

Figure 2.2: The socio-technical system of the European road system (Source: Adapted from Geels et al. (2017))

2.1.1. Social Subsystem

When dealing with the social subsystem, the social dynamics between humans are considered. These humans can act as individuals or organizations continuously forming the socio-technical system. Hereby, rules are formed, from conventions that emerged over centuries to dynamic adjustments dealing with recent developments. Within these social rules, ethical considerations according to the corresponding society are deeply embedded, shaping the embeddedness of the social subsystem. Further, this embeddedness resembles the path dependency of the social system as their principles are not dynamic and persist over generations.(Williamson, 2000).

In accordance with the embeddedness, the social subsystem incorporates an institutional environment setting the formal rules of the game by distributing power in the system and allocating responsibilities. In terms of the exemplary EU road network, the emergence of the EU can be seen as an institutional environment. The transition from individual states to the alliance changed the formal rules of the game by reallocating power in road infrastructure decision-making, for instance, cross-border road development.

Based on the emergent environment, the governance of the EU road system concludes contracts or decides regulations that Williams calls the play of the game. This part of the social subsystem can be exemplified by the EU Net zero vision of the future transport system as it spans a road map until 2050. Not only does this play of the game impact the continuous operation and management of the social subsystem, but also the technical subsystem.

An example of the entanglement of the layers and subsystems is the ban on Huawei´s 5G infrastructure equipment in several countries (Radu & Amon, 2021). The Chinese company is suspected of carrying out information espionage for the state via critical infrastructure. This threat of technical artifacts under the social influence has led to governance decisions that influence the communication network, thus, the technical subsystem.

2.1.2. Technical Subsystem

On the other hand, the technological subsystem deals with the technology itself. With the technical detail considered in this work, the layers and their interconnections are governed by the laws of nature and physics. Higher-level design choices constrain and enable developments. Further, new designs or technological advancements might be less dynamic due to their path dependencies and the cost of significant investments in socio-technical systems. Please note that designing in the technical subsystem focuses on technology, however, the decisions or restrictions for technology and its development are made by humans in the social system. This interplay can be identified on every layer of the matrix. The emergence of prior large-scale technology systems, such as the first road networks for countries in Europe, can be allocated towards the embeddedness layer. For instance, their general objective of being robust and efficient in transportation guides the lower layers in an informal way.
The lower institutional layer represents the decisions of the corresponding social layer for broad variables of the technical artifact. In terms of the road network, the general understanding of the regulation of the road by traffic lights and signs or the characteristic of roads being bidirectional can be examples for this layer. These design paradigms shape the technical construction of the road network.
The responsibility of the technical system's governance is to plan and design specific artifacts within the system, including the architecture of the technical systems and the control processes. These artifacts should be designed in a way that allows them to be executed and maintained by the operation and management layer. Considering these complex constraining and interacting layers horizontally, vertically, and diagonally, a complex artifact emerges within the socio-technical system.

2.2. Vehicular Communication Networks

As described above, the EU road network resembles an upper-level socio-technical system. It represents a system of systems as technical, social, and socio-technical subsystems interact and unite to form this road network. One of these subsystems is the vehicular communication network responsible for the road's communication between actors and entities. It involves numerous actors, including vehicles, pedestrians, and network operators, leading to emergent behavior. The system is further characterized by deep uncertainty, influenced by factors such as weather conditions, accidents, and interactions between social and technical subsystems, including communication protocols and social norms of drivers and pedestrians. Furthermore, technical artifacts such as wireless communication technology are the foundation for the network. Thus, it can be classified as a complex or socio-technical system itself.
The following subchapters introduce common concepts of VCNs, including the overarching scientific term Internet of Vehicles describing future vehicle-to-everything communication and VANET a Vehicular Ad Hoc Network. These concepts are introduced as they represent different terminologies and research directions impacting VCNs.

2.2.1. VANET

The Vehicular Ad Hoc Network is an infrastructure-less network that evolved as an application of Mobile Ad Hoc Network (MANET) (Rasheed et al., 2017). Ad Hoc translates to nodes establishing connections and their configuration to the network without infrastructure, thus, a central entity managing the process. For the purpose of this work, MANETs can be understood as a mobile peer-to-peer network without relying on a master node. Each participating node can send and receive data to other nodes close to its range. Moreover, nodes can bridge traffic within the network or the internet in case of a connection. An exemplary application of this technology is military communication in rural areas or emergency response where infrastructure is damaged.
These principles are also incorporated in the VANET. Hereby, communication is enabled between vehicles (nodes) with neighboring vehicles (V2V) by dedicated-short-range-communication and vehicles to infrastructure (V2I) by cellular communication technologies (Annoni & Williams, 2015). This concept is shown in Figure 2.3. A unique characteristic of this network is inherent to the nature of the vehicles themselves. High mobility causes a short lifetime of established links and frequent switching between networks which poses a different context than the MANET. A comprehensive study highlighting the differences can be found in Al-Sultan et al. (2014).

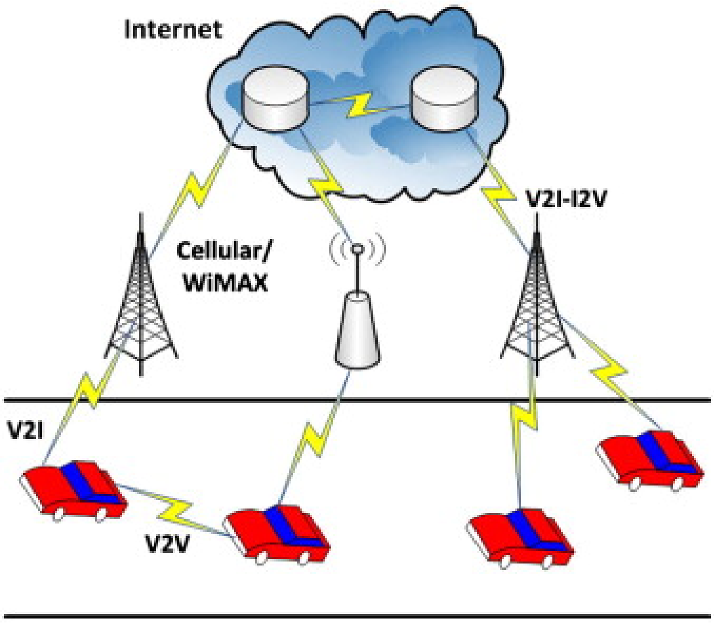

Figure 2.3: VANET concept (Olariu & Weigle, 2009)

The main purpose of the VANET is to improve driving safety and manage traffic (Al-Sultan et al., 2014; Rasheed et al., 2017). More recent definitions include infotainment as an objective, however, no general consent can be identified. These objectives are realized by VANET´s collision warnings, traffic sign alerts, and traffic overview on site. Further, data can be retrieved and sent about the road and traffic situation if the vehicle is within range of communication infrastructure. On the one hand, this makes the system robust as it is not relying on infrastructure and only responds to local events such as an accident or a car braking hard. However, in reality, the harsh road environment causes signal attenuation and packet loss through buildings or trucks blocking the signal (Lu et al., 2014). On the other hand, its ad-hoc character limits possible future applications based on real-time communication or involving a larger part of the system such as route redirection. VANETs are part of vehicular communication networks and can be a way of communication on the road. The most prominent example of a VANET is the communication protocol ITS-G5 introduced in the EU.

2.2.2. Internet of Vehicles

The Internet of Vehicles resembles an anticipated next step from the current vehicular ad-hoc communication network (Zhang & Letaief, 2020). This transition adjusts the ad-hoc and infrastructure-less character of the VANET to a real-time communication network which is partly infrastructure-based (Sakiz & Sen, 2017). Hereby, the IoV aims at connecting all road actors and entities equipped with sensors and network access to build an internet on the road achieving reliable data exchange and advanced data processing (Li et al., 2023). Therefore, it allows the vehicle to communicate to everything (V2X) that is connected to the network. This concept is shown in Figure 2.4. It is anticipated that these characteristics enable advanced intelligent transportation system applications such as seamless cooperative driving in autonomous vehicles but also internet-based infotainment applications and traffic congestion control (Musa et al., 2022). Thus, the objective of this highly complex network can be concluded as improving road safety, relieving traffic congestion, commercial entertainment, and reducing fuel consumption through smart communication and decision-making (Li et al., 2023). Currently, no standards are set for this concept.

Literature is elaborating on the potential of this concept, however, many technical but also socio-technical challenges remain unsolved and possibly unidentified. Furthermore, a strong focus on the technical challenges and possibilities can be identified neglecting potential social and institutional aspects. Since the transition from the VANET to a future communication network resembles a significant socio-technical intervention in the current network which potentially requires substantial investments, it is important to reflect on its purpose, limits, validity, and feasibility of the technical subsystem, so-

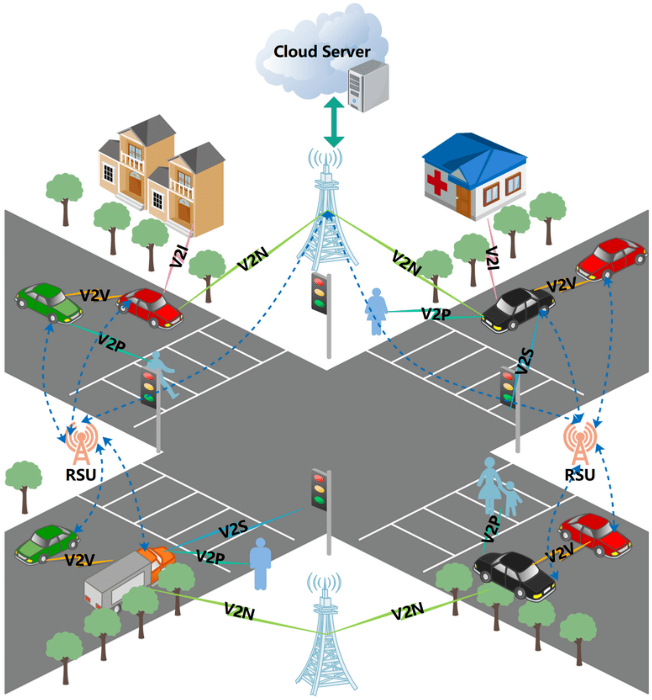

Figure 2.4: Vehicle to everything (V2X) in the Internet of Vehicle concept (Hamida et al., 2015)

cial subsystem and its dependencies. Thus, this work aims at providing a socio-technical view as a contribution to the concept.

2.3. Systems Engineering

Complex systems are characterized by their intricate interconnections, diverse components, and the emergence of unexpected behaviors from their interactions. Managing such complexity necessitates a comprehensive methodology that ensures all aspects of a system are considered throughout its life-cycle. A vehicular communication network is a socio-technical system of systems with a magnitude of design challenges, so a structured approach to design is essential. Hereby, systems engineering can contribute to the development and design.

Systems engineering is an interdisciplinary field that applies engineering principles, methods, and tools to address the complexity of large-scale projects. By focusing on the integration of various subsystems and their interactions, systems engineering aims to optimize the overall system's performance, reliability, and safety. It provides a structured approach to define system requirements, design architectures, manage interfaces, conduct trade-offs, and verify and validate system functionality. (INCOSE & Wiley, 2015)

To facilitate the practice of systems engineering, standards have been developed. One crucial standard is ISO 15288, titled "Systems and Software Engineering - System Life Cycle Processes". This internationally recognized standard provides a systematic and comprehensive framework for implementing systems engineering practices across different industries. ISO 15288 guides practitioners through the entire lifecycle of a system, from concept development to disposal, and emphasizes the importance of considering the system's stakeholders, requirements, interfaces, and risks. Applying systems engineering principles to the VCN design and development ensures the validity and reproducibility of the selected methods. Furthermore, it allows decomposing a large-scale VCN's complexity into its subcomponents while adhering to the engineering principles.

2.4. Literature Review

To identify the research gap, three literature review rounds are conducted according to the PRISMA 2020 guideline for reporting systematic reviews (Page et al., 2021). Hereby, the bibliography search engine Scopus is used. Only English-language articles which were accessible through the TU Delft institution are included. Figure 2.5 demonstrates the literature rounds and their purpose. Note that this literature review is part of the "Master Thesis Preparation Course" (SEN2321).

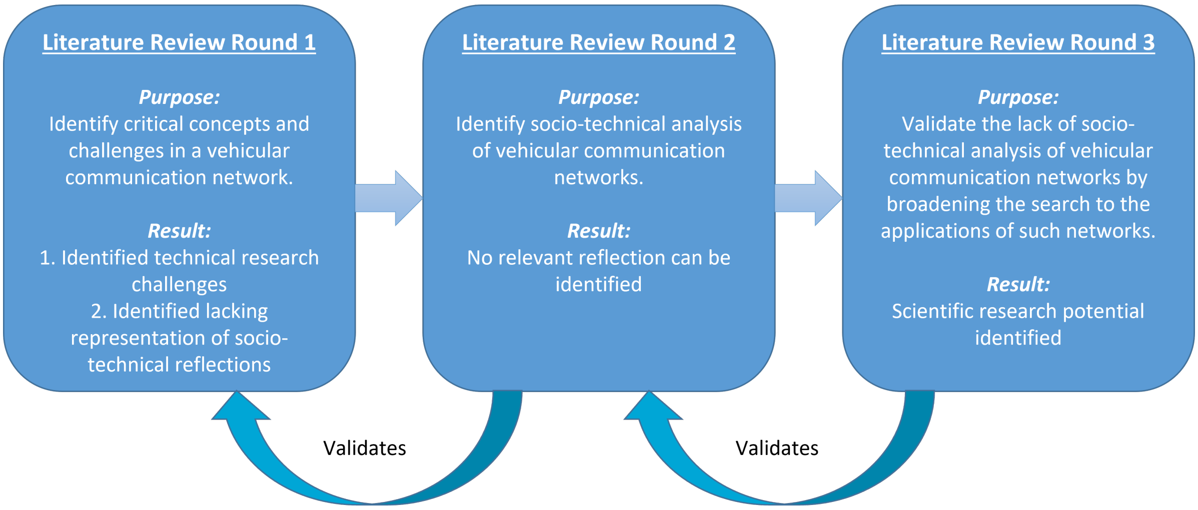

Figure 2.5: Literature review rounds

The first literature review aims at understanding the critical concepts within vehicular communication networks and their inherited challenges. Table 2.1 contains the first review's search strings, hits, and selected sources. Hereby, exclusion reasons are a strong focus on artificial intelligence, protocol proposal, or a strong focus on technical communication subsystems. Based on the relevant articles, the backward snowballing method was used to identify additional literature. In total, 13 articles were selected due to their feasibility of core concepts and identified research gaps within these concepts. Furthermore, Table 2.4 provides an overview of the selected articles and the corresponding scientific gaps. The literature review process is summarized in Figure 2.6 displaying the PRISMA 2020 diagram. In addition, to the identified research gaps, a lack of scientific reflection on the socio-technical properties of VCNs is identified.

Table 2.1: Search strings: First literature review

Search String	Scopus Hits	Selected Paper
"internet of vehicles" & "edge computing" & "connectivity"	12	7
"communication framework" & "Edge computing" & "vehicle"	4	1
"edge AI" & "autonomous driving"	9	4

The second literature review represents the focused version validating this underrepresentation. The aim hereby is to identify socio-technical analyses of VCNs. For this purpose, the accumulated search strings from Table 2.2 are used, and their hits are analyzed. Relevant and basic terminology, including synonyms, is used to broaden the search. In addition, the term "Social internet of vehicles" is explored in the context of the European Union. This term indicates that a social perspective might be included, however, the authors define social as either an interaction between computer systems or as an application of the IoV focusing on creating a temporary social network between passengers in nearby vehicles. Nonetheless, the term is explored systematically to review its relevance. As mentioned above, hits and selected sources are presented. Twenty papers are identified and screened on SCOPUS. Papers not focusing on vehicular communication networks or their challenges beyond the technical subsystem are excluded. Two publications dealing with ethical considerations are identified. To the best of our knowledge, none of the papers address the research gap or provide an analysis going beyond the technical discussions of future or current communication networks. Thus, a scientific gap can be concluded.

Furthermore, a gap for a socio-technical analysis can be identified as no publications address the interconnections between the domains. To explore this gap, a third literature round is conducted to analyze

Table 2.2: Search strings: Second literature review

Search String	Scopus Hits	Selected Paper
("IoV" OR "Internet of Vehicles" OR "Vanet") AND ("socio-technical" OR "multi-disciplinary" OR ((institutional OR holistic OR societal) AND (analysis OR aspects OR approach OR perspective)))	0	0
("Social Internet of Vehicles" OR SIoV) AND "EU"	14	0
(VANET OR IoV) AND (ethical OR ethics)	6	2

the socio-technical VCN properties from the application perspective. In addition, this analysis serves to generate input for the requirements elicitation. For this purpose, the search terms are supplemented by anticipated VCN functionality such as autonomous driving, infotainment, and offloading. Furthermore, the geographical scope is added as a limitation, and unsuitable domains such as agriculture and sea engineering are excluded. Lastly, only articles that contain a socio-technical analysis/reflection and were published after 2013 are considered. The search terms and corresponding hits are presented in Table 2.3.

Table 2.3: Search strings: Third literature review

Search Term	Scopus Hits	Selected Paper
(((((autonomous OR selfdriving) AND (car OR vehicle)) OR (its OR "intelligent transportation system")) AND ("socio-technical" OR "multi-disciplinary" OR ((institutional OR holistic OR societal) AND (analysis OR aspects OR approach OR perspective))) AND (eu OR "european union")))	8	3
(((infotainment) AND (car OR vehicle)) OR "intelligent transportation system") AND ("socio-technical" OR "multi-disciplinary" OR ((institutional OR holistic OR societal) AND (analysis OR aspects OR approach OR perspective))) AND europe AND NOT (aerial OR agriculture OR aircraft OR sea)	2	2
(((offloading) AND (car OR vehicle)) OR "intelligent transportation system") AND ("socio-technical" OR "multi-disciplinary" OR ((institutional OR holistic OR societal) AND (analysis OR aspects OR approach OR perspective))) AND NOT (aerial OR agriculture OR aircraft OR sea)	0	0
(((connected) AND (car OR vehicle)) OR (its OR "intelligent transportation system")) AND ("socio-technical" OR "multi-disciplinary" OR ((institutional OR holistic OR societal) AND (analysis OR aspects OR perspective))) AND NOT (aerial OR agriculture OR drones OR aircraft OR sea) AND "EU"	274	23

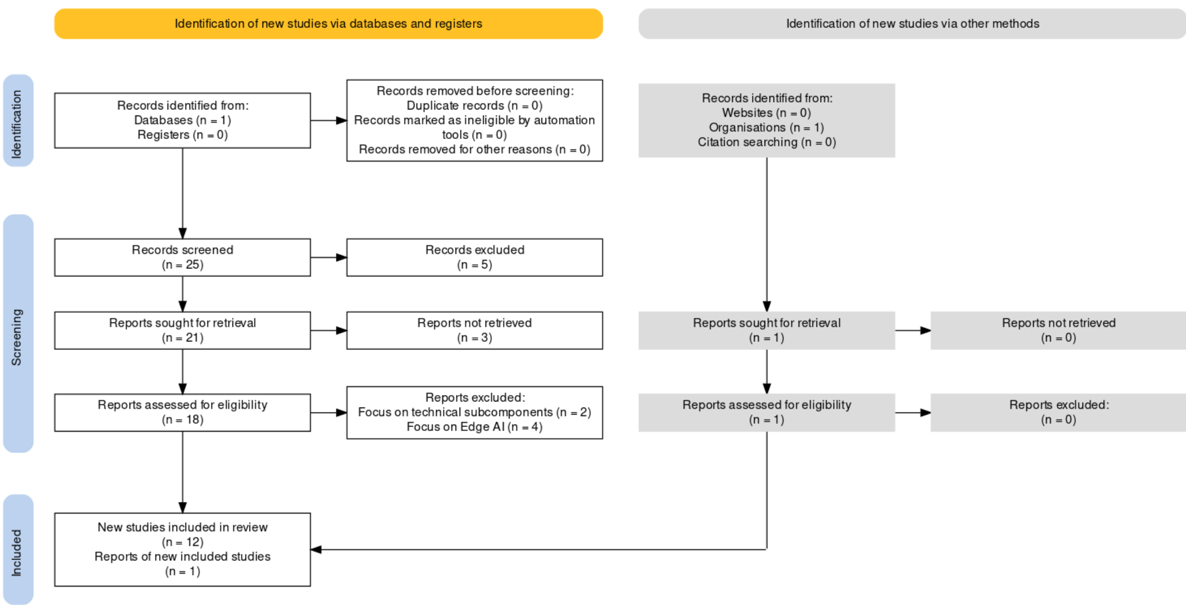

Figure 2.6: Prisma 2020 diagram: First literature review

2.5. Academic Knowledge Gap

The first literature review addresses the relevance and challenges of new solutions for vehicular communication networks. Potential applications and road/driver security improvements are mostly mentioned as a basis for the argumentation. However, it is noticeable that the identified challenges and the publications themselves have a technical focus. None of the identified works addresses challenges and dependencies outside the technical subsystem, which suggests a lacking representation of social aspects, institutional influence, and socio-technical thinking. Only privacy and security concerns are mentioned by the authors but are related to the technical origin of the problem. Moreover, it is striking that proposed solutions such as edge computing are highlighted, and technical challenges are identified, but related infrastructural challenges are barely mentioned. The selection of the search terms may cause this lacking representation. Thus, the second literature review concisely searches for the potential knowledge gap.
Nevertheless, multiple technical knowledge gaps can be identified by the first review. Table 2.4 shows the main clusters from the first round.

Table 2.4: Technical research gaps

	Resource efficiency	Privacy and Security	Communication / Connectivity	5G Architecture / Integration	Multi-path	Orchestration
(Sharma & Kaushik, 2022)	X	X	X			
(Wan et al., 2021)		X		X		
(Bréhon–Grataloup et al., 2022)		X			X	x
(Vermesan et al., 2021)	X	X			X	x
(Mahmood, 2020)	X	X	X	X		
(Chen et al., 2018)	X	X				X
(Ibraheem, 2021)						X
(El-sayed & Chaqfeh, 2019)	X	X	X			
(Kaiwartya et al., 2016)			X			
(Singh et al., 2020)			X	X	X	X
(Bwalya, 2020)	X		X	X		
(Fadhil & Sarhan, 2020)			X		X	X
(AECC, 2021)			X			X

The following paragraph briefly summarizes the identified technical challenges of the technical subsystem. After that, the finding of the second and third reviews are highlighted, and the main research question is derived.

First literature review As edge computing is a novel topic, no universal framework employing the technology as an enabler in the vehicular environment is introduced in literature (Fadhil & Sarhan, 2020). Multiple considerations must be done and challenges tackled for such an endeavor. Ibraheem (2021) identified the challenge of feasible solutions within edge communication as data is inconsistent on roadside units (communication units along the road) and in the IoV. Further, El-sayed and Chaqfeh (2019) pointed out that edge deployment in the IoV first must address processing capabilities, signal transmission, and limited energy. These challenges and the heterogeneity of the IoV complicate the understandability of the ecosystem resulting in a lack of frameworks. Moreover, Mahmood (2020) pointed out that the desired IoV characteristic of a scalable architecture itself remains a field of research as the network itself is exposed to not only a significant number of vehicles/nodes but also to a time dependency of capacity utilization as nodes drastically increase and decrease over time. Substantial efforts must be made to archive and ensure this characteristic combined with the aforementioned challenges.

In addition to this context, multi-access networks, which simultaneously use different communication technologies and providers, as well as the orchestration between the edges, remain a field of research as no standards are yet introduced (Chen et al., 2018; Fadhil & Sarhan, 2020; Sharma & Kaushik, 2022). Therefore, a need for a protocol enabling and orchestrating simultaneous communication of vehicles with other edges in the IoV for latency and processing purposes can be identified (Fadhil & Sarhan, 2020; Sharma & Kaushik, 2022; Vermesan et al., 2021). This communication protocol should further consider seamless switching between the communication channels and edges due to the mobile character of the IoV (Wan et al., 2021). This is mandatory according to Fadhil and Sarhan (2020) and Vermesan et al. (2021) to achieve a low latency enabling the applications of the intelligent vehicle and reducing energy consumption. Another crucial point is privacy and security concerns at the edge, which several authors acknowledge, thus, it needs to be taken into account.

Second and third literature review The second review results in no relevant scientific articles dealing with vehicular communication networks from a socio-technical perspective. To the best of our knowledge, no publications analyze social aspects such as the institutional role within these networks. Moreover, neither of them addresses the dependencies between the technical and social subsystems. Please note that Silva and Iqbal (2019) provides ethical rules for the SIoV context resembling a part of the social subsystem. In addition, Iqbal (2018) analyzes the technical aspects of the IoV regarding ethical design rules. The findings of these publications are considered for the analysis of the social subsystem. To conclude, no design for future vehicular communication networks from a socio-technical viewpoint can be identified. An evident lack of institutional and social analysis of these networks is detectable. However, a multidisciplinary approach can be helpful to design a socio-technical system like the IoV. Therefore, the following research question is formulated to address the aforementioned technical but also socio-technical challenges:

What are fundamental socio-technical factors to consider in a future European vehicular communication network design?

3
Methodology

This chapter contains the methodology of this work. Firstly, the research approach in Chapter 3.1 is presented and aligned with systems engineering. Thereafter, the research framework that guides this work is introduced in Chapter 3.2. A detailed version of the systems engineering alignment is applicable in Appendix A.

3.1. Research Approach

To answer the research question and the corresponding problem breakdown, conceptional design work must be done due to its novel character. The main research question tackles how future vehicular communication networks need to be conceptualized, which is aligned with the design science research´s goal of developing and validating prescriptive knowledge (Kessler, 2013).
Moreover, the question implies that the outcome is a designed artifact resolving a question rather than explaining circumstances (Simon, 1988). Therefore, a design science research approach is applied to this work. Hereby, the Peffers et al. (2007) framework for design science about ICT systems is selected as guidance. This framework incorporates the designing steps of problem analysis, requirement conception, artifact design, implementation, evaluation, and communication which can be seen in Figure 3.1. According to this cycle, an in-depth socio-technical analysis of vehicular communication networks is carried out based on a literature review and expert interviews. Furthermore, Peffers et al. (2007) framework is advantageous for the VCN design due to the iterative but clear structure, which can be helpful with complexity. However, subprocesses in this cycle can vary in scope and execution depending on the project. Furthermore, no in-depth explanation of the execution and methods to be used in the steps of the design science framework is provided by the author. Based on the scope and topic of the thesis, the framework is complemented by systems engineering concepts to surpass the shortcomings.

The novel alignment of the systems engineering iso standards and their contribution to Peffers et al. (2007) design science framework is explained in Appendix A.

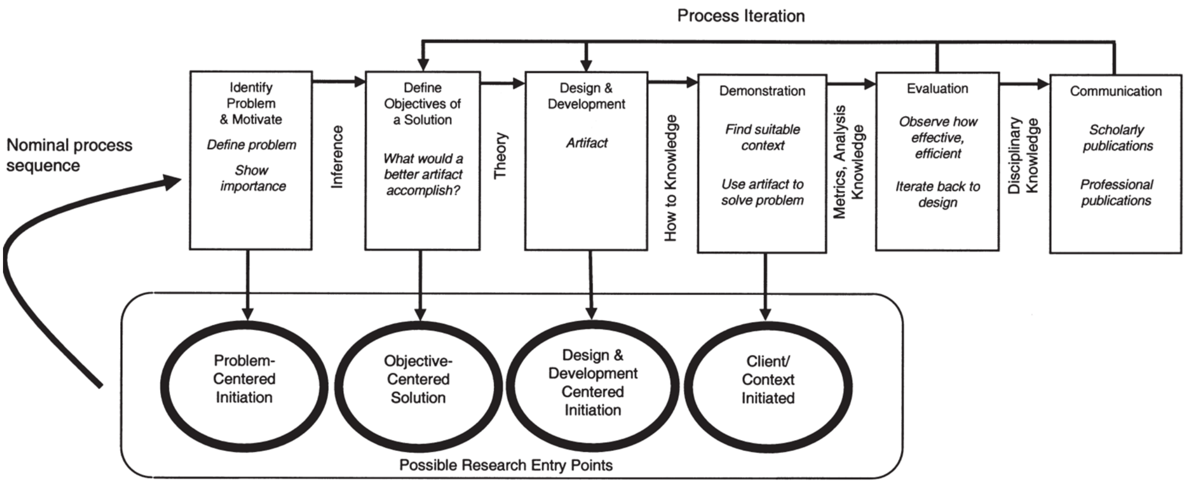

Figure 3.1: The Peffers et al. (2007) DSR Framework applied from Hevner (2007)

3.2. Research Framework

Figure 3.2 contains the research framework of this work. An enlarged version is applicable in Figure A.3 in Appendix A. Its purpose is to guide the research by linking relationships between the main research question and the subquestions. Hereby, the framework is divided into input, research flow, and output. The input contains methods and data sources necessary for the corresponding research sub-questions in the research flow section. Furthermore, the research flow section incorporates the deliverables of this work linked to the linked research question. Lastly, the output is described per sub-research question resembling each question´s gained knowledge and results. Each of these outputs contributes to the main research question. The research flow is further aligned to the design science research framework from Peffers et al. (2007). This ensures the integrity of the approach.
The following analyses each step (research sub-question) in the research flow based on their required input and anticipated outcome in a separate paragraph.

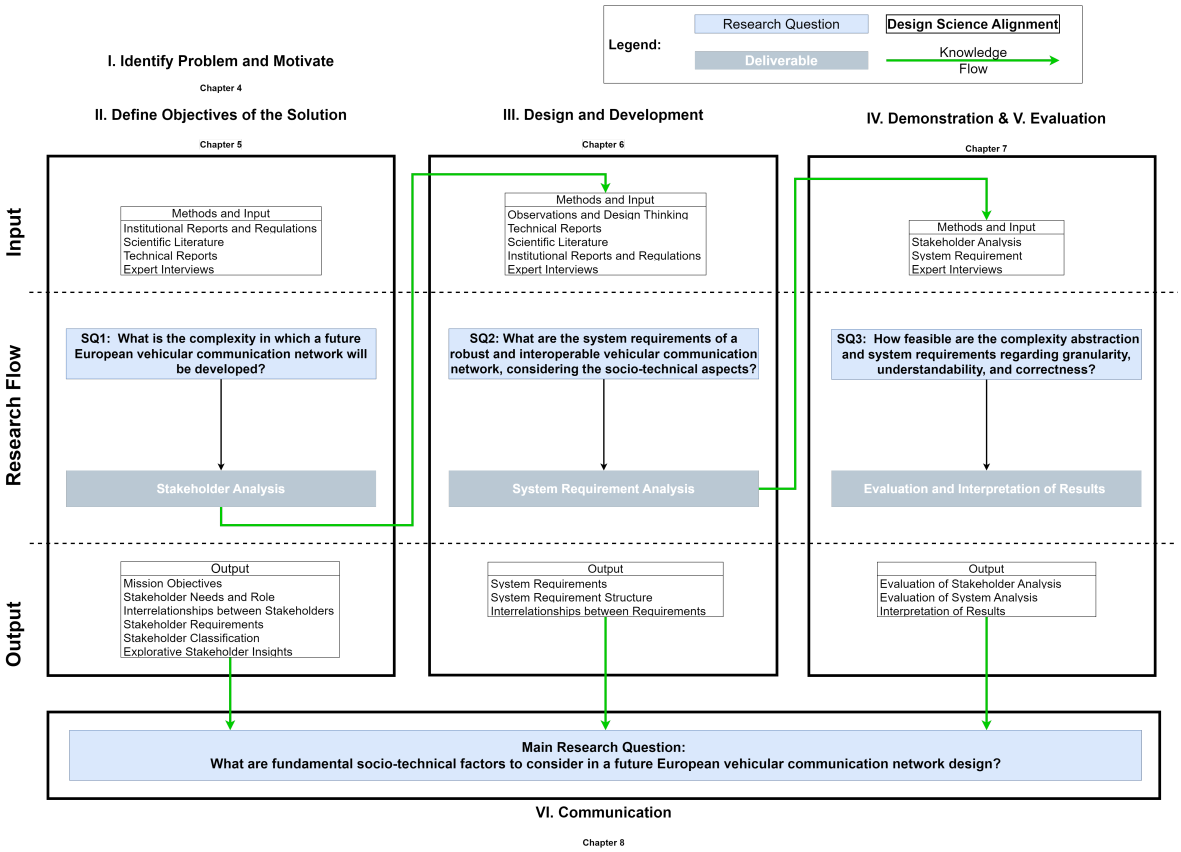

Figure 3.2: Research framework (Large version in Figure A.3)

First research question The first research question focuses on synthesizing an understanding of stakeholder needs and compositions in a VCN. Hereby, it is aimed to gather the information through a combination of a desk study and empirical data gathering. Technical reports, institutional regulations, and scientific literature are reviewed for the desk study. The high interest of industry, institutions, and science in future vehicular communication networks results in a base of existing knowledge. Therefore, the desk study is promising to build upon this prior work. However, due to the field's novelty, valuable data and insights can also be acquired through interviews, ensuring a scientific contribution. Therefore, expert interviews resembling the empirical data gathering will validate the findings and potentially provide further detail. It is critical to ensure the validity of the gathered interview data by double-confirming the information. This ensures that the interview insights will be novel, objective, and profound.
In order to define the problem space for a VCN in a Dutch European context, the mission of the relevant decision-makers is analyzed in Chapter 4. This step is intended to guide a solution space for the stakeholder analysis and ensures that the artifacts designed in this thesis address the problem (Hevner,

2007), thus, resembles Peffers et al. (2007) first design cycle step.
Thereafter, the objectives of the solution and subsequently the design artifact are defined by the stakeholder analysis in Chapter 5.2 representing Peffers et al. (2007) second design cycle step. From this analysis, stakeholders are categorized and described by their roles, tasks, and needs with respect to the problem space and current solution approaches. Further, the interrelationships are explored among these stakeholders. These outcomes generate insights into the complexity of the stakeholder constellations and how it impacts the VCN development. Hence, they contribute to answering the first research question.

Second research question The second sub-question aims at designing and developing the artifact of the thesis, thus, is aligned with the third step of the design cycle (Peffers et al., 2007).
Hereby, the observations of the stakeholder analysis are transformed into requirements and used as a starting point for the VCN system requirement analysis. Further, technical reports, scientific literature, and institutional reports/regulations are used as data input to define the state of the art and complement the system requirements. This input is analyzed, and a collection of key system requirements from a multidisciplinary view of the VCN is created and evaluated. Thereafter, these requirements are structured by design thinking methods to enhance understanding and make interrelations visible.
This ensures that the research contributions are embedded in the design artifact. For this, reflecting on the different subsystems and their respective domain is critical. Further, these interrelations and interactions between the requirements are analyzed to understand their importance and interconnections to the properties of such a design.

Third research question Based on the input of the stakeholder and system analysis, the third sub-question in Chapter 7 demonstrates and examines if the generated system perspective can guide the design of a future VCN. Hence, the fourth and fifth steps of Peffers et al. (2007) are aligned with this question.
For this, Venable et al. (2016) framework for evaluation in design science is applied to the expert interviews. Hereby, the experts demonstrate and evaluate the artifacts based on design, understanding, and context granularity. This input reiterates the result but is also taken to evaluate against the weighting of the system analysis to form an understanding of the focal points in the multidisciplinary design.

Main research question Each research question´s output contributes to the main research question as indicated in Figure 3.2. This approach is based on Peffers et al. (2007) introduced design science research approach. Hereby, the first research question is the process sequence of identifying the problem and defining the objectives of the solutions. Peffers et al. (2007) thereafter stage of design and development corresponds to sub-questions two. Lastly, sub-question three resembles the Peffers et al. (2007) process of demonstration and evaluation. This process is communicated by answering the main research question of the thesis and ultimately discussed in Chapter 8.

4
Mission Analysis

This chapter outlines the vision and current mission objectives for a future vehicular communication network. For this, the European and Dutch vision statements, strategies, and regulations are analyzed to describe the problem/solution space for future VCN development. As the Netherlands is a member of the EU, a joint analysis is made using the top-down principle. In Chapter 4.1 the objectives of the EU are summarised. After that, Chapter 4.2 focuses on the objectives of the Dutch government.

4.1. European Union

The EU Commission publishes each legislation term a strategic plan summarizing the most important short- and long-term goals. Within the most recent guidelines, the three key themes “European Green Deal”, “Fit for Digital Age”, and “Promoting our European Way of Life” can be applied to the development of a future VCN. Furthermore, the “Sustainable and Smart Mobility Strategy” communicates more specific objectives for future mobility. Lastly, the Union has an “ITS system legacy” from which VCN objectives can be derived. Table 4.1 summarizes these objectives based on their source.
The following paragraphs introduce each document and its relevancy for a future VCN.

European Commission strategic plan The strategic guidelines of “Promoting our European Way of Life” sets the ethical framework for a VCN. Thus, the overarching objective can be separated into various subtopics, such as user equality, service accessibility, data protection, consumer protection, and environmental concerns. As this is at an abstract level, the objective does not lead to functionality in the system but instead to fundamental considerations in all sub-parts of the system.
The second relevant guideline of the “European Green Deal” is an additional emphasis on the environmental aspects of the European core values. It is highlighted that the EU is committed to being climate neutral by 2050 (Emission reduction of 90% in the transport sector (European Commission, 2021d)) and to reducing their emission by 55% by 2030. Considering this target, the objective “A future VCN contribute to the Emission Reduction” can be derived. This constrains and guides VCN applications in an environmentally friendly direction but also the selection and deployment of technologies. Furthermore, life cycle considerations are implied, which points to the necessity of implementing circular economy principles.
The last relevant policy guideline “A Europe Fit for the Digital Age” contains Europe’s Digital Decade Framework. This framework specifies digital objectives, targets, and multi-country projects in a policy program that have direct implications for a future VCN as it resembles a large-scale cyber-physical infrastructure project. The four main targets impacting the VCN system are a digitally skilled population and highly skilled digital professionals, secure and sustainable digital infrastructures, digital transformation of businesses, and digitalization of public services. In accordance with these targets, the VCN-relevant objectives of the regulation are extracted and applicable in Table 4.1. Please note that according to the regulation, national digital decade strategic roadmaps will be published by the end of 2023, showing their plans and projects for a digital future.

Sustainable and smart mobility strategy In addition to these sector-unspecific objectives, case-related VCN objectives can be derived from the “Sustainable and Smart Mobility Strategy” and the ITS Legacy of the EU. The strategy highlights the importance of sustainability, smartness, and resilience of future transportation systems and subsequentially elaborated targets/objectives on various mobility means. Further, the EU commits within this document to a European ITS communication network and emphasizes its relevance for the EU core values and the digital transition. The derived core objectives in the context of the to-be-designed VCN are summarized in Table 4.1.

EU ITS system legacy Lastly, mission objectives from previous ITS pilots and the ITS directive can be concluded. To this end, the EU has laid four pillars as a foundation for future developments. The basis for this development is the ITS Directive delegated act, which aims at ensuring legal certainty. However, the member states rejected the directive, which is why it has no binding effect. Complementary to the directive, a C-ITS strategy was published, from which mission objectives can be derived. The completed pilots were summarised in the platform C-roads, and the findings and vision from these projects are documented in the platform C-ITS. These four pillars form a starting construct upon which the system analysis starting in the next Chapter is built. The overarching derived objectives from these documents are shown in Table 4.1. (European Commission, n.d.-a)

Table 4.1: EU objectives for the development of a future vehicular communication network

Source	Objectives	Document
Promoting our European Way of Life	• A future VCN adheres to European Core Values.	(European Commission, 2012; Von der Leyen, 2019)
A European Green Deal	• A future VCN contribute to the Emission Reduction.	(European Commission, 2021d; Von der Leyen, 2019)
A Europe Fit for the Digital Age	• A future VCN allows the interoperability of digital technologies and services where high performance, edge, cloud, quantum computing, artificial intelligence, data management and network connectivity work in convergence. • A future VCN has high security and privacy standards and complies with the Union data protection rule. • A future VCN is accessible to all. • A future VCN observes and enhances EU principles, rights, and values. • A future VCN has a secure and accessible digital/data infrastructure capable of efficiently storing, transmitting and processing vast volumes of data that enable other technological developments, supporting the competitiveness and sustainability of the Union's industry and economy. • A future VCN, including their supply chains, become more sustainable, resilient, and energy- and resource-efficient, with a view to minimising their negative environmental and social impact and contributing to a sustainable circular and climate-neutral economy and society. • A future VCN is resilient to cyberattacks.	(European Commission, 2021a, 2022a; Von der Leyen, 2019)
Sustainable and Smart Mobility Strategy	• A future VCN is socially accepted. • A future VCN adheres to the European Core Values. • A future VCN is cyber secure. • A future VCN contributes to sustainability and safety goals. • A future VCN has harmonized standards. • A future VCN contributes to connected and automated multimodal mobility. • A future VCN is sustainable, smart, and resilient.	(European Commission, 2020a, 2021c)
ITS Legacy	• A future VCN enables sustainable, efficient, and accessible transport systems in the long run. • A future VCN supports the energy-efficient transport system and technologies. • A future VCN contributes to optimising road safety and integration/interconnection of transport modes. • A future VCN allows the interoperability of transport services. • A future VCN helps to improve traffic management. • A future VCN is safe and secure.	(European Commission, n.d.-b, 2016a, 2019, 2021b; European ITS Platform, 2022)

4.2. Government of Netherlands

As member countries often have different or more stringent requirements for the implementation of the EU roadmap, the national vision is analyzed to identify potential deviations. In this context, the Government of the Netherlands advocates and commits to a future VCN and the implementation of autonomous driving infrastructure (Government of the Netherlands, n.d.-b). Therefore, compliance with the EU vision can be concluded. In addition, the Netherlands positions itself as a pioneer and trailblazer concerning transport innovation and smart mobility, which indicates its commitment and mission to large-scale implementation. Another indication of the validity of the summarized objectives in Table 4.1 is the signed Declaration of Amsterdam (Government of the Netherlands, 2016). This agreement is intended to lead the participants toward the development and implementation of connected and automated driving. Also, in this respect, the Netherlands has taken the initiative and demonstrated its vision with the Experimenteerwet zelfrijdende auto (law governing the experimental use of self-driving vehicles) with the aim to remove legal barriers (Government of the Netherlands, 2019). The identifiable mission objectives of the Netherlands are summarized in Table 4.2.

Table 4.2: Dutch objectives for the development of a future vehicular communication network

Objectives	Document
• A future VCN contributes to improving traffic flows on our roads in terms of safety, efficiency and environmental impact. • A future VCN enables Smart Mobility Applications. • A future VCN has coherent international, European and national rules. • A future VCN make use of the available data. • A future VCN ensure privacy and data protection. • A future VCN is interoperable at the European level and coordinates investments towards reliable communication coverage, exploits the full potential of hybrid communications, where relevant, and improves the performance of location accuracy. • A future VCN ensure the security and reliability of connected and automated vehicle communications and systems. • A future VCN is socially accepted. • A future VCN is based on global cooperation and common definitions.	(Government of the Netherlands, n.d.-b, n.d.-c, 2016; Ministry of Infrastructure and the Environment, 2016; Ministry of Infrastructure and Water Management, 2019)

4.3. Key Findings

It can be concluded that the vision of the member state Netherlands is mostly harmonized with the EU vision. However, considering the initiative taken so far, the Netherlands tends to take on a leading role in developing and deploying a VCN in Europe. This may be due to the self-imposed goals or the greater agility of a country. Due to the multitude of objectives at different levels, five overarching VCN mission objectives are synthesized. These objectives overlap with the European-Dutch vision and are guiding a future VCN and, subsequently, for this work.

- OBJ1: A future VCN contributes to sustainability and safety goals.
- OBJ2: A future VCN enables efficient, standardized, modular, and heterogeneous communication.
- OBJ3: A future VCN allows interoperability of heterogeneous cyber-physical technologies and actors.
- OBJ4: A future VCN establishes a high level of security and privacy.
- OBJ5: A future VCN is socially accepted among all stakeholders.

5

Stakeholders in a Vehicular Communication Network

This Chapter provides a comprehensive stakeholder analysis. Firstly, relevant actors are identified, and a stakeholder classification in the context of a future vehicular communication network is proposed in Chapter 5.1.1. According to the classification, the stakeholders and their roles are set in relation to each other. This complexity mapping is the subject of Chapter 5.1.2. In addition, the system of interest for this work is defined. Based on these findings, a stakeholder analysis which consists of a desk study and interviews is presented in Chapter 5.2. In order to make the findings understandable and contextualize them, Chapter 5.3 positions the stakeholder in a power-interest grid and thereafter highlights the conflicts among them in Chapter 5.4. Finally, Chapter 5.5 transforms and summarizes the finding of the aforementioned chapters into guiding stakeholder insights.

5.1. Stakeholder Identification

The subject of this chapter is stakeholder identification. The learnings from this identification form the knowledge basis for the following chapters and the research question. As noted above, this is divided into three subchapters: stakeholder classification, stakeholder complexity mapping, and system of interest.

5.1.1. Stakeholder Classification

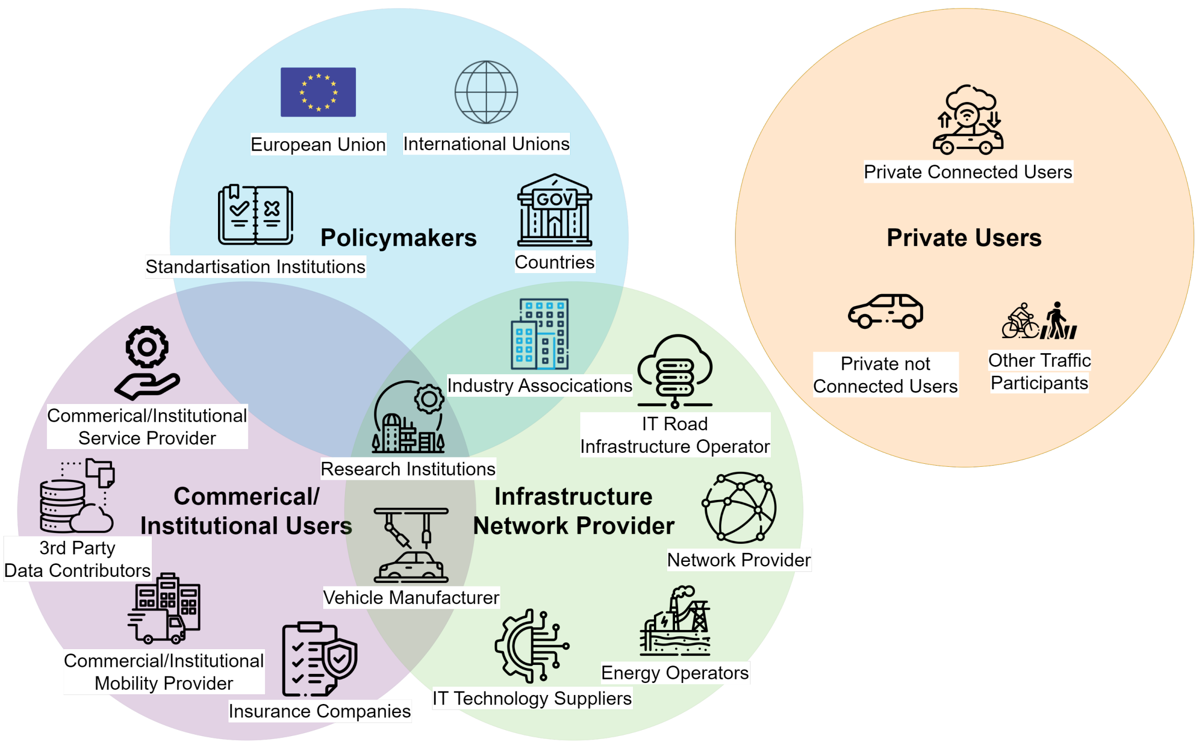

Figure 5.1: Vehicular communication network stakeholder classification

As described in Chapter 2.2, a vehicular communication network is a complex network containing multiple actors and their unions. In order to cope with the system´s inherited complexity, relevant actors must be identified and understood. For this Frötscher et al. (2022) pilot project stakeholder findings are used as a baseline and extended by Hamadneh et al. (2022). Furthermore, large-scale infrastructure projects are inherently multidimensional. Thus, the scope and viewpoint are crucial for analysis. Institutional stakeholders may have different views and interests in the system than the local network operator. Therefore, the viewpoint and scope of the system of interest must be clearly defined to design successfully.
For this work, the perspective of a system engineer responsible for bringing relevant actors together is chosen. The scope is set to design a vehicular communication network on the Dutch highway with respect to the EU´s influence and character. Despite this context, the rest of the system should not be neglected, and island thinking should be avoided. Therefore, a stakeholder classification is presented in Figure 5.1 aiming at supporting a multi-disciplinary design.
The classification separates the stakeholders into four categories: Private users, commercial and institutional users, network infrastructure providers, and policymakers. In the following, each stakeholder group is elaborated in a separate paragraph. A detailed description and role assignment of all stakeholders in the classification can be found in Table B.2.

Private Users The category of private users contains the stakeholders affected by the system without an economic interest. These actors are the end-users of the to-be-designed system, thus, their needs and interests can be given high priority. Further, this cluster additionally represents the ethical layer of the system as it addresses human behavior and needs such as safety. The private users can be distinguished into connected vehicles, not connected vehicles, and other road traffic participants such as pedestrians and cyclists.

Commercial and Institutional Users As the future vehicular communication network also promises commercial interest, commercial and institutional users can be identified as stakeholders representing the second cluster. This branch of the classification contains all actors who use the infrastructure for a business model. Hereby, it can be differentiated into commercial and institutional service providers or mobility operators, insurance companies, and data contributors. These user types provide essential needs to make use of the system economically. Therefore, this cluster can represent the economic and financial values of the socio-technical system. It shall be noted that vehicle manufacturers can partly be allocated to this branch, as they might be commercial network users. In this context, it is conceivable that this stakeholder uses its position as a data source to offer data or mobility services based on the vehicular communication network.

Network Infrastructure Provider Given this characteristic, the vehicle producers can additionally be assigned to the cluster of network infrastructure providers due to the critical role of data for the infrastructure. This branch of the classification is responsible for the technical conception, planning, implementation, and potentially the operation of a future VCN. In accordance with the definition of a socio-technical system in Chapter 2.1, this stakeholder conglomerate represents the technical subsystem. Five main stakeholders (vehicle manufacturers, network operators, IT infrastructure providers, energy operators, and technology suppliers) can be identified in this categorization. Each stakeholder contributes to the physical and cyber-physical components of the VCN, depending on their role in the system.

Policymakers Lastly, the cluster policymaker can be identified in the system. This group of stakeholders is responsible for the rules of the game. Thus, they decide and guide the other stakeholders by setting the problem and solution space. This group can be split up into standardization institutes, the EU, member countries, and international key players such as economic powers (China, Japan, US) or intergovernmental organizations (e.g., UN). Since decisions about the system should be based on sound evidence, some influence can be allocated to Knowledge Institutions resembling the last stakeholder in this classification. This actor refers to public universities but also private commercial science/research organizations such as TNO or Fraunhofer. In addition to the influence on the policymakers, this stakeholder is also represented at the Commercial and Institutional Users and Infrastructure Network provider cluster as their knowledge impacts technology development, selection, or implementation.

The graph indicates that the three upper clusters have close links through overlapping stakeholders. This is due to the complex nature of designing a VCN and the relevance of close cooperation between stakeholders. The private users are graphically excluded as they do not formally participate directly in the decision-making process and implementation. However, there are substantial implications to consider as their acceptance, needs, and concerns are decisive for a future VCN, thus, for its success. A detailed description and role assignment of all stakeholders in the classification can be found in Table B.2.

5.1.2. The Layered VCN Stakeholder Complexity

Since a VCN is a cross-border system affecting multiple layers of society in which different interests are represented, designing and decision-making is a challenge. As shown in the classification, stakeholders from diverse political and economic levels are part of the system. This imposes the question of when and how these actors will be involved in the decision-making and implementation of a future VCN. Moreover, how can the coordination among these emerging layers be determined and the cross-dimensional interest united? Addressing this complexity by embracing system thinking can help to cope with these VCN challenges and avoid a failure like the rejected EU ITS regulation. Figure 5.2 proposes such an abstraction of complexity mapping in order to understand the VCN dimensions and relationships within. An enlarged version is shown in Figure B.1 in Appendix B.
The following paragraph describes the proposed model and its components. Thereafter, the four geographical complexity layers International, European, National, and Regional/Local will be explained and analyzed. Lastly, the system of interest is defined, which is the reference point for the design.

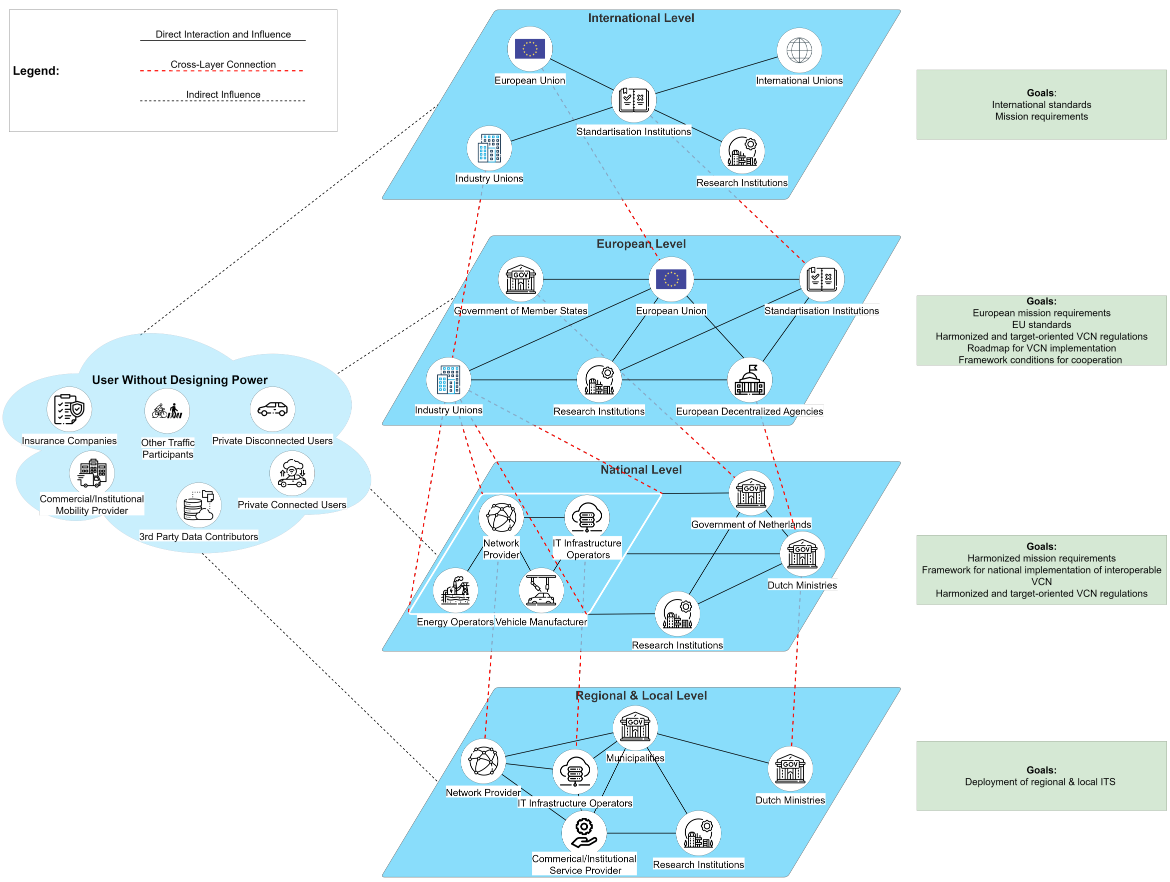

Figure 5.2: 4-Layer stakeholder complexity model (Large Version in Figure B.1)

Figure Components The Figure consists of three main components to be understood: layers, connectors, and goals. Each layer represents a hierarchical level of power and decision-making. Further,

the layers directly correlate with the geographical scope and magnitude of influence. Per layer, goals and challenges to be solved are represented in the green box next to the layer. This separation of goals resembles the approach needed to contribute to this complex system´s design and decision-making. The connectors represented by the lines can be distinguished into cross-layer direct relationships (dashed red), in-layer interaction (black), and indirect influence (dashed black). Cross-layer relationships are links visualizing the actors that are represented on multiple layers, thus, contributing and working on different impact levels. In-layer links represent the communication, contribution, and cooperation within a layer to reach that level´s respective goals. Indirect influence links represent the influence of stakeholders (users) who are not actively participating in the decision-making and designing of the VCN. All connectors are bidirectional and can be considered as input and output.
In addition to the components, a cloud containing the users without designing power is incorporated into the graph, symbolizing the indirect influence of the VCN end users on the designing process. Their needs and importance must be considered, however, they do not formally participate in the decision-making. Thus, no separate paragraph is elaborating on their role in this model.

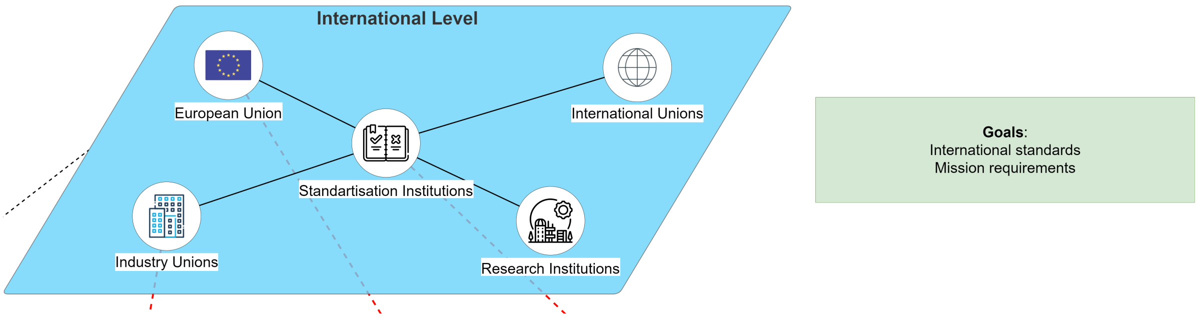

Figure 5.3: 4-Layer stakeholder complexity model: International level

International Layer At the international layer, the five key actors, EU, International unions, standardization institutions, research institutions, and industry unions, are coming together to achieve the high-level goals of determining international standards and mission requirements/objectives. These goals ensure a certain degree of interoperability of systems and a unified approach to shape the distributed development of technology and society. The mission requirements and objectives are formed by exchanging information and discussions among international policymakers, including the EU, and international unions/key players such as the USA, China, or Japan. Naturally, this forms emerging mission objectives and directions that will shape policy for the future. Findings from these interactions are taken to the next layers and are recorded in associations such as the UN as vision and guidance. In addition to this exchange, all five stakeholders are trying to define technical and legal standards by addressing their perspectives, needs, and knowledge. The aim is to combine the institutional interests with the industry unions´ economic interests and base the agreement on sound scientific knowledge. In case of consensus between the stakeholders, the findings are recorded in standards published and maintained by the respective international standard organizations such as ITU, IEC, or ISO. Along with the mission requirements, the standards harmonize decentralized development worldwide. The EU and the standardization institutions transport these findings to the next layer.

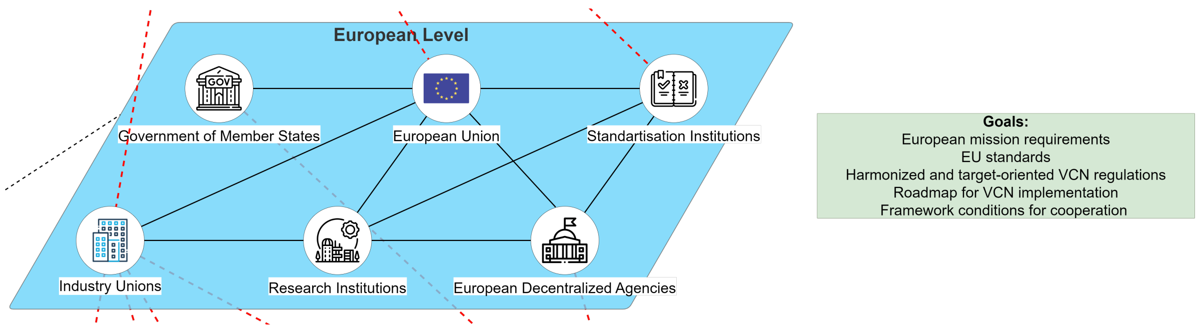

Figure 5.4: 4-Layer stakeholder complexity model: European level

European Layer Six key players can be identified at the next lower EU level, with the EU at the center of focus. In accordance with the derived international mission requirements and international standards, the goal of the level is to define a European equivalent. These European versions of the mission and standards are based on the principles of the previous level. However, an adjustment and intensification which adheres to the EU values is expected. In addition, this level´s further aims are to determine a legal framework by introducing harmonized and target-oriented VCN regulations. This framework shall create legal certainty for member states and be supported by a road map for VCN implementation across the states resembling another aim of the level. Lastly, advantageous conditions for stakeholder cooperation are to be created at this level.
As noted above, the EU is at the center of attention, as they are responsible for reaching the goals but also being in the debt of delivery for the member states. To achieve this multitude of deliverables, intensive cooperation with a clear role distribution must be defined. The EU, which represents the legislative body of the EU (EU Commission, Council of the EU, and European Council), are decision makers and are influenced by all other stakeholders of the level. The member states are part of the council, enabling them to participate indirectly at this level and represent their interests. To ensure the quality of European regulation and frameworks, the decentralized agencies support the EU with legislative proposals, recommendations, and technical work. These proposals are then elaborated and implemented by the EU under consideration of standards from the EU standard institutions, the knowledge and influence of the industry unions, and the scientific work and advice of the knowledge institutions.
Based on this constellation of interactions, 4 out of 5 targets can be elaborated on, excluding the European standards. For them, the European standardization institutions ETSI, CEN, and CENELEC are adopting international standards and creating new European standards in cooperation with knowledge institutes and decentralized agencies.
Please note that knowledge institutions are in a certain relationship with industry unions and decentralized agencies. Since science is partly funded by industry, the results and knowledge can be connotative to a certain degree. Therefore, the relationship between industry and knowledge institutions must be highlighted to be aware of its impact. Further, the relation of knowledge institutes to the decentralized agencies is of consultative and participatory character. Due to the character of the EU, strong interconnections with the national layer can be identified as national stakeholders are represented in the EU.

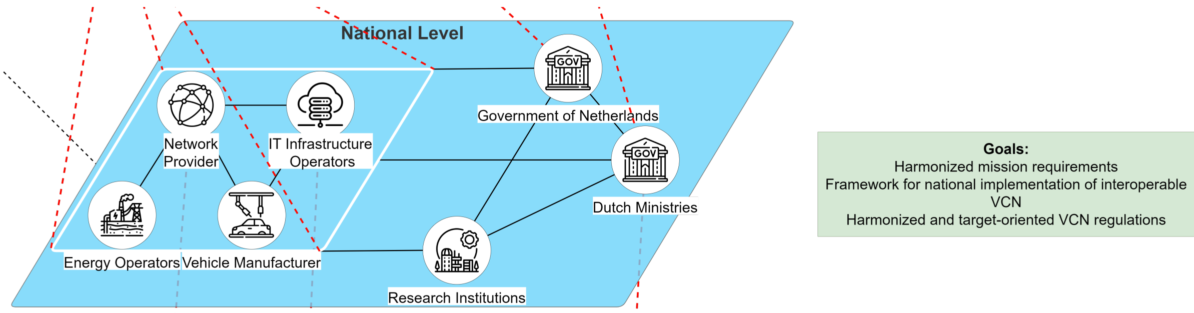

Figure 5.5: 4-Layer stakeholder complexity model: National level

National Layer Like the level before, the higher level results are put into the national context. The goals of the national level include harmonizing mission requirements with the EU mission and national target-oriented ITS regulations in accordance with the European regulation and other member states. In addition, if the above line is agreed upon, a national road map or framework for implementation should be envisaged. This should be consistent with the potential EU roadmap and provide guidance at lower levels.
To achieve this, an interplay of seven actors can be identified. It is highlighted that the industry unions are now split up into individual interest groups. This is due to the implementation´s concretization of the rather abstract higher-level decision-making and the power distribution in favor of single economic actors.
Nevertheless, the policymaker Government of the Netherlands is still at the center of attention within this layer, as they are the level´s problem owner and responsible for delivering the goals. To achieve them, this actor gets supported by all other players in terms of advising, task distribution, and contract-

ing. Like the EU, the government consists of various elements, described here as ministries, which are subordinate to the parliament and perform different tasks for it. Given the fact that this is a VCN design influence graph, Rijkswaterstraat, the Ministry of Economic Affairs and Climate Policy, and the Ministry of Justice and Security can be identified as relevant ministries. In this context, the ministries resemble the national approach of task and responsibility distribution in the system. Thus, each ministry cooperates with the industry stakeholders and the research institutes to accomplish their functions. However, due to this distributed governmental character, each ministry advocates different interests while advising and influencing the government in its decision-making. This separation of authority creates a complexity within the national government, which has been greatly simplified in this graphic for understandability purposes.
As noted above, the industry unions are divided into the relevant industry sectors (vehicle manufacturers, IT infrastructure operators, network providers, and energy providers). This conglomerate of industry interests interacts in each case with the other stakeholders at this level through consultative functions, implementation, and joint decision-making. In addition, the industry partners themselves interact with each other. Since a VCN consists of many components, technical solutions must be interoperable. This interoperability requires a degree of co-development and incorporation of industry needs. The focus here is on coordination between network operators, IT infrastructure providers, and vehicle manufacturers. Each of these stakeholders has to contribute to the VCN at the same time in order to build a functioning communication network.
This strong dependency can be described as a chicken-egg problem since vehicles are waiting for the corresponding infrastructure, and the infrastructure is waiting for functioning connected vehicles.
Moreover, the energy providers play a restrictive role in this problem since they have to provide the energy for the infrastructure beforehand, which brings their interests and power into the system.
It must be pointed out that national standardization institutes define national standards. However, due to the European harmonization of regulations, these derivations can be neglected since a minimum of interoperability between the individual states in the EU can be assumed. Moreover, this assumption is supported by the European vehicle type approval, which forces a single market for vehicles in the EU (European Parliament and Council of the European Union, 2018). The decisions and visions are transported to the next layer by the ministries. Further, the economic decisions of the IT road infrastructure operators and network providers are the baseline for the development in lower layers.

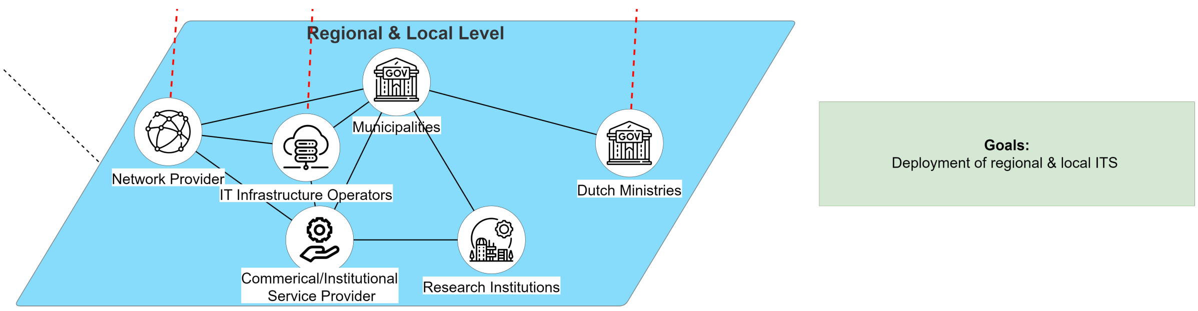

Figure 5.6: 4-Layer stakeholder complexity model: Regional and local level

Regional and Local Layer Lastly, the regional and local design and decision level are displayed as a layer. In contrast to the previous layers, the focus and goal are only on the deployment of regional and local VCNs and their potential applications. This level is essential to reflect the complexity of the design decision-making process, as it represents the scope and magnitude of such a large-scale infrastructure project from top to bottom. Moreover, it signifies the dependencies and influence of all layers on each other, thus, designing requires system thinking to introduce an effective system.
To reach the goal of this layer, an interplay of six key stakeholders is visualized in the Figure. Hereby, the outcomes and work packages from the national layer are translated by the Dutch ministries to this layer and passed on to the municipalities which are the regional/local problem owners. Moreover, the design and decision choices of the network provider and IT infrastructure operators are transferred to this level as they work together with the municipalities on the implementation.
This adoption of the findings has a restrictive character due to the national decision in the upper layer. To realize and implement VCNs in this layer, municipalities, network operators, IT infrastructure providers,

and commercial and institutional service providers cooperate. All of these stakeholders need to work together and sign contracts to establish an effective network that meets national requirements but also meets the local needs of commercial and institutional service providers.
For this service transformation and local VCN project implementation, research institutes are supporting the municipalities and service providers. Outcomes and problems are reported back to the upper layers over the indicated connected actors, which creates a dynamic character in designing the VCN.

Figure 5.2 aims at enhancing the understanding of the complexity and dimensions of VCN designing. With an increased awareness of the entire system, designing and decision-making can be more effective as it avoids island thinking. Three key takeaways are derived from the visualization for all perspectives and actors:

- Designing and decision-making for the VCN must happen on many layers, where each layer has individual tasks to accomplish, but which must consider the overall context of all layers.
- The design of a VCN is a co-evolution of requirements that arise from the co-development of multiple stakeholders.
- Cooperation and harmonization are essential for overcoming the VCN challenges. In this context, special attention must be paid to the integration of industry and institutions in order to create a common environment and understanding.

5.1.3. System of Interest

As the multi-layered complexity of the system is understood, the system of interest is defined to narrow down the focus of this work. By delving into the system of interest, in-depth exploration can be achieved, and its outputs can be transposed to the rest of the system. This process is called recursion, a technique to develop and refine an effective system beyond trivial complexity (International Organization for Standardization, 2018b). Further, this scoping allows for eliciting stakeholder requirements, which can be translated into design requirements and ultimately into a design.
For this, the national and European level is selected as they resemble the center of decision-making in an early stage. A VCN is not in the implementation phase, thus, the regional aspects are non-decisive as they do not deal with strategic decisions. Further, the international level resembles a suboptimal point of attack due to the heterogeneous and stiff constellation of actors as well as different legislation systems across borders. Therefore, the European and national levels are selected to be the system of interest as they are more strategic and impact than the regional level, as well as they have fewer emerging variables than the international level.

5.2. Stakeholder Analysis

Based on the selected system of interest, this Chapter presents a stakeholder analysis. First, a desk study is performed in Chapter 5.2.1. Thereafter, exploratory insights are generated in Chapter 5.2.2.

5.2.1. Stakeholder Desk Study

With an understanding of the system´s scale and the newly set scope, the stakeholders can be analyzed in detail. The focus here is on specifying the stakeholders in the context of a VCN so that individual components and interrelationships of a stakeholder conglomerate, such as the EU decentralized agencies, can be identified. In addition, roles and tasks in the context of VCNs are defined, and needs are derived. This basic understanding of the individual actors in the system of interest serves as a basis for requirement elicitation. Each need is assigned an identifier to ensure traceability. Finally, sources for the origin of the information are listed for each stakeholder. Table B.3 in Appendix B shows the analysis.
These findings are a synthesis of a desk study that analyses the available information on the stakeholder´s publications and supporting scientific documents. Since this is a section of the current situation, a reversal of certain information cannot be ruled out, and information must be validated and iterated upon closer examination and design.

5.2.2. Stakeholder Interviews

To validate and iterate the findings of this work, 15 experts have been interviewed. According to ISO15288, this process is a feasible approach for understanding the stakeholder position and exploring the needs. Moreover, addressing these points can contribute insights and identify development directions as, to the best of our knowledge, publications do not incorporate a multidisciplinary stakeholder perspective for future VCN requirements. The selection criteria for the participants were to possess relevant knowledge and experiences in the field of VCNs, VANET, ITS, IoV, or working within the EU. In order to ensure the range of perspectives and diversity of the information, key stakeholders from governmental institutions, the industry, and research institutions have been asked to participate. Thus, efforts were made to include individuals from different backgrounds, disciplines, and organizational levels to capture a comprehensive understanding of the subject matter. Table 5.1 shows the demographic constellation of the interview partners. Eight experts represented the industry side, eight the institutional side, whereof four worked in the European context, and four represented scientific views. During the semi-structured video call interviews, the experts were asked to provide statements on the following main topics:

- What are technical enablers/barriers for a future vehicular communication network enabling V2V and V2I?
- What are institutional enablers/barriers for a future vehicular communication network enabling V2V and V2I?
- What are social enablers/barriers for a future vehicular communication network enabling V2V and V2I?
- What are the roles and interests of stakeholders in a future vehicular communication network and do they have clashing/common interests in the system?

Table 5.1: Interview partner demographics

Interview Partner	Country	Stakeholder Group	Position
INT1	Netherlands	Knowledge Institution	Security-Safety Consultant
INT2	Netherlands	Technology Supplier/Knowledge Institution	Scientist/ Professor
INT3	Netherlands	Rijkswaterstraat	Security Architect
INT4	Netherlands	Rijkswaterstraat/ Industry Associations	Manager
INT5	Netherlands	Rijkswaterstraat/ EU Decentralized Agencies	Product Owner
INT6	Germany	German Ministry/ EU Decentralized Agencies	Scientist/ Consultant
INT7	Germany	German Ministry/ EU Decentralized Agencies	Head of Section
INT8	Germany	Technology Supplier	Safe Solution Architect
INT9	Germany/Belgium	Vehicle Manufacturers	Director
INT10	Finland	Knowledge Institute/ EU Decentralized Agencies	Principal Advisor/ Professor
INT11	Germany	German Ministry	Engineer
INT12	Germany	Network Provider	Manager
INT13	Netherlands	Technology Supplier	Project manager
INT14	Germany	Knowledge Institution/ Technology Supplier	Manager
INT15	Greece	Industry Associations	Engineer

The questions were asked openly to avoid restricting the solution space. Automatic transcription and recording ensured the correctness of the obtained information. The complete question list can be seen in Appendix B. These questions aimed at exploring stakeholder positioning and barriers or enablers from various viewpoints. The findings of the interviews are summarized in Table 5.2. The content is separated into common and individual points as well as technical, social, and institutional barriers/enablers. Moreover, the findings are marked with an identifier for traceability purposes. In addition, Table B.4 presents relevant stakeholder information generated by the experts.
The following three paragraphs highlight critical findings for technical barriers/enablers, social barriers/enablers, and institutional barriers/enablers.

Table 5.2: Interview insights: VCN barriers and enablers

	Common Points	**Unique Points**
Technical Barriers/Enablers	• Heterogeneity/interoperability of infrastructure, geographical characteristics, and vehicle technologies is a challenge. (INT1, INT2, INT3, INT5, INT6, INT7, INT8, INT10, INT11, INT13, INT14, INT15) • Hybrid communication of Wi-Fi and Cellular is an enabler (INT2, INT3, INT5, INT6, INT7, INT8, INT10, INT11, INT13, INT14, INT15) • Correct data management and availability (quality and validity) is a challenge (INT4, INT5, INT6, INT8, INT10, INT11, INT14) • Missing standards and agreement on them are a barrier (INT4, INT5, INT8, INT12, INT14) • Connectivity coverage is an enabler and a must-have (INT7, INT9, INT11, INT12, INT15) • Emergent technologies such as edge computing can be enablers for functionalities (INT3, INT12, INT14, INT15) Investment costs are hindering the technical implementation of functionalities/architectures for VCN (INT5, INT9, INT12, INT15)	• Integrated Safety-Security design in the VCN can be an enabler. (INT1) • Emergent technologies such as quantum computing can threaten security/safety/privacy in a VCN. (INT1) • AI and machine learning enable efficient VCN applications. (INT8) • Bandwidth limitation Wi-Fi (G5) in a traffic jam is a barrier (INT2) • The slow admission process of connected vehicles is hindering the implementation of the VCN. Hereby, the validation of connected functions and software is hard to validate. (INT1) • Current security certificate design does not ensure validity & relevance INT2) • Current GPS accuracy is a technological barrier for VCN applications (INT5) • Functional safety is an enabler for the social acceptance of OEM (INT9) • Finding use cases that can't be achieved by in-vehicle sensor technology is an enabler. (INT9) • The false positive rate is too high for short-range communication, thus, a barrier due to user concerns. (INT9) • Active and constant testing to raise awareness is an enabler (INT13)
Social Barriers/Enablers	• Strong Cooperation is an enabler (INT2, INT4, INT5, INT6, INT7, INT8, INT9, INT10, INT11, INT12, INT13, INT14, INT15) • The absence of a private-public business case is a barrier (INT3, INT4, INT6, INT8, INT9, INT10, INT13, INTE12, INT14) • Understanding and Interpretation of standards hinder the development of a future VCN. (INT1, INT2, INT5, INT6, INT7, INT8, INT10) • Distrust of actors (especially OEM) in communication/other entities is hindering the implementation of a future VCN. (INT1, INT2, INT3, INT7, INT10, INT13) • Different speed of actors makes cooperation/deployment harder (INT2, INT4, INT9) • Consensus about which application type/objective to commit is an enabler (INT2, INT4, INT7) • Data sharing is an enabler. (INT10, INT12, INT14) • Industry disagreement over Wi-Fi is a barrier (INT5, INT9, INT14) • OEM´s missing adoption of technology is a barrier (INT3, INT5, INT6) • NCAP is an enabler for the OEM acceptance and relevance of VCN applications (INT13, INT14) • The focus of current VCN discussions (e.g., ITS-G5 and c-v2x) is too technology-focused and not value-creating (INT8, INT9, INT11) • Unifying the mission requirements of stakeholders is an enabler (INT7, INT8) • The availability of vehicle data is lacking as OEMs are not incentivized to share them. (INT8, INT12) • The benefit of VCN data is not clear to the user. (INT8, INT14) • It is questionable whether users want to give up their advantages of the fast route to increase the safety of the public through VCN routing. (INT8, INT14) •	• Understanding and view on risk, security, and safety are uneven among stakeholders. (INT1) • Potential VCN business cases are not in the interest of society, thus a barrier. (INT8) • User social acceptance of VCN applications becomes a self-perpetuating process through experiencing and is therefore not a barrier. (INT9) • The misconception of full Wi-Fi network coverage is needed is a barrier. (INT13) • Incorporating the user in the design and testing phase is an enabler (INT11)
Institutional Barriers/Enablers	• Regulations can be an enabler (INT2, INT3, INT6, INT7, INT8, INT11, INT13, INT12, INT14, INT15) • The institutional push by introducing regulations/funding/business cases can be an enabler. (INT1, INT2, INT4, INT6) • Unclear Responsibility for investment/case of Failure is a barrier. (INT1, INT3, INT4, INT15) • Regulation can hinder cooperation, thus, can be a barrier to a VCN (INT5, INT6, INT15) • The handling of the vehicle manufacturer´s liability concerning infrastructure and 3rd party data needs to be clarified as it is a barrier (INT9, INT10) • Technology-agnostic regulation is an enabler. (INT10, INT12)	• Addressing the VCN on every layer with its respective goals is an enabler (INT4) • Standardized regulations in the EU regarding testing conditions for VCN technologies such as autonomous driving is an enabler. (INT9) • The governmental approach of focusing on only one type of communication technology is a barrier. (INT13)

Technical barriers/enablers Most of the experts agreed that inherently heterogeneous components of a VCN, including actors, infrastructure, and technologies such as hybrid communication, are a technical challenge with no solution at the moment. Furthermore, it is striking that only a third of the experts mentioned missing standards and the agreement on them as a technical barrier. Interview partners even stated that there are a sufficient amount of standards in an acceptable quality which contrasts a magnitude of publications highlighting this as a main barrier. In addition, half of the participants are

concerned about data management, quality, and availability. Noticeably, only a fifth of the interview partner highlighted a certain type of technology as the disruptive enabler during the process. A general consensus on validity and impact was evident among the interview partners, but none saw this as a critical turning point.
A surprising individual technical point is that an integrated safety security understanding approach and design could enable development and that the key stakeholders needed to understand it correctly. This goes hand in hand with the unique concern of the uncertain validation and admission process of connected vehicle functions. Due to the digital character of these functions, safety and functionality tests remain challenging as digital security heavily impacts the vehicle´s and its passengers´ physical safety. Typical testing and admission procedures are not suitable for advanced computer-aided functions. Furthermore, self-learning applications are an open field, as there is no consensus on approval and responsibility in case of an emergency. Considering the technological heterogeneity of vehicles and producers, the problem is amplified and creates a wicked challenge.
Other remarkable insights were generated by interview partner nine from a Vehicle Manufacturer. According to this interview, short-range communication has too many false positives, thus not functioning applications that can even be translated to economic damage due to the returning policy. Therefore, the interview partner suggests finding use cases for a VCN that cannot be solved through in-vehicle sensing and computation.

Social barriers/enablers In order to deal with these complicated problems, cooperation and harmonization were mentioned by most interview partners as social enablers. This is specifically needed as the heterogeneity of stakeholders causes a variety of standards interpretation among entities, resulting in interoperability concerns. In addition, it could enable a future VCN by finding a consensus about the application types and objectives to commit to, which would guide development and implementation.
Another remarkable finding mentioned by the experts is the absence of a private-public business case. Since a VCN involves the institutional and industrial sides, one might think that there is a certain basic coherence in the objectives of the actors. However, the interests in a VCN barely overlap as the institutional side has the focus on safety and privacy functions. In contrast, the economic aspects drive the industry and therefore focus on other functionalities. Furthermore, it shall be highlighted that general dislike of the VCN discussion´s focus among the interview partners can be identified, as the disagreement about technological choices is not value-creating. Thus, a stronger impact can be achieved by highlighting the social and institutional factors as well as implementing the technology.
An unexpected unique remark is that including the user in the development process can be an enabler, which is aligned with user concerns identified as barriers by the participants.

Institutional barriers/enablers The point on which the experts disagreed was intervention via regulation. Here, the majority of the participants noted that the regulations would intervene compulsorily and could represent an enabler. However, two disagreed, saying that such intervention would have a negative impact on cooperation between stakeholders, which is essential for the realization of a VCN. This disagreement is an example of why delegated ITS regulation could have failed.
Interestingly, the majority were sure that an institutional push would be needed for the introduction of such technology, as they see the institutional side in the lead here. Special funding programs, appropriate regulations, and the introduction of the private-public business case discussed earlier are conceivable here.

The results of the exploratory analysis have created novel insights into the requirements for a VCN. In addition, the relevance of VCN barriers and enablers is derivable from overlapping opinions. These insights are guiding the further design of the system. In summary, four key insights are highlighted.

- First, there is a clear consensus among experts on critical issues such as interoperability and stakeholder cooperation, which are crucial for developing and realizing the VCN.
- Furthermore, social and institutional barriers are more significant than technical feasibility. This implies that the socio-technical problem is linked to more fundamental social/institutional problems and that the technical realization is not decisive in the discussion.
- An example is the lack of overlapping objectives of industry and institutions, which represents the third key learning. Because of these conflicting interests in the system, experts identify the

abstinence of a public-private business case as a critical barrier.

- Finally, the cause of the chicken-egg problem is linked to the associated investment costs. This vital issue of who bears initial costs must be addressed and resolved when designing a future VCN.

5.3. Stakeholder Positioning

Based on the insights of the chapters above, a power interest grid is developed for the system of interest. This grid aims at helping to understand the complexity and power structures in the system and managing the stakeholders (Ackermann & Eden, 2011). Figure 5.7 demonstrates the grid whereby the interest is displayed on the x-axis and power on the y-axis. The following analysis is based on Bryson (2004) approach to classifying the actors and Ackermann and Eden (2011) recommendations and strategies for the stakeholder clusters.
In the following, the four clusters high-power high-interest, high-power low-interest, low-power high-interest, and low-power low-interest are analyzed.

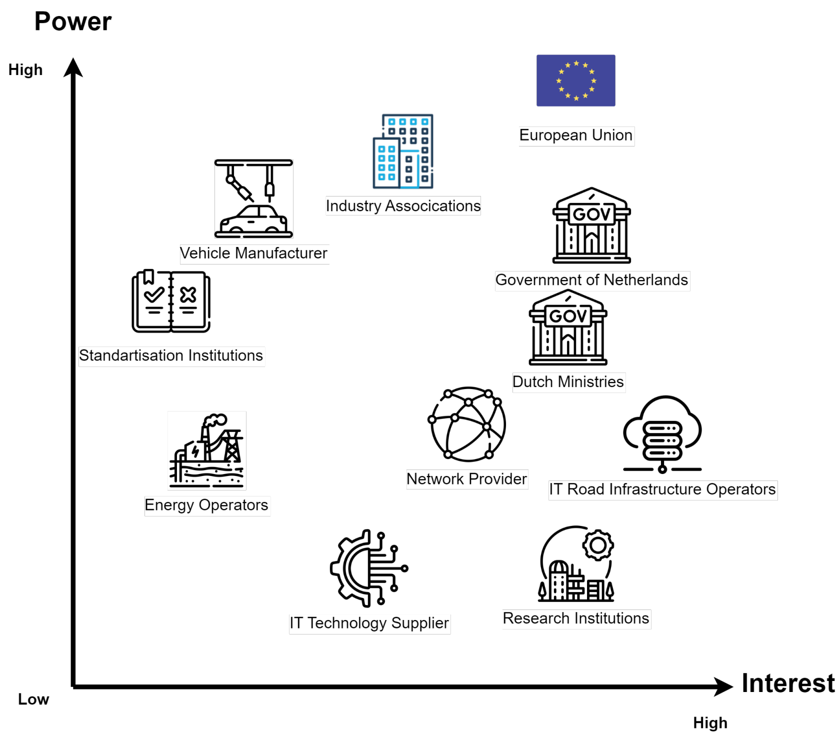

Figure 5.7: Power interest grid

High Power High Interest The stakeholders with high power and interest are key stakeholders in the system as they can heavily influence the process and outcome of the to-be-designed system. According to the Ackermann and Eden (2011) stakeholder theory, engaging in active communication, involvement, and addressing their needs is crucial for the system. This group includes the stakeholders EU, the Government of the Netherlands, industrial unions, and decentralized EU agencies. The power of these actors relies on the decision-making process and legislative character, except the Industry Unions, which are influential through their economic power and strength. Moreover, each stakeholder committed themselves to a future VCN through their mission and vision statements. This demonstrates that these players will shape the development of a future VCN, which is aligned with the classification in Chapter 5.1.1. Therefore, their interactions, positions, and needs must be understood and incorporated to design successfully. However, an imbalance in interest and power in perspectives can be identified. Whereas the institutional/social subsystem is well represented in this stakeholder group, economic and technical concerns might be underrepresented by only the industry unions. Thus, keeping this imbalance in mind while designing can be recommended.

High Power Low Interest Unlike the previous cluster, this group of stakeholders consists not solely of policymakers. Standardization institutions and vehicle manufacturers can be allocated within this group. As identified in the interviews, car manufacturers´ commitment and compliance are crucial to establishing a VCN. Thus, their power over the system and its design are high but lower than the related industry unions since their primary influence is on different layers and magnitude (see Figure 5.2). Unlike their power over the system development, their interest seemed to be lower considering the implementation of early EU approaches of a VCN (ITS or C-roads). Hereby, the missing private-public business case can cause the lack of interest of the manufacturers. According to the expert interviews, functionalities and applications are developed and could be tested on a larger scale. However, the unsolved challenges of aligning objectives, defining responsibilities, or funding structure discourage and disincentivize participation. Please note that individual vehicle manufacturers can have increased interest and are, therefore, close to the borderline of high interest. However, as their primary influence lies united within the industry associations, the individual power is allocated lower. Therefore, vehicle manufacturers are located on the right side of low interest.
The standardization institutions have power over the VCN to a certain extent, as their technical rules decide the shape of the solution and processes. Moreover, finding consensus for and defining standards is a main deliverable of top-level VCN layers. Therefore, the importance of standardization institutes in the phase of designing and decision-making is exceptionally high. However, the interest of these institutes is limited since it is part of their business model, yet they are not profiteers of the realization and operation of VCNs. Therefore, no significant interest in the system can be identified. It is recommended to manage and understand the needs and expectations of this cluster of groups, as they yield the power to disrupt. Therefore, satisfying these stakeholders is of primary concern when designing the VCN so no undesirable reaction/action emerges.

Low Power High Interest Stakeholders in this category need to be informed and consulted to understand their needs and input. However, as their power is limited, not every need has to be incorporated into the VCN design. Four stakeholders can be allocated to this cluster: Dutch ministries, network providers, IT road infrastructure operators, and research institutions. Like the EU´s decentralized agencies, the ministries can be seen as an extension of the government of the Netherlands. Since they have rather executive power in the form of implementation than decision-making, their high-level design consolidation is lower than higher-ranked institutions, and subsequentially is their power. This is further reinforced by the fact that no independent authority is assigned to the ministry in the context of VCNs, and they can only act on the request/initiative of the Government of the Netherlands. However, as the ministries are represented in the decentralized agencies and can speak out recommendations for the government of the Netherlands, they have the highest power in this cluster.
The network providers and IT road infrastructure operators have high interest, as VCNs can be built up on the infrastructure they build and operate. Thus, a design beneficial for these economic stakeholders and their business model is of high interest to them.
In addition, introducing VCNs may restrict or impose service responsibilities. However, as these actors do not have legislative authority, their power can be allocated as low yet on the higher side as they are the implementer of VCNs. This creates the necessity of close cooperation with the deciding stakeholder to develop and implement a feasible solution.
Lastly, research institutions need to be informed. Legally speaking, no up to little power can be allocated to this group as they do not decide nor operate the future system. However, as they are heavily involved in the predevelopment of technologies and concepts as well as consultation for technical and socio-technical problems, an indirect influence on other key players can be identified. This influence, however, does not impose economic or self-serving interests due to their ethical orientation and responsibility. Despite the limited power, their interest is on the high side due to the novelty of the domain. Hereby, research potential attracts these institutes in order to contribute to society. It shall be noted that despite the stakeholder´s allocation to this cluster, their needs and constraints must be considered for a feasible design. Such a large-scale infrastructure project requires the co-development of all actors on respective layers to introduce VCNs effectively.

Low Power Low Interest Energy operators and IT technology suppliers are in the low-interest and low-power cluster of the system of interest. These stakeholders should be considered from a design perspective as they can have valuable requirement information. However, due to the lack of interest

and power, minimal efforts of communication should be made. The energy operators certainly constrain the design by their technical implementation of energy supply. However, no conflicts of interest with other stakeholders are apparent, so their position is more or less a technical supplier rather than a participating stakeholder.
The same applies to the IT technology supplier. They have neither an operational nor a strategic role in design or operation, which is why their interest and power are low. However, compared to the energy operators, they have an increased interest in the implementation of the system, as they want to provide the stakeholders with the necessary technology. Thus, a certain economic interest can be identified. This cluster provides additional technical framework conditions, which is why they have a technical design influence on functionalities. However, this influence is only of limited relevance for the current design phase as more fundamental problems and issues must be clarified. In addition, a continuous improvement of the technology can be assumed, which means that the current framework conditions are not valid for the next few years.

Two main takeaways can be synthesized from this system of interest power-interest diagram.

- Firstly, an intense concentration of policymakers can be identified as key players in the system, and this creates the risk of homogeneous opinion formation, which must be avoided. Economic and technical interests are underrepresented in the decisive, high-power, high-interest cluster. Therefore, cooperation with economic stakeholders is recommended in order to design effectively.
- Secondly, due to the complex nature of a VCN, co-evolution and co-development of the high-power high-interest, high-power low-interest, and low-power high-interest clusters is recommended. Accordingly, the classic stakeholder approaches to this categorization are to be viewed critically, and novel ways of stakeholder management are conceivable.

5.4. Clashing Goals and Common Interest

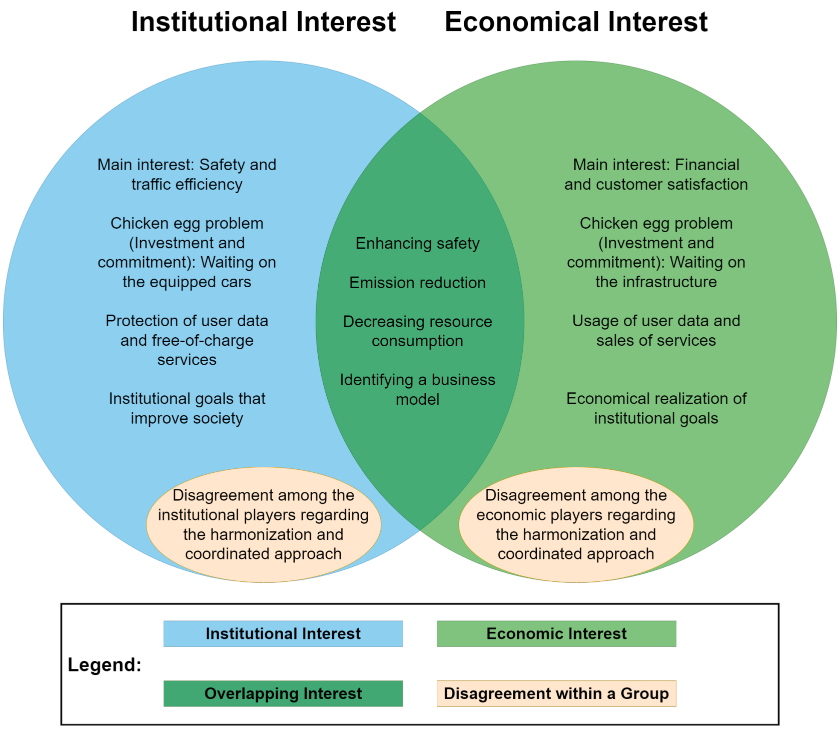

Figure 5.8: Clashing goals and common interest of the institutional and economic side

As power and interest vary among stakeholders, it is crucial to identify common interests and clashing goals to find a solution space that is appealing to the relevant stakeholder. For this, the following paragraphs present fundamental challenges and common interests. These can be taken as a foundation for

design attempts. The elaborated points are a selection rather than a complete list. A more extensive identification of clashing goals and common interests is recommended and can be the basis for further scientific work.
The following introduces five clashing goals in a separate paragraph, followed by a paragraph emphasizing the common interest. Figure 5.8 visualizes these points.

Diverging Institutional and Economic Interest A fundamental conflict is the different interests of the institutional and economic stakeholders in VCNs. Here, the institutional decision-makers clash with the economic players since the objectives are not the same (INT7). In principle, it is in the interest of all stakeholders to move forward together, however, the focus of these parties is on different values. The institutional side, mainly the EU and national governments, have an increased interest in the predicted increased road safety and traffic efficiency, whereas the economic stakeholders are interested in monetary means and customer satisfaction. This discrepancy in overlapping objectives forms an asymmetry of desired applications and, thus, requirements or technologies between the parties.
One example of this is the effort to enforce ITS-G5 communication. Through this WIFI protocol-based communication, safety messages can be broadcast (V2V and V2I). The road authorities have increased interest in such an application as it is hoped to increase road safety through early ITS communication. However, the advantage for the economic actors is initially absent since this type of communication is free of charge for the end user (European Commission, 2019). It is questionable why a network operator should participate in this if this is the main task of the infrastructure. In addition, the market penetration of such a technology is currently failing. To establish effective V2V communication, a large number of vehicles must communicate. However, despite efforts on the political side, this has hardly become established in the European market, as only about 0.6% of newly sold vehicles in 2020 are equipped with such technology (Svegander, 2021). This is evidence of a lack of overhang of common alignment and objectives.

Harmonization and Coordinated Approach However, not only do stakeholders from different interest groups clash, but also within a stakeholder cluster, especially when it comes to a common approach and harmonization. Probably the most prominent example of this is delegated ITS regulation. Due to the national interest of several states within the EU, the decentralized development of security-related ITS functions has resulted in the EU taking a cooperative and cross-border approach. However, faced with different environments, conditions, and development speeds, the member states voted against a regulatory commitment to the displeasure of a highly engaged EU. Moreover, the industry has different intentions for potential communication technologies, which comes down to the clash of ITS-G5 by the industry union Car2Car and C-V2X by 5GAA. Mainly since some OEMs and IT technology providers are represented in both industry unions, the lack of consensus within the industry is highlighted by that (INT9, INT13).

Investment and Commitment Another major conflict of stakeholders deals with investments and commitment. As mentioned in Chapter 5.1.2, the codependency of infrastructure and connected vehicles is a chicken-egg problem, especially regarding short-range communication over a WIFI protocol. Legal uncertainty and lack of trust cause the vehicle manufacturer and network provider to wait on the infrastructure and regulations, whereas the hesitation of the economic players causes the legislator and, subsequently, the infrastructure provider to wait on the development of the market. Moreover, this issue is closely related to the general conflict of interests between the economic and institutional sides since a solution requires a common goal and, thus, objectives.
Even if this conflict can be resolved, the question of coverage for the operational costs remains.

Commercialization of VCN Data The commercial use of the generated data can represent a business model for economic players such as service providers or vehicle manufacturers. However, this is a critical issue from the user´s point of view and, thus, a clash of interests between the user and the VCN operator. While the user has a right to privacy, the service provider wants the data for potential applications but also to generate value from it. This raises the question of which data can be distributed ethically, how misuse can be prevented, who has data ownership, and, above all, who is responsible for a serious failure. This multi-layered complex of data issues is causing conflicting interests on many levels, hence, resembling research potential for further work.

Institutional Goals and Economic Viability Lastly, the conflict between the network provider and the European Union is highlighted. While the EU is striving for nationwide high-speed connectivity, it is in the interest of the network operators to run their business economically. In the event of a regulatory requirement for network coverage, the cost-technical aspects of the network operators may clash with the EU objectives due to insufficient utilization.
In addition, the EU´s net neutrality regulation restrains advanced 5G applications such as network slicing and prioritization of messages. Here, it is questionable whether an adjustment of the legal situation is necessary for a VCN in order to enable intelligent tasks to increase efficiency. At present, however, this is ruled out because the regulatory situation conflicts with the developments of the network providers. This clash does not only refer to these two stakeholders but can be transposed to any emerging technology.

Common Interest In order to overcome these challenges cooperation is crucial, and a win-win situation should be aimed at. Moura and Teixeira (2009) proposed to rather focus on common interests, not on positions or conflicts. Thus, the identification of common interests is critical to building a bridge that deals with the aforementioned challenges.
The most obvious objective is enhancing safety. The institutional key players have committed themselves to enhance safety through policy initiatives, but also vehicle manufacturers and service operators have an increased interest in enhancing safety, as this can positively correlate with customer satisfaction.
In addition, emission reduction and decreasing resource consumption can be identified as a common goal between users, policymakers, and vehicle manufacturers in the context of the Paris climate agreement. The question is how to incentivize the infrastructure and network operators beyond the regulatory obligation.
Finding a business model can help. Automated driving can potentially provide such a business opportunity, as users and legislators are interested in the increased safety and convenience, but economic actors can also generate monetary value out of it. Therefore, aiming at functionalities beneficial for multiple stakeholders can be an approach to unify objectives.

5.5. Key findings

Chapter 5.1 consists of four main parts, each of whose main findings are highlighted in a paragraph.
The stakeholder identification proposes a taxonomy and complexity mapping model. The taxonomy shows that various stakeholders are involved in a VCN and that private end-users are decoupled, as they do not overlap with the other taxonomy groups. The 4-level model presents layered thinking for VCN development and clarifies the interconnectedness between the layers. Thus, high dynamics and dependency on different geographic scopes are observed. In addition, due to the range of a VCN, a harmonized approach that covers all levels is advantageous, as otherwise, work is done against each other.
The stakeholder analysis lays the foundation for the following analyses as stakeholder needs are summarized in Table B.3. In addition, novel insights regarding technical, institutional, and social barriers/enablers are generated through the expert interviews. They can be found in Table 5.2. From these insights, it can be particularly emphasized that interoperability and stakeholder cooperation are of major concern for the design. Further, it is highlighted that data management and finding a private-public business case must be considered in the design.
The stakeholder positioning provides a power interest analysis. To summarize this section, the key takeaway is the system's fragility regarding decisions due to the stakeholder power distribution. Furthermore, an underrepresentation of industry can be identified in the high-power high-interest category.
Finally, the various stakeholder conflicts and common interests can be identified, with the main points being as follows. The interest of the institutional perspective on a VCN differs from the economic one. Further, the interest within a stakeholder group can differ in certain areas, thus creating the need for harmonization. Another conflict between the institutional and economic sides is about investment and commitment. Hereby, the responsibility of which stakeholder is responsible for which investment in the system is unclear.

6
System Analysis

This Chapter presents the system analysis of the future VCN system. For this, the insights of the stakeholder and mission analysis are transformed into system requirements guiding future design attempts. Firstly, Chapter 6.1 defines the system analysis perspective and its reasoning to scope the requirements. Thereafter, a system requirement structure from the before-defined perspective is proposed and analyzed in Chapter 6.2.

6.1. System Perspective and Purpose

For this chapter, it is crucial to understand the recursion of the system of interest and the perspective change that takes place in the system requirement definition process. Within the system of systems scope, the stakeholder and user-oriented views are transposed into the technical perspective. It is essential that the requirements still meet the operational needs of the stakeholders during the transformation. When this process is contextualized to a VCN, the requirement process aims to unify the multitude of stakeholder interests and define a common system that is functional and feasible for the relevant stakeholders. Further, ISO15288 highlights that no implementation and technical solution should be specified in the requirements. Thus, the elicitated requirements shall not indicate a solution (International Organization for Standardization, 2015).
Typically this process is aimed at the perspective of the technical supplier of the system as development and conceptualization are their responsibility (International Organization for Standardization, 2018b). However, due to the system's complexity and its interconnectedness, a purely technical view is insufficient. Hence, the viewpoint of the system implementer Rijkswaterstraat is adopted, representing the responsible road authority of the Netherlands. This includes considering their role in the technical execution of a prospective VCN, as well as their institutional nature as a ministry and integral component of both the national government and European decentralized agencies. Thus, their viewpoint represents a socio-technical viewpoint of a VCN.

6.2. System Requirements

The system requirements are defined and analyzed in this Chapter. Firstly, the system requirements elicitation strategy and outcomes are presented in Chapter 6.2.1. Based on these findings a VCN system requirement structure from the socio-technical perspective is proposed in Chapter 6.2.2. Thereafter, this structure is analyzed on requirement relationships in Chapter 6.2.3, and fundamental challenges within the structure are highlighted in Chapter 6.2.4.

6.2.1. System Requirements Elicitation

In order to formulate a scientifically sound requirements definition, a combined strategy shown in Figure 6.1 is pursued. Hereby, exploratory aspects/insights from the interviews are combined with the stakeholder analysis and literature review rounds. This combined approach enables conducting a multilayered requirement elicitation in which literature and exploratory insights validate, complement, iterate, and challenge each other. This approach is chosen to generate new insights and provide a system perspective as a contribution to a VCN design. This synthesis aims to establish a foundation of top-level requirements for a VCN from various perspectives and understand their relevance.

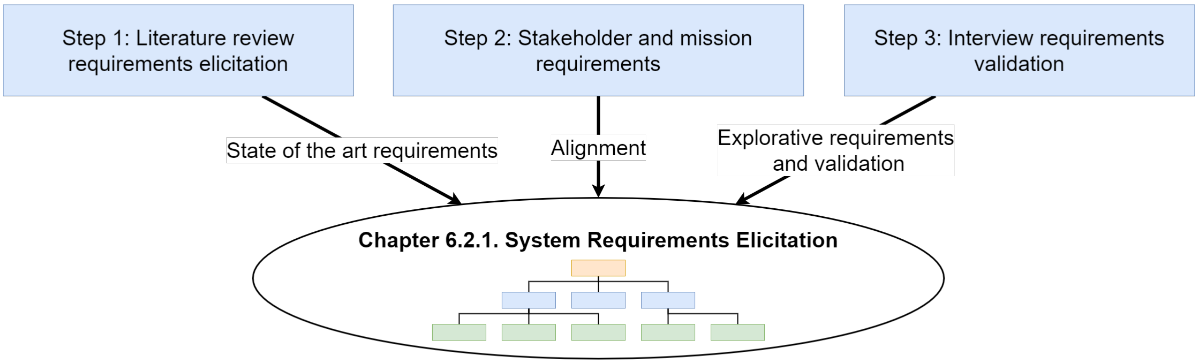

Figure 6.1: Requirements elicitation process

The following paragraphs are introducing the requirement synthesis in three steps. Each of these steps contains two paragraphs that describe the process and thereafter analyze the outcome of the step. The first step is requirement exploration through the literature reviews. This step serves as a base for the requirements elicitation representing the state-of-the-art. The second step is the alignment of the state of the art with the stakeholder and mission analysis. Hereby, it is the goal to complement and compare the state of the art with the outcomes of the previous analyses. Lastly, the system requirements are evaluated and weighted against the exploitative interview insights.

Literature Review Requirements Description Table 6.1 contains the literature review findings, which are visualized by a word cloud in Figure 6.2. The Appendix Cintroduces the complementary Tables C.3, C.4, and C.5 containing the elaborated version of Table 6.1. Within the review, 57 documents are analyzed and distinguished into the origin of their source, including the categories of the Government of the Netherlands, EU, Knowledge Institutions, and Industry Associations. As mentioned in Chapter 5.2, scientific literature can be funded by the industry or policymakers. Thus, a connotation of research objectives must be considered. In total, 33 main high-level requirements for a VCN can be identified. Each requirement is described in the supplementary Table C.1 in Appendix C. Further, this table specified the reasoning for papers to be found in this category.

Figure 6.2: Requirement word cloud

Table 6.1: Requirement analysis

Type	Requirement	Institutional: Government of Netherlands (7 Documents)	Institutional: European Union (12 Documents)	Industry Association (7 Documents)	Knowledge Institutions (31 Documents)	Total (57 Documents)
Institutional	Mission Requirements	2	3	0	1	6
	Regulation: System Operation	5	8	4	10	27
	Regulation System Architecture	4	3	0	1	8
	Standards	2	6	5	6	19
	Stakeholder Cooperation	4	6	1	5	16
Social	Ethical Requirements	1	5	1	9	16
	Social Acceptance	2	0	1	4	7
Technical: System Architecture	Application Requirements	1	3	1	5	10
	Robust	4	5	4	16	29
	Safe	3	4	2	11	20
	Adaptive	1	0	4	7	12
	Secure	3	10	4	18	35
	Privacy Preserving	2	8	2	19	31
	Efficient	4	5	5	19	33
	Effective/ Reliable	3	5	6	19	33
	Resilient	0	6	1	3	10
	Interoperability / Heterogeneity / System legacy	2	7	6	14	29
	Architecture Choice: Centralized/Decentralized	0	3	2	3	8
	Comply With Standards	1	2	1	1	5
	Automation	2	2	0	3	7
	Spatial Differentiation	0	1	0	2	3
	Data Management System	2	5	3	12	22
	Scaleable	2	0	4	8	14
Technical: System Operation	Continuity of the Service	3	3	2	2	10
	Trust and Control Management	0	4	2	8	14
	Change Management / System Update	0	2	3	1	6
	Monitoring	1	3	1	2	7
	Data Management	2	4	3	12	21
	Maintenance	0	1	2	3	6
	Communication Management	1	2	4	9	16
	Computation Management	0	0	3	9	12
	Disaster Management	0	0	0	2	2
	Risk Management	1	2	0	2	5

Literature Review Requirements Analysis Overall, an increased focus on system architecture requirements can be observed. Publications often focus on individual components of the system, which may be due to the time and technical limitations of the publishing platforms. If this fact is analyzed per domain, the relevance of the VCN system architecture seems to be more in the focus of scientific publications. Institutional publications, especially those of the EU, show a broader spectrum of requirements for a VCN. This discrepancy of institutional reflection in science can be caused by a lack of system thinking resembling a potential scientific gap which can be the subject of further research. Furthermore, it is remarkable that among all domains safety and security are not intertwined subjects. Most publications deal with security issues in the context of potential privacy threats and implications.

However, experts such as in Renner et al. (2020) lack safety implications. This separate view can create an insular development among stakeholders neglecting essential interrelationships of such a complex system. Hence, objectives might be targeted in a questionable manner.
Within the aforementioned system architecture requirements, a strong focus on the technical characteristics can be identified, such as robustness, efficiency, effectiveness/reliability, data management, security and privacy, and, above all, heterogeneity of all components and actors. It is striking that resilience and spatial differentiation tend to play a subordinate role in these papers. This is especially interesting since VCN-related publications mostly involve and assume communicating road infrastructure. However, the development of this critical infrastructure is less illuminated, and thus important key requisites such as resilience are underrepresented. In addition, the expected data volume gathers interest among scholars, and the related potential and challenges are often discussed. However, scholars rarely question the relevancy of the data for the entire system and to what extent spatial differentiation is necessary for a VCN. Unlike this underrepresentation in this analysis, the decentralized architecture proposals are enjoying greater popularity in recent publications.
When looking at the institutional aspects, it is noticeable that the main concern is regulations relating to the system's operation. The uncertainty about data ownership, responsibility allocation, legal facts, and licensing are basic issues that are criticized in the literature. Legal requirements for architecture are less the subject of discussion, and if at all, only in connection with the subsidization of certain technologies. The literature review also makes the correlation of regulatory requirements with ethical requirements evident. Ethical issues such as trust, fairness, and responsibility in the event of a serious incident are firmly anchored in the values of policymakers, hence, are the subject of regulatory intervention. In the VCN, the question of safe design and, thus, the person's safety is particularly addressed in the selected literature.
It is striking that, compared to regulation, stakeholder cooperation is less of a requirement from the institutional perspective. Especially in socio-technical systems, social barriers are often decisive and let projects flourish or fail. Considering that exploratory insights from Chapter 5.2.2 emphasize this requirement, a scientific underrepresentation can be derived. A final institutional requirement that is highlighted is standardization. Due to the technological heterogeneity of the VCN components as well as the social heterogeneity of the societal structures within the EU, harmonization is a fundamental challenge. Therefore, it is hardly surprising that there is a considerable amount of interest in the development as well as the agreement of target-oriented standards.
Finally, implications for technical system operation can be drawn from the literature analysis. Here, the emphasis is on data management coherent with institutional and architectural requirements. The authors also focus on trust management and communications management, which are closely linked to ethical principles and regulatory interventions such as an authorized security certificate over institutional trust domains. Surprisingly, there are hardly any requirements for risk management, maintenance, and system update-ability (change management), although these are classic requirements of systems engineering and life-cycle considerations. Accordingly, these requirements should be examined more closely for further conception.

Stakeholder and Mission Requirements Description Table 6.2 adds the alignment of the stakeholder needs and mission objectives to the findings. It shall be noted that this combination is not a holistic view of all objectives and stakeholder needs. It represents rather the intuitive and directly linked needs/objectives which the actors themselves state. Further, it is intended to find the most critical overlapping requirements by reference to the deeply inherited needs and objectives. This shall ensure finding the core of overlapping interests in order to focus the development on these points.

Stakeholder and Mission Requirements Analysis A general alignment for the most core needs and derived requirements can be identified by merging these analyses. However, not all identified requirements that draw substantial attention from the literature overlap with the primary needs and objectives. This is because some requirements, such as privacy and security, are strongly related to each other and are therefore contextualized. In addition, requirements such as data management tend to be secondary requirements that arise from the need for functionality or regulation and are therefore not directly highlighted.
Nevertheless, four critical interpretations can be derived from the alignment. Firstly, ethical considerations seem to be a bigger concern for the stakeholder than reflected in the analyzed literature.

Secondly, social acceptance is an important factor in the VCN design, which is barely reflected in the literature. Thus, This requirement should be considered more in the development of a future VCN.
Another major concern of the stakeholders is the trust and control management of the operational VCN system. Hereby, it emerges from the needs that this subsystem is a critical point for acceptance among implementing parties such as vehicle manufacturers and service providers. Thus, it can be considered system critical.
Lastly, stakeholder needs and mission objectives approach the perspective of a VCN from the functional side. Benefits such as travel convenience or traffic efficiency are the main needs and could be an approach to designing with the application in mind. This can ensure the focus on the components that are beneficial to the user.

Table 6.2: Requirement alignment with stakeholder needs and mission objectives

Type	**Requirement**	**Literature Review (57 Documents)**	**Mission Objectives**	**Stakeholder Needs**
Institutional	Mission Requirements	6		
	Regulation: System Operation	27		SN1, SN6, SN12, SN17
	Regulation System Architecture	8		SN1, SN6, SN12, SN17
	Standards	19	OBJ2	SN12, SN17
	Stakeholder Cooperation	16		SN5, SN8
Social	Ethical Requirements	16		SN1, SN2, SN5, SN9, SN16, SN17
	Social Acceptance	7	OBJ5	SN5, SN12, SN14, SN15
Technical: System Architecture	Application Requirements	10	OBJ1	SN7, SN12, SN14, SN15, SN17
	Robust	29		SN6, SN7, SN10, SN14, SN15, SN17
	Safe	20	OBJ1	SN1, SN2, SN12, SN14, SN15, SN16, SN16, SN17
	Adaptive	12		SN11
	Secure	35	OBJ4	SN2, SN4, SN5, SN7, SN12, SN14, SN15
	Privacy Preserving	31	OBJ4	SN14
	Efficient	33	OBJ1, OBJ2	SN2, SN3, SN5, SN10, SN11, SN16, SN17
	Effective/ Reliable	33		SN10, SN14, SN15,AN16, SN17
	Resilient	10		SN4, SN7
	Interoperability / Heterogeneity / System legacy	29	OBJ2, OBJ3	SN11, SN14, SN15, SN16, SN17
	Architecture Choice: Centralized/Decentralized	8	OBJ2	
	Comply With Standards	5	OBJ2	
	Automation	7		
	Spatial Differentiation	3		
	Data Management System	22	OBJ4	SN12
	Scaleable	14		SN10
Technical: System Operation	Continuity of the Service	10		SN6
	Trust and Control Management	14	OBJ4	SN4, SN7, SN12
	Change Management / System Update	6		
	Monitoring	7		SN4
	Data Management	21	OBJ4	SN12
	Maintenance	6		
	Communication Management	16	OBJ2	SN7, SN14, SN15
	Computation Management	12		
	Disaster Management	2		
	Risk Management	5		

Interview Requirements Description In order to validate the results and compare the requirements with the insights from the interviews, an alignment is presented in table 7.1. It shall be noted that this table indicates the critical points of the interview partners and should not represent a holistic requirement elicitation by them. A certain requirement was tagged for an interview if the participant mentioned or described a familiar requirement and elaborated on its relevance for a VCN. The requirements structure itself was shown to the participants after the interview for further iteration. Further, it is acknowledged that the scope of the interview was limited, thus, not every aspect has been covered by each expert. However, the comparison provides valuable insights into the valued and critical components of a VCN from an exploratory perspective.

Interview Requirements Analysis The critical requirement for the design of a VCN is close stakeholder cooperation. Hereby, each participant highlighted that more cooperation in decision-making and development is crucial to implement a VCN or its functionalities in a meaningful way. This strong emphasis is a contrasting picture to the Literature requirements analysis and specifically scientific publications. Therefore, a mismatched focus of scientific efforts to the needs of the system perspective can be concluded.
Another example of a requirement that got less attention in publications and great attention from the interview participants is social acceptance within a VCN. According to the interviewees, this social factor is a decisive point in a VCN, as commitment and market penetration can be reached by it. However, little to no interest is given to the highlighted articles in the literature review. Hence, a potential for research efforts can be identified.
Unlike the literature results, the experts address security and safety in an intertwined way. Another key difference is that the experts did not focus on the system architecture properties adaptive, resilience, automation, and scalability. This is rather surprising as scalability and adaptiveness gather considerable interest in the literature. Lastly, the interest in spatial differentiation is highlighted by experts, whereas the selected publications disregard its importance for a VCN design.
This comparison shows that the intuitive challenges and main tasks related to VCNs are partly different from the focus of the published literature. In addition, the interview insights can be taken as an indication of more burning issues and can therefore serve as an inference for future focus areas for VCN publications. Another interpretation of these results is the focused depth of the literature. Due to the direction of the research, it is logical that the publications do not systematically illuminate the areas of interest since subcomponents are usually the focus of the research. However, the literature review rounds have specifically examined the system perspective and multi-disciplinary approaches. Thus, it can be assumed that this perspective, the interconnectedness, and the complexity are disregarded. This can be seen critically since such a large-scale infrastructure project is multidimensional and lives from the dynamics of the actor constellations influencing development directions.

These three steps result in the systems requirements foundation from the socio-technical perspective. The following summarizes the outcome of this elicitation process:

- 33 fundamental VCN requirements are identified. Further, these requirements are weighted through the quantity in literature, connected to the stakeholder analysis, and evaluated by experts.
- Literature focus on technical system architecture requirements. Further, stakeholder cooperation and ethical requirements receive less attention from scholars
- A general alignment of the most core needs and derived state-of-the-art requirements can be identified.
- The expert validation of the requirements results in a shift in the requirement's importance. The identified underrepresentation of cooperation and social acceptance in literature is considered critical as experts heavily emphasize these requirements and consider the technical implementation as less critical.

6.2.2. System Requirements Structure

The findings of the chapters above are summarized in a system requirements structure and applicable in Figure 6.3. An enlarged version is applicable in Figure C.1. This tree follows the approach of defining the system of interest viewpoint as the top of the tree and forming subsystems with functional requirements, process requirements, or enabling subsystems leaves at the end of the tree. This classification is done according to ISO15288 to enhance the understanding of the system and separate the function space from the design space. For further clarification please consult International Organization for

Standardization (2015). Due to the complex character, the high-level subsystems are not technical but rather complex systems themselves. This requirement structuring aims to visualize the interrelationships and conflicts among the system's subcomponents. Please note that the tree resembles a multidisciplinary requirements structure due to the development stage and selected viewpoint. The focus here is not on analyzing a technical sub-function of a VCN. Rather, this requirement structuring serves as a stopping point for the design of such functions. This system perspective is intended as a foundation for effective and aware design to make fundamental decisions within a VCN and avoid systematic island development.
In this context, four main subsystems (institutional, social, technical, and economical) are mapped below in the system of interest, which are explained in the following paragraphs.

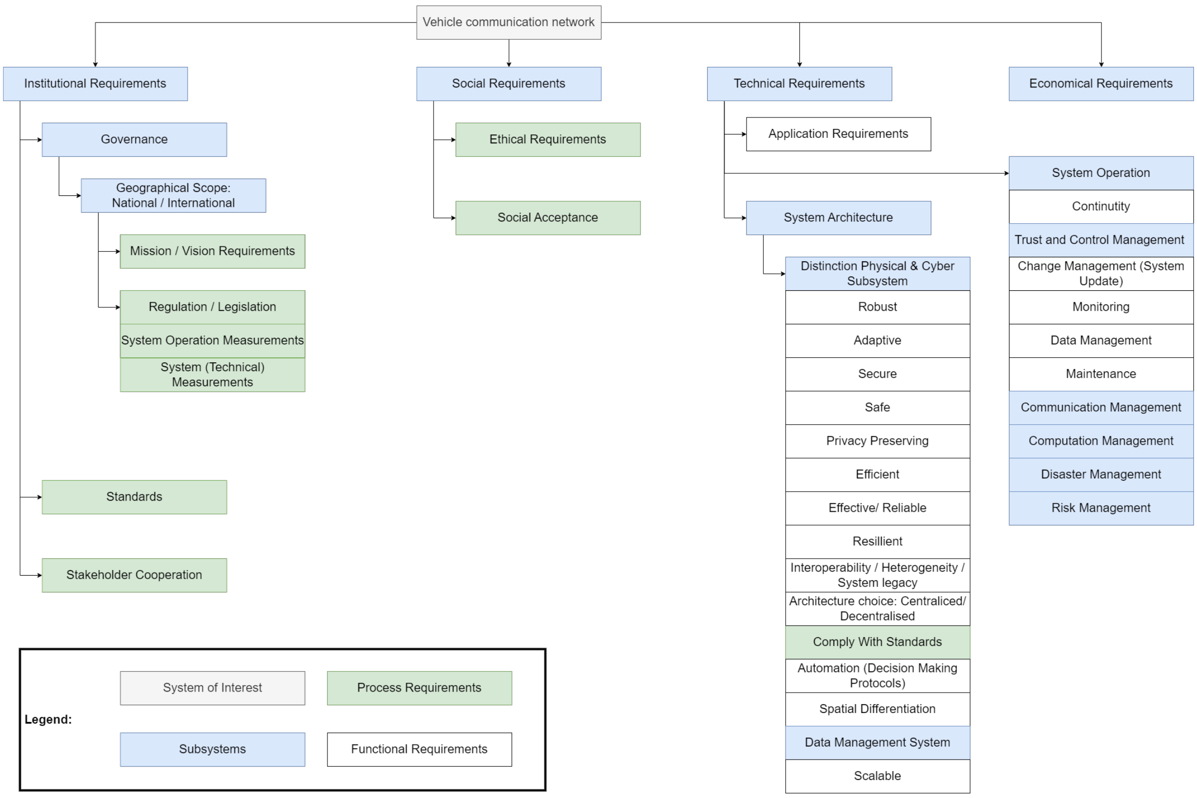

Figure 6.3: System requirements structure (Large version in Figure C.1)

Institutional Requirements The first subsystem contains the institutional and governance aspects of the desired system and can be aligned with Williamson (2000) social subsystem. This branch primarily represents the institutional view and requirements of the system.
A subsystem within this cluster is governance, which can be broken down by geographic scope (international, European, national). Each of these governance subsystems influences the VCN with its decisions through the functional requirements of regulation and the set mission.
Further, the analysis resulted in a systematic breakdown of these regulations into system operation measurements and system architecture measurements. This distinction is critical as implications differ depending on the choice. Whereas system operation measurements define political frameworks for objectives, responsibilities, promoting action, or political interventions, system architecture measurements rather focus on definite choices and technical specifications. An example of a system operation measurement in the context of a VCN is the European climate law, as it sets sustainability objectives and targets. A political intervention through a system architecture measurement is, for example, the regulatory obligation to install the eCall system for vehicles (European Commission, 2015b).
Standardization concerns are another essential functional requirement that can be attributed to institutional requirements. This may sound inconsistent at first glance, as standards are associated with technical aspects. However, these specifications are formed in institutional environments. Moreover,

the background of standardization requirements is institutional since the harmonization and decentralized coordination of development and understanding efforts are the focus of developing standards. This functional requirement is not only about the development of standards but also about implementing and agreeing on them. Especially the commitment is challenging since modularity to emerging standards and technologies is crucial. Furthermore, the geographical levels potentiate the requirement´s complexity.
The final institutional requirement for the development of a VCN is cooperation. The different hierarchies and decision-making levels from Chapter 5.1.2 indicate an increased necessity for cooperation and coordination.

Social Requirements The next branch highlights the social subsystem and respective requirements. For a multidisciplinary analysis, ethical requirements and social acceptance can be identified. These requirements represent the human component in the socio-technical VCN system. This can also be seen as a mediator between the technical and the institutional side as it forms an ethical framework for the objectives and thus directly influences the requirements and their validity. Including these aspects in the VCN design is essential, as the implications of human security and invasion of private rights for the individual and society are considerable.
The ethical requirements include fundamental questions about trust, privacy, and accountability. The requirement of social acceptance represents the essential but often ignored human reaction and opinion to the VCN.
Regardless of the benefits and technical implementation, public opinion can be an enabler or a restriction, so attention to this requirement and positive implementation is critical. Social acceptance is also made relevant by the aforementioned chicken-egg infrastructure problem and implementation of the corresponding vehicle technologies. When pursuing the voluntary vehicle implementation approach, the vehicle manufacturers' acceptance and relevance must be gained so that relevant VCN messages can be received at all. Even in the case of an institutional regulatory obligation, this requirement plays a role since consensus and acceptance of such a measure must first be achieved.

Technical Requirements Technical requirements which are closer to classical engineering are summarized in the technical subsystem of a VCN. Hereby, this branch represents Williamson 's (2000) technical subsystem, whereby Williamson 's (2000) first three levels are found in the subsystem: application requirements, system architecture, and system operation. The previous analyses have shown that the stakeholders' interest in the design and development process is focused on these three directions.
In the case of application requirements, VCN requirements are derived from the desired application and imposed on the system architecture as minimum technical requirements. In this case, the requirements usually arise from the four application clusters traffic management, autonomous driving, safety applications, and infotainment. From a technical point of view, minimum requirements differ per application, and priorities are imposed on the architecture, resulting in an indispensable specification of the desired applications. Hence, a clear breakdown of the selected applications is recommended to design a capable system.
Such a capable system is built upon a system architecture representing the second subsystem of the technical aspects. Hereby, a VCN must consider an integrated design of a physical and cyber subsystem. Each of the systems is associated with a set of requirements visualized in Figure 6.3. This conglomerate of functional requirements represents the main multi-disciplinary requirements for a VCN from different design perspectives. Furthermore, this set specifies how the architecture should be and which consideration must be taken while designing.
In addition to the requirement specifications of the architecture, system operational requirements are crucial for a VCN. Figure 6.3 visualizes the relevant functional requirements and subsystems from the previous analysis falling into the system operational. Hereby, the identified requirements are enabling and obligatory systems as well as critical processes and conditions for operating a VCN.

Economical Requirements Lastly, a significant consideration of a VCN is economic and financial requirements. This branch is represented within the tree, however, a refinement is excluded due to the scope. However, it is acknowledged that significant relevance can be allocated towards these concerns as costs can not outweigh the gains and benefits. A VCN represents a large-scale infrastructure project, hence, institutional stakeholders have increased interest in a reasonable investment framework and justifiable operating costs. Likewise, economic actors are constrained in the design to achieve a positive investment return ratio, which allows this requirement branch to classify itself more as a constraint. Furthermore, the missing public-private business case can be allocated toward this branch.

Three key insights emerge from this synthesized structure.

- First, a clear representation of different domains is evident and essential to reflect the socio-technical character of a VCN.
- Further, the figure illustrates the system perspective and its relevance. A separate island development and design of a VCN and its sub-components are insufficient, hence, the multi-layered VCN characteristic should be incorporated into the designing process.
- Finally, this system perspective thrives on iteration and recursion. Since development takes place on a smaller scale for sub-components, this tree can be taken as a base input for a subsystem or function. It is important to note that the knowledge gained from such developments can be dynamically applied to the structure as they serve as input.

6.2.3. Relationships

Due to the complexity, the subsystems cannot be considered separately from each other. Each requirement is directly or indirectly connected to each other. Therefore a visualization and description are not appropriate for the scope of this work. For this reason, this chapter presents a systematic view of interrelated impactful requirements that affect each subsystem and are considered a fundamental discussion in the VCN cosmos. This symbolizes exemplary how such a relationship analysis can be carried out. Hereby, the approach consists of examining a requirement from different viewpoints. These include the infrastructure viewpoint, which can be seen as the backbone consisting of the IT road infrastructure operator and the network operator; the institutional viewpoint, which covers regulatory aspects; the industry viewpoint, which stands for the implementation of the technology and harmonization, and finally the user viewpoint which takes into account ethical principles as well as user needs.

The following two paragraphs highlight the relationships of the interoperability and robustness requirements, which are the focus of this work. In addition, the requirement for privacy is analyzed for relationships in a separate paragraph, as it is of particular interest in the EU GDPR context.

Robustness Robustness is a fundamental VCN requirement from the socio-technical perspective. It resembles the ability of the technical subsystem to respond to abnormal circumstances without losing functionality (International Organization for Standardization, 2018a). To achieve this, designers must make interdisciplinary efforts, as this requirement is closely related to the other perspectives and requirements, which is illustrated in Figure 6.4.

A robust VCN system is desirable from the institutional viewpoint, as it is part of the critical infrastructure of one's territory (Ministry of Justice and Security, n.d.-a). Therefore, the development is strongly connected to the vision of the respective institutional decision-makers as a robust system is more resistant to threats, thus, safety concerns.
Due to this, robustness must go hand in hand with regulatory requirements for VCN operation. Therefore, regulations have a relation to the robustness requirement. However, this link is bidirectional. As much as the institutional perspective needs robustness, a VCN system needs robust legislation. Only through regulatory certainty and a clear framework robust design and implementation efforts be accomplished. Otherwise, no consensus can be found in such a large-scale infrastructure project, as the industry players' financial risk is too high, and guidance for national decisions is lacking.

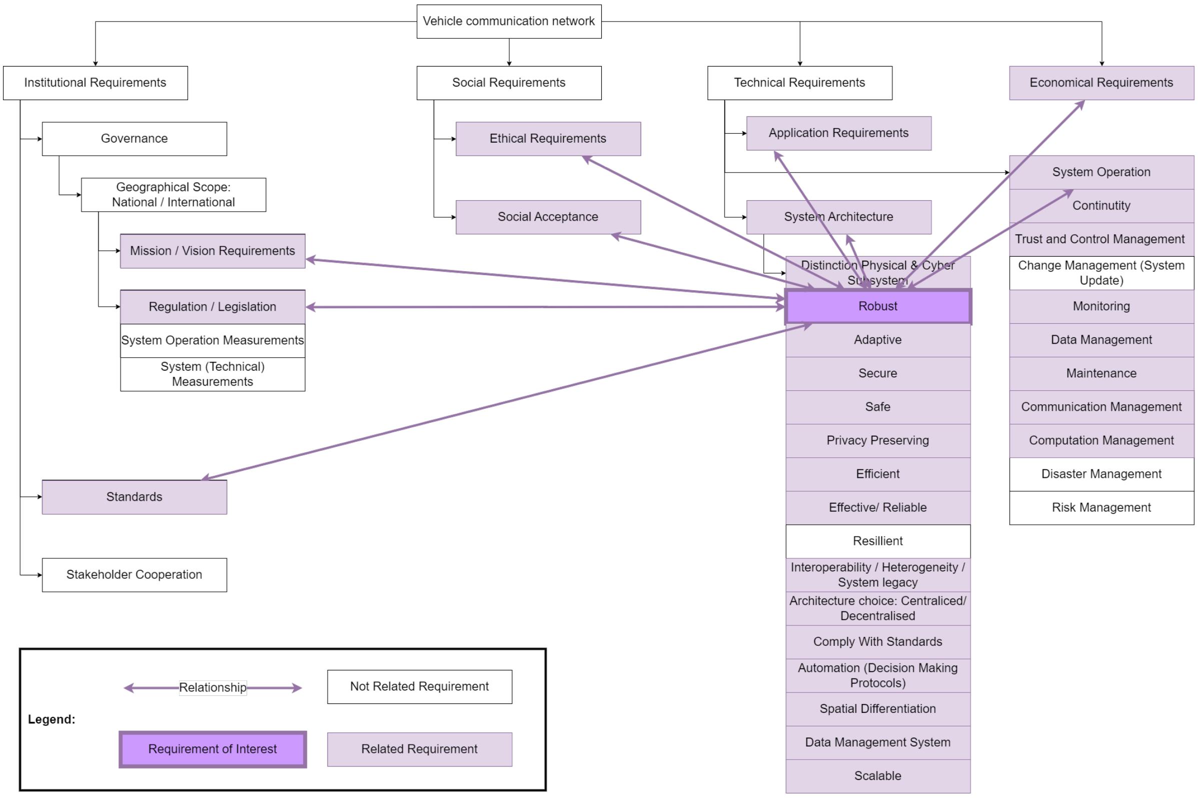

Figure 6.4: Relationships to the robust requirement

As noted above, robustness is essential to create safety within the infrastructure. This idea draws the link to social requirements. Ethical considerations such as human safety and security must be principles for the robustness attributes of the technical design so that network failures and the potentially resulting fatalities are minimized. In this context, due to the thematic proximity to automotive, the functional safety standards that dictate the fail-safe in exceptional circumstances functionality of the technical subsystem must be considered (Wang et al., 2020). These ethical principles are not optional for robust functionality because neglecting them opposes the interest of the institutional and ethical perspective and thus inevitably affects the social acceptance of the decision-makers and users. Therefore, there is a strong correlation between robustness and the requirement of social acceptance.

Strong dependencies on almost all requirements can be identified within the technical requirements and, thus, the infrastructure implementation perspective. In the system architecture, the individual sub-requirements must be fulfilled robustly to meet the robustness requirement. Hence, all requirements are connected except redundancy, representing a different dimension of system attributes and evaluation. Scholz et al. (2012) explains this relationship between robustness and resilience and can be used for further consideration. Especially the relation to safety or security is mentioned by authors such as GSMA (2019) or Ministry of Infrastructure and the Environment (2016) concerning robustness.
In addition, the operation of a VCN must be robust from an infrastructure perspective. These relationships are primarily dictated by the regulatory framework, thus, creating a relationships triangle. As a result, requirements such as service continuity are regulated by the EECC, and data management by the GDPR. The institutional perspective implements their interest in a robust operation of the VCN. Furthermore, Sharma and Kaushik (2022) highlighted that communication and its management must be robust. However, the relation to maintenance or system-critical functionalities such as monitoring or control management is not identifiable in the literature. Depending on the selected degree of robustness (infrastructure's redundancy and availability), maintenance considerations are implied.

The costs caused by the operation of the VCN, but also the investment cost, must be reasonable and in balance with the benefits of VCN functionalities. Thus, the economic perspective and their requirements influence the robustness requirement with this trade-off.

Interoperability Another significant relationship complex in the development and deployment of a VCN is the inherent heterogeneity of the system, thus the linked interoperability requirement. Mastering this requirement is a balancing act as it is closely related to all requirement branches signifying the importance of interoperability. These relationships are visualized in Figure 6.5.

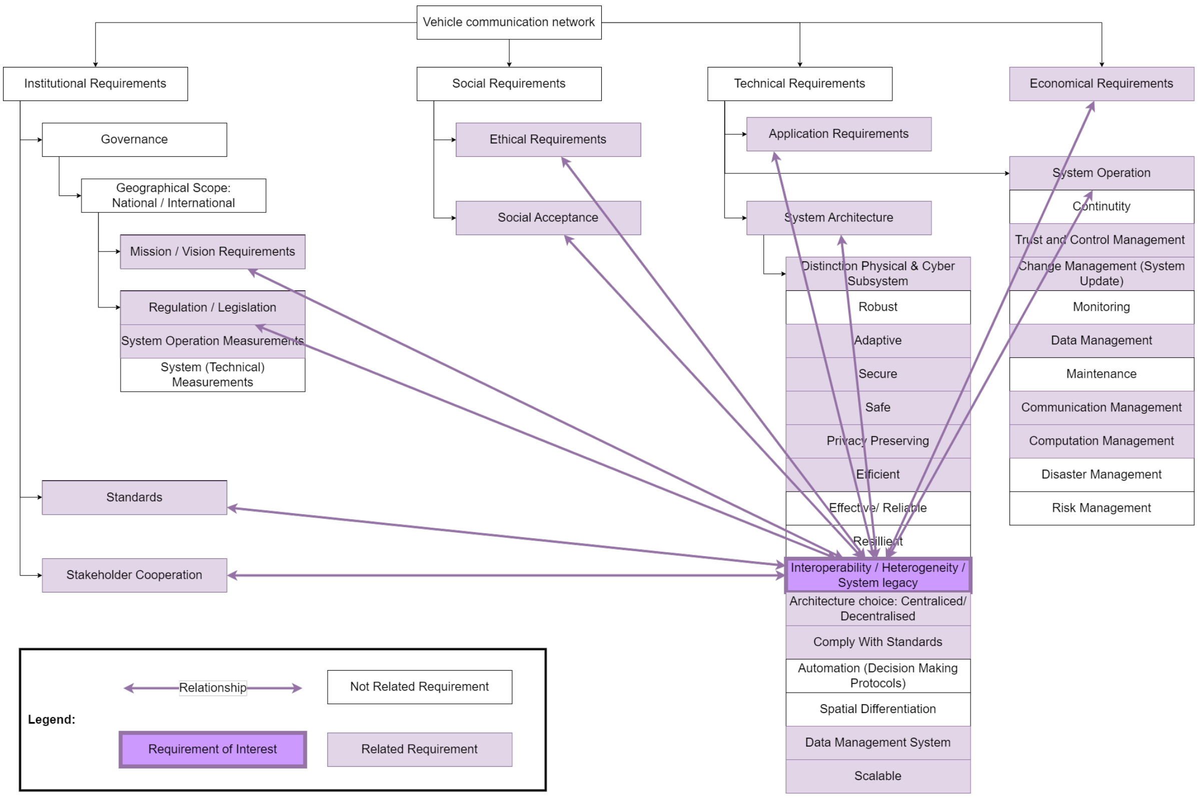

Figure 6.5: Relationships to the interoperability requirement

Here, interoperability is directly related to all institutional requirements. Given the multitude of actors in the VCN cosmos, particularly within the EU, it is crucial to unifying potentially diverse approaches among governments and industry players. Therefore, vision and mission requirements on a European and national level are crucial for interoperability as they guide the VCN development and its functionalities into a cross-border interoperable system. However, due to the geographical circumstances of the regions, system architecture approaches will differ. Hence, enabling the compatibility of various VCN architectures is mandatory and communicated by political documents such as European Commission (2020a) or Government of the Netherlands (2016).

In order to achieve this interoperability, harmonizing the regulatory framework plays a crucial role, creating a strong link between the requirement and regulatory interventions (Frötscher et al., 2022). Moreover, this harmonization is necessary to meet the European single market's vision and create a system that has economic relevance for the implementing actors. Vehicle manufacturers are producing on an international level, therefore, VCN implementation of this actor presupposes that the framework conditions are shaped on a European level.

In addition, the harmonization of standards plays an essential role in interoperability, as it unifies the technical decentralized developments and develops a common language for the subsystem (Hamadneh et al., 2022).

To achieve this, stakeholder cooperation is a critical issue and thus closely linked to interoperability (Frötscher et al., 2022). Consensus on regulatory conditions and standards must be reached in cooperation to ensure the interoperability of geographic zones within the EU. The industry players, such as automotive companies or network providers, and all countries of the EU must come together and work out the minimum level of interoperability to successfully develop a VCN.

This point is especially critical for the vehicle manufacturer stakeholder group, as only legal and social certainty about the functionality across the entire European market will lead to social acceptance of the technology and its implementation in connected vehicles. Hence, enabling the heterogeneous character of the VCN to be interoperable relates to the social acceptance requirement.
It should not be neglected that the variation of countries imposes ethical questions on interoperability, as the same development and deployment speed for required infrastructure can not be assumed. Addressing such inequality issues must be represented in cooperation and decision-making.

Moreover, the interoperability requirement is central to the VCN architecture development. Due to the conditions described above, seamless integration is a constraint for physical as well as cyber architecture design. According to Vermesan et al. (2021), the integration of different VCN platforms and applications into the architecture can help reach the anticipated potential of VCN.
To ensure the functionality of these VCN applications and platforms, interoperability of communication technologies must be enabled. In this context, the coexistence of WIFI technology such as ITS-G5, cellular communication, and satellite communication is conceivable in order to achieve seamless connectivity.
Since this interoperability is rather challenging and complex, attention must also be paid to ensure efficiency and effectiveness while integrating the heterogeneous character. Task scheduling or communication handover can be taken as examples of this (Li et al., 2023). In task scheduling, it must be possible to process heterogeneous requests of connected vehicles on different infrastructures and to provide answers efficiently. This process is made more complex by the high degree of mobility leading to communication handover between infrastructures (Li et al., 2023). Therefore, addressing these interoperability considerations is critical for the implementation of VCN functionalities from all perspectives.
Another relation of the interoperability requirement is to the data management system. According to INT4 and INT5, unifying the heterogeneous data structures of the national ITS data points is an objective for the VCN design, thus, creating a relationship among the requirements. Further, 5GAA (2022) identified the institutional intervention or industry workarounds by third-party operators such as here technologies or tomtom as approaches to deal with this relationship.

Lastly, heterogeneity is closely linked with the economic requirements and the industry view. By mastering heterogeneity, service providers can build on the VCN with their offerings. In addition, the economic interest of the vehicle manufacturers increases with interoperability since they can focus on an economically large area with their VCN application and can work in a cohesive manner.

Privacy One of the fundamental concepts in a future VCN is privacy. The anticipated growth of data in the VCN space comes with unresolved privacy discussions around all levels of the VCN design. Thus, extensive efforts are needed to align privacy by design principles with all design levels. This deeply rooted relationship of privacy to the other aspects of a VCN is illustrated in Figure 6.6.
In the European context, the general data protection regulation (GDPR) opposes strict obligations on all designing actors in the VCN (European Commission, 2016b). Hereby, the GDPR bridges privacy aspects into different dimensions, causing a magnitude of relationships to the privacy requirement. Therefore, a strong relationship between privacy and institutional requirements can be identified.
Due to the European strategy and values, privacy aspects are deeply rooted in its vision and mission. Hence, privacy is often the subject of relevant VCN communications such as the smart mobility strategy (European Commission, 2020a), but also of the political agenda itself (Von der Leyen, 2019).
This vision shapes regulatory interventions, such as the GDPR, which can draw the link from regulations to privacy. Especially here, the implementation of the GDPR impacts the system architecture but also the system operation. However, not all privacy aspects and concerns are addressed in the current regulation (Hahn et al., 2019).
With regard to future developments, an expansion of legal data transmission is necessary, specifying which data should be exchanged with the network. Concerns such s data ownership, destination, and passengers are critical and need further elaboration. In addition to these points, accountability in case of data breaches impacting the privacy of individuals needs special attention as no clear responsibilities are allocated among the stakeholders. This regulatory privacy discussion of a VCN will impact future development.

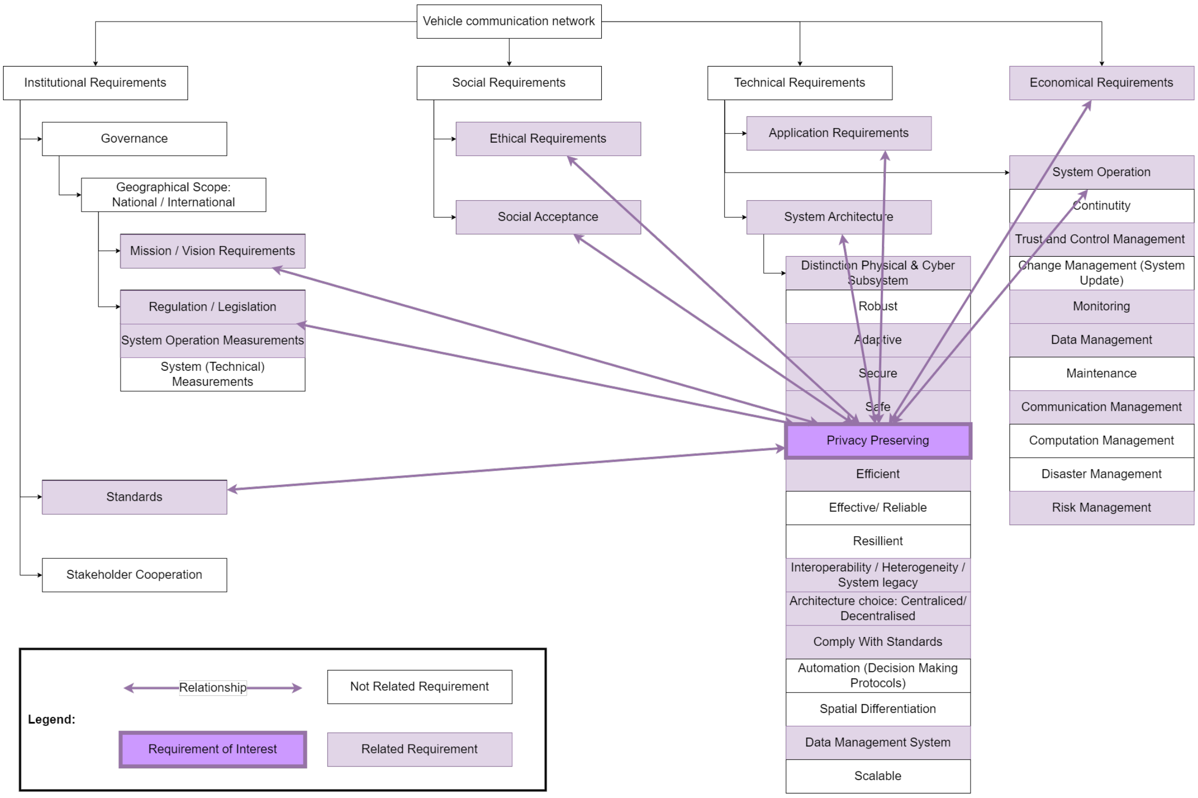

Figure 6.6: Relationships to the privacy requirement

Addressing these issues requires an ethical reflection on privacy in the VCN context, as the nature of these conflicts is ethical. Here, the privacy requirement is primarily in relation to the user perspective. Anticipated connected safety functionalities, such as automatic emergency situation detection where a driver is impacted physically during a ride, will require an ethical trade-off with privacy. It must be clarified to what extent private data can be incorporated into the functionality of a VCN in order to maximize the security aspect and bring it into relation to the privacy invasion.
Such ethical discussions are then transferred to the regulatory framework, which indicates a relationship triangle. This also applies to the above-mentioned privacy considerations. This relation will focus on location data, movement patterns, and private health data as they will be weighed against the functionalities.
Moreover, ethical issues of inclusiveness must be incorporated into the privacy requirements. Sandeepa et al. (2022) highlighted that even non-personal, third-party personal data or anonymized data can be dangerous for privacy, as these data can sometimes have precis conclusions on sensitive data such as disability, ethnicity, or sexual orientation. This must be contained by regulation, as otherwise discriminatory aspects can be incorporated into the service design of the VCN and providers on the basis of private data.

The institutional and ethical viewpoints directly impact the privacy implementation, representing the road operator's view concerning the infrastructure and industry view if applied to the services and vehicle manufacturer. Hereby, the privacy requirement influences both the system architecture as a whole and the system operation.
Since privacy is represented in data form within the cyber subsystem of the architecture, it is closely intertwined with the security requirement. Here, the actors who interact with personal data must implement appropriate technical/ organizational measures to comply with the GDPR and protect personal data from unauthorized access, accidental loss, or disclosure.
However, these measurements must consider the performance and thereby the efficiency requirement. Wang et al. (2020) identified that encryption as a measurement comes at the cost of latency, which is a critical constraint for the system functionality. Therefore, a trade-off between efficiency and security can be identified, which directly links the privacy requirement with efficiency. A suitable example of

the functionality is seamless authorizations. Here, the vehicle must re-identify itself when changing infrastructure access points in order to maintain a high level of privacy. Such multi-level security/privacy measures are already included in smartphones, but it is not feasible to implement these principles while driving as they require the focus of the driver (Wang et al., 2020).
Another aspect of the system architecture that is related to privacy is the choice of the architecture itself. The infrastructure's centralized and decentralized approach must respect privacy by design principles, but the choice results in different focal points. In the decentralized architecture, the number of attack points complicates the guarantee of privacy, and in the centralized approach, it is the single point of failure. Therefore, a sophisticated security system is necessary for both choices and is closely linked to a GDPR-compliant data management system. According to the findings of the C-roads pilot projects, it is important to highlight that the storage of data is not obligatory.
Furthermore, substantial considerations on sensor data management have to be made regarding privacy. In the future, the connected vehicles in a VCN and also the infrastructure will have improved sensors that record the environment. It must be ensured that only the relevant data is processed and saved and that any filters on the sensor data have a secure safe design to avoid malicious invasions. Thus, privacy requirements must be incorporated into various subsystems.
Privacy is heavily linked to the subsystem trust and control management in the system operation. As this subsystem is responsible for establishing trusted communication among actors, a certain degree of information exchange, possibly containing private data, is required. Therefore, a clear relationship to the privacy requirement can be established. In addition, the implementation of privacy in trust and control management is made more difficult by security-related relevance. In the case of untrustworthy behavior, the management system must reserve the right to identify the actors for the sake of general traffic security/safety, but this implies that identification is possible at any time, creating an inherent conflict in data management.
Another point that needs to be addressed in the literature is the relevance of privacy in risk management and disaster management. Privacy should be seen as a risk, especially for the operators, as they are accountable for failing the preservation. Hence, adequate risk management for privacy risks must be incorporated into the operational use of the system. This further includes mitigation strategies and disaster scenario thinking. An example of this could be a stroke suffered by a driver in a connected vehicle. Can the vehicle send the personalized data to the emergency departments in order to get the emergency under control? Is it legal and ethical to monitor this data? To what extent can this be classified as a serious case, and what happens if communication is triggered by a false positive? Private data can be wrongly sent here, which is why these privacy aspects must be anchored in the design to ensure user privacy.
Above all, the privacy system operation is influenced by institutional requirements and ethical guidelines. This impact illustrates that a simple relationship of two requirements in the VCN has a cascade of co-relationships that can dynamically adjust as insights are discovered.

Lastly, the relationship of the privacy requirement has to be reflected in an economic context representing the industry view on a VCN. A prerequisite for a functioning and thriving VCN is a public-private business case that drives industrial acceptance and implementation. However, this can lead to a conflict of interest between the economic actors and the users represented by the institutional side since data value and revenue generation are the main factors. One of the main interests of the industrial players is to use this data to make personalized recommendations and close sales via VCN services. In view of the regulatory and ethical framework of the EU, however, this must be viewed critically and thus creates a strong relationship between economic interests and privacy. Furthermore, it is foreseeable that when scaling a VCN and connected vehicles, big data and the use of AI for automated analysis of the data will become relevant. According to Silva and Iqbal (2019), however, the alignment with privacy is difficult since ethical questions in this context still need to be clarified.

Understanding the relationships and interrelationships within the VCN is essential to design. Analyzing the three requirements, robustness, interoperability, and privacy lead to the following conclusions:

- The development of the VCN is highly complex, and requirements are connected across domains. Therefore, a system perspective is indispensable for successful development.
- Ethical, institutional, and economic factors strongly influence technical requirements such as interoperability. This can be attributed to the socio-technical characteristic of the VCN system.

- Robustness and interoperability are critical requirements that must be fulfilled to convince decision-makers and implement the system successfully.
- The growth of data in the VCN space brings unresolved privacy discussions at all levels of VCN design. Efforts are needed to align privacy with design principles at all design levels. Further, the trade-off between economic and institutional/user interest in privacy must be addressed and clarified.

6.2.4. Challenges

The highlighted relationships within the requirement structure emphasize the complexity and interconnectedness of all design elements in a VCN. This strong influence, if not codependency of requirements, creates challenges within and across subsystems. The following introduces fundamental challenges and related trade-offs that can be identified in a VCN design. The selection of conflicts highlighted in the thesis are visualized in Figure 6.7.
Firstly, the conflicts with the institutional requirement “Regulation / Legislation” are analyzed in a paragraph. Thereafter, a paragraph highlights the conflicts surrounding the technical requirement “Architecture choice”.

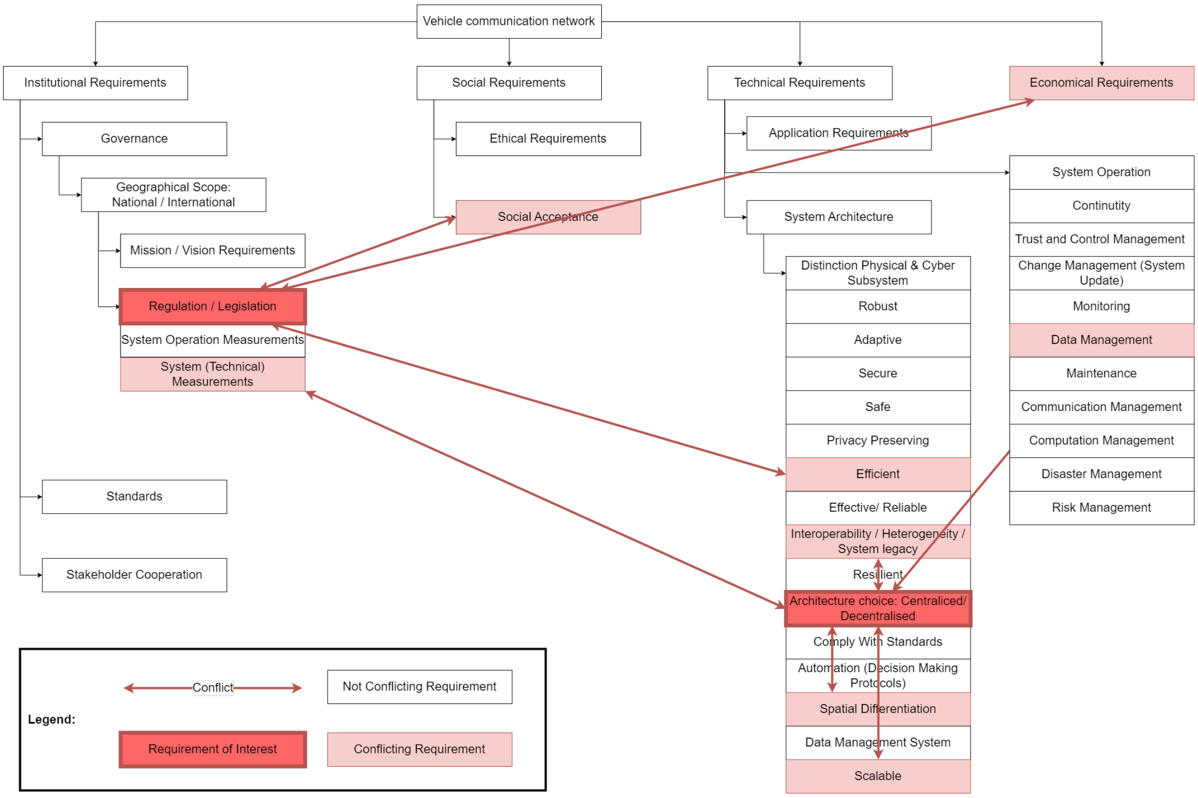

Figure 6.7: Highlighted challenges within the requirements

Regulation / Legislation Firstly, the institutional view faces a variety of challenges concerning the deliverable of a regulatory framework. Hereby, the challenge is not only to adapt already existing regulations to the constant technological and social developments but also to develop and enforce new required VCN regulations.
A highly relevant example for needed adjustment is the 2015/2120 Net Neutrality and Open Internet Access Regulation of the European Union, which prohibits the prioritization and blocking of internet traffic (European Commission, 2015a). This intervention in network management aims to ensure network integrity, security, and fairness. However, future VCN applications are anticipated to profit from the 5G connectivity and efficiency-increasing techniques such as network slicing, which clashes with this regulation if not classified as an exemption. Hence, an adjustment is needed in case of a commitment toward this direction.

Another regulation that can clash with the economic and connectivity requirements is the EECC regulation, which sets the regulatory framework for network operators. Here, Briglauer et al. (2017) criticizes, in particular, the regulatory intervention of access sharing in the context of co-investment into the next-generation network by network operators. This can lead to disincentivizing investments and thus impair the expansion of (cellular) connectivity. Depending on the commitment of the stakeholder to a communication type and the network coverage situation of a country, an adjustment or trade-off needs to be addressed.
As can be seen from the previous analyses, the demand for new regulations is considerable. Given that ITS regulation has been delegated, introducing new VCN regulations represents an endeavor in the European context. This is highlighted in the visualization of the requirement, as such regulations require the social acceptance of the member states and their industry, which is not given due to different interests. This acceptance is further complicated by the need to strike the right balance between restrictive and enabling interventions in system operation and system architecture decisions, which are linked to economic and ethical interests. Therefore, introducing new target-oriented regulations can be seen as a major challenge as aligning the stakeholder needs in a justifiable way to gain their acceptance is a complex subject.

Architecture choice Another challenge within the requirements is the decision about the architecture of a VCN. Here, a selection of an approach can depend on the type of application, infrastructure, and which type of communication is required. In addition, hardware and software decisions must be made considering the physical and cyber systems in coordination with the desired applications. Therefore, the infrastructure perspective is confronted with a major conflict of integrating these aspects into an architecture and remaining interoperable with other systems. This clash is further complicated by the heterogeneity of the countries in the EU, which in case of doubt, pursue different VCN strategies. As a result, the infrastructure architecture can vary substantially, which further complicates the interoperability of vehicles in these infrastructures.
Figure 6.7 further highlight the arising issue of scalability in the context of architectural choices. Safety-critical VCN applications require low latency, which can clash with the selected approach when scaled up.
With respect to the decentralized approach, the problem of feasibility and maintenance of the magnitude of the edges may be an issue, whereas, with the centralized approach, the question of functionality due to increased roundtrip time and network congestion must be raised. Hence, the trade-off from the infrastructure perspective must be made between centralized and decentralized deployment with a view to future scaling.
Another challenge of the architectural choice will be the related data management system and dealing with relevant spatial data. Since the data generated can be of limited spatial and temporal relevance, the architecture must be able to consider these attributes separately from the system-relevant events. An accident on a country road away from busy roads is less relevant than a system-critical collapse of a bridge. Thereby, the system and industry view must find the trade-off between data completeness and efficiency to retrieve and process the data.
Lastly, a conflict is highlighted between the regulations and the architectural choice. Stakeholders are developing and implementing different architecture choices, which clashes with a regulatory intervention that restricts the architecture solution space. The network operator Vodafone for example, is already testing C-ITS applications in the greater Munich area enabled by edge computing (INT12). The road authorities, however, are pursuing the approach of a central data collection point per country, which poses architecture integration challenges. Because of this interplay of different technological setups, regulatory interventions will clash with current system developments and stakeholder approaches regarding the architecture.

In this subchapter, challenges of the technical requirement “Architecture choice” and the institutional requirement “Regulation / Legislation” are analyzed. The findings are summarized as follows:

- The complex nature of a VCN naturally raises conflicts among the requirements as a multitude of interests (economic, institutional, user, ...) come together. Addressing these conflicts with feasible trade-offs is crucial for the social acceptance of a VCN system.
- Developing and enforcing VCN regulations is challenging. Existing regulations must be adapted

to technological and social developments, and new regulations must be developed and enforced. However, finding the right balance to be agnostic and to gain acceptance among decision-makers has yet to be solved.

- The selection of a VCN technical architecture is inherently complex due to the heterogeneous system character. This results in multiple conflicts within the technical but also social subsystem.

6.3. Key Findings

The system analysis results in a weighted requirement elicitation aligned with the stakeholder needs and objectives. A key finding is that publications focus on technical architecture, and social as well as institutional factors are rather neglected. Furthermore, the magnitude of the identified state-of-the-art requirements does not link to the primary needs of the stakeholders. In addition, publications seem to lack a joint reflection on the connection between security and safety. Furthermore, a system requirement structure is proposed with the four identified subsystems representing domain perspectives (institutional, social, technical, and economical.). Each requirement is highly connected within the structure and the different branches, exemplified by the interoperability and privacy requirement. Moreover, key challenges are described concerning regulation implementation, such as the net neutrality clashing with 5G applications and system architectural choices that influence the system design.

7
System Evaluation

This chapter evaluates this thesis's outcomes and analyzes how the results support the solution to the research problem. For this, Venable et al. (2016) framework for design science evaluation is selected due to the applicability and number of different strategies. Thus, the optimal one can be selected according to the parameters of this work. Since the thesis presents social or user-oriented artifacts and the validation can be done at a low cost, the "Human Risk & Effectiveness" strategy is chosen. With the strategy chosen, 15 interview partners were asked to evaluate the stakeholder and requirements analysis deliverables in the interview. This was done in two rounds during this thesis project. The demographic information of the interviewees is applicable in Table 5.1. Depending on the deliverable, a different evaluation goal (artifact properties) and a different time scope of the evaluation were followed.

Chapter 7.1 evaluates the 4-layer stakeholder complexity model. Thereafter, Chapter 7.2 presents the evaluation of the system requirement structure.

7.1. Stakeholder Complexity Model Evaluation

Figure 5.2 from Chapter 5.1.2 is the subject of the first evaluation as it is the outcome answering research question one. This evaluation is done in two interview rounds of 15 participants. For both rounds, an iterative character is selected (ex-post). Thus, the developed artifact is presented and evaluated. The following presents the two evaluation rounds in a separate paragraph. Each paragraph states the goal, the evaluated model, the evaluation outcome, and the taken adjustments to the model.

First evaluation round The goal of the first evaluation round is to evaluate the level of complexity granularity (Sun & Kantor, 2006) and test the rationality/understanding of the graph (Smithson & Hirschheim, 1998). Hence, the first seven interview participants were asked whether the complexity abstraction was sufficient to visualize the stakeholder complexity and if they understood the model's content. Figure 7.1 shows the initial model which was presented to the participants.
Six of seven experts stated that the level of abstraction is sufficient and the system's complexity is well represented. One expert questioned the abstinence and potential impact of users and stakeholders without designing power. In terms of understanding, the following recommendations were made by two experts: First, a legend helps to understand the different types of connections between stakeholders. Second, it needs to be clarified what the goals of a level are and its relevance.
Based on this feedback, the following adaptations are considered for the model:

- First, end users, and stakeholders without designing power are included in the design, as it clarifies the indirect influence of these non-decision-making stakeholder groups.
- Secondly, layer goals are added to explain the individual tasks among layer stakeholders.
- Thirdly, a legend explaining the components of the graph is added.

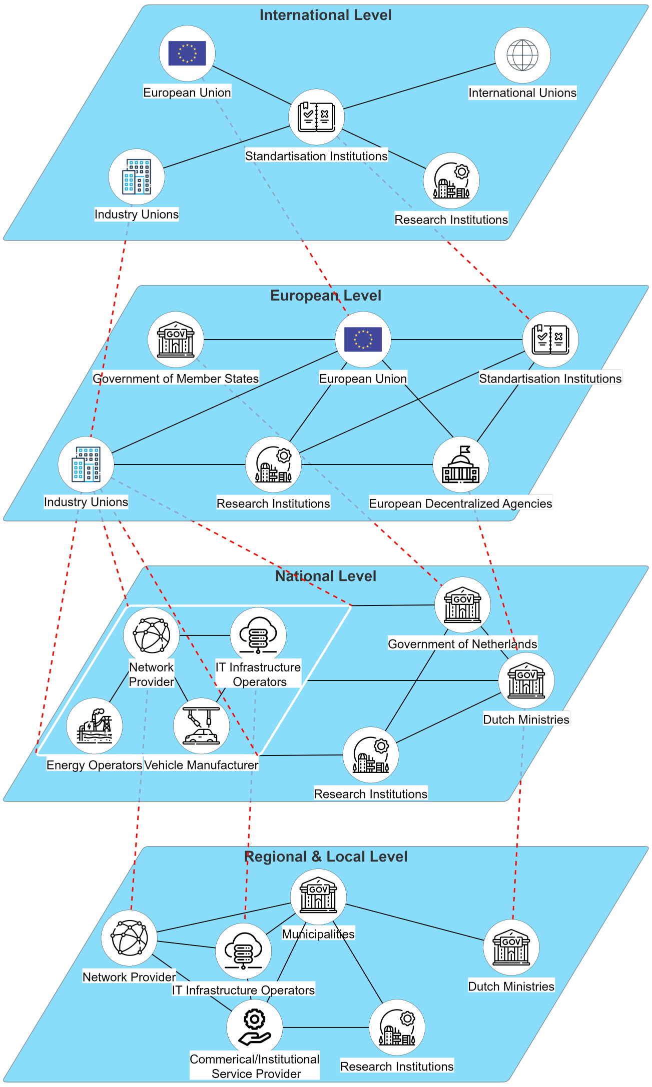

Figure 7.1: Initial 4-layer Model

Second evaluation round Figure 5.1.2 shows the adapted and final graph, which was the base of the second evaluation. The goal of the second round with the remaining eight experts was to evaluate the completeness and stakeholder representation within the graph.
Seven of eight experts perceived the model as complete, given the chosen level of abstraction. One expert mentioned the absence of consumer associations at the international and European levels. This suggestion is acknowledged and represents the basis for further iteration. In terms of representation, all experts perceived themself and their collaboration partners as well represented. Thus, both evaluation criteria are sufficiently met.

Implication for the first research question Through this evaluation, a feasible abstraction of the complexity can be validated. Both granularity of interactions and interrelationships, as well as stakeholder dependencies, have been positively validated. The expert approval also validates splitting the stakeholder complexity into four levels to comprehend the VCN dynamics. Thus, the proposed stakeholder model can improve the understanding of the complexity of the VCN system. However, external experts must further validate the model to issue general validity. In addition, VCN developments are dynamic, so the abstraction of completeness must be critically evaluated over time.

7.2. System Requirement Evaluation

From Chapter 6, the system requirement structure applicable in Figure 6.3 and the associated requirement synthesis outcome is evaluated in this Chapter. These artifacts are selected as they answer research question two. For this, a continuous evaluation with a tendency toward the ex-post characteristic is selected, as the first seven experts suggested no improvement. The evaluation is split into two parts per expert interview. Firstly, interview participants were asked to provide requirements on an intuitive basis over the whole interview to identify the focal points in the system. After that, the requirements system structure was presented, and participants were asked to criticize and iterate the structure.

The following paragraphs state the goal and the evaluation outcome of each step. Thereafter, a paragraph summarizes the implication of the system analysis evaluation for the second research question.

First evaluation: Requirement synthesis The first evaluation aims to validate the result, the associated context (Stufflebeam, 2000), and the requirements structuring granularity (Sun & Kantor, 2006) of the requirement synthesis in Table 6.1. This is accomplished by comparing the frequency of mentions in both literature and interviews. The findings of this evaluation are presented in Table 7.1, which compares the focus of the interview partners and the focus of the requirement analysis to identify alignment and discrepancy.

The evaluation through the open conversation revealed the focal points in the discussion and the development of VCNs compared to the literature results. Whereas the majority of the literature highlights/elaborates on technical system architecture requirements, the critical system requirements emphasized by the interview partners were of social and institutional nature. The requirements of stakeholder cooperation, social acceptance, and communication management exemplify this mismatch of interest. Nevertheless, an alignment of multiple criteria in terms of importance can be identified. Therefore, the validity of the reflected dimension is positively evaluated.

Furthermore, the experts have increasingly commented on economic considerations, which is why they are included in the table despite their exclusion in the literature review. Thus, another outcome of this evaluation is that a socio-technical perspective needs to incorporate the economic view.

This evaluation shows that mastering and understanding the complexity of a VCN is vital for conceptualization, design, and decision-making. Neglecting this characteristic results in a lack of cross-domain analysis that reveals the critical interrelationships and context. An example of this is the requirement for social acceptance brought into the system by the socio-technical system perspective. This essential component for a VCN is not sufficiently considered in the literature to the detriment of the interview findings.

Second evaluation: System requirement structure The goal of the second evaluation is to evaluate the systems requirement structure in Figure 6.3 on the feasible distinction of domains, requirement clustering, and logic. To achieve this, experts were asked to criticize and iterate the structure openly.

The feedback on the structure and completeness of the requirements was consistently positive for all 15 participants. Suggestions for improvement included only requirements that are defined as sub-parts of the existing requirement. Thus, a positive validation regarding the distinction of domains, requirement clustering, and logic can be derived from this evaluation.

Implications for the second research question By this evaluation, the identified requirements and the system structure from Chapter 6 are validated. The focus of the experts and literature overlaps for the most part. However, it is implied from the expert interviews that social and institutional requirements, as well as socio-technical interrelationships, need to be considered more closely by the literature.

Type	Requirement	INT1	INT2	INT3	INT4	INT5	INT6	INT7	INT8	INT9	INT10	INT11	INT12	INT13	INT14	INT15	Interview Quantity (out of 15)	Requirement Analysis Quantity (out of 57)
Institutional	Mission Requirements				x			x	x								3	6
	Regulation: System Operation		x	x	x		x		x	x	x	x	x	x	x	x	12	27
	Regulation System Architecture																0	8
	Standards	x	x	x	x	x	x		x	x	x	x	x	x	x		13	19
	Stakeholder Cooperation	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	15	16
Social	Ethical Requirements	x	x					x	x	x	x					x	7	16
	Social Acceptance		x	x	x	x	x	x	x	x	x	x	x	x	x	x	14	7
Technical: System Architecture	Application Requirements		x			x	x	x	x	x			x	x	x	x	10	10
	Robust		x	x			x	x	x	x			x			x	8	29
	Safe	x	x	x	x		x	x	x	x	x	x	x	x	x		13	20
	Adaptive		x		x							x					3	12
	Secure	x	x	x			x		x	x		x	x			x	9	35
	Privacy Preserving	x	x	x									x			x	5	31
	Efficient	x		x	x	x		x	x			x	x				8	33
	Effective/ Reliable			x		x		x	x	x		x	x				7	33
	Resilient								x				x				2	10
	Interoperability / Heterogeneity / System legacy	x	x	x		x	x	x	x	x	x	x	x	x	x	x	14	29
	Architecture Choice: Centralized/Decentralized					x	x	x	x	x			x	x	x	x	9	8
	Comply With Standards	x	x		x	x	x		x	x	x	x	x				10	5
	Automation																0	7
	Spatial Differentiation		x			x	x		x				x	x	x		7	3
	Data Management System	x	x		x				x	x	x	x	x	x		x	10	22
	Scaleable												x				1	14
Technical: System Operation	Continuity of the Service			x			x	x	x	x		x				x	7	10
	Trust and Control Management	x	x	x			x	x		x	x	x		x			9	14
	Change Management / System Update	x					x	x			x	x					5	6
	Monitoring																0	7
	Data Management	x	x		x		x		x	x	x	x	x			x	10	21
	Maintenance		x	x				x				x					4	6
	Communication Management		x	x			x	x	x	x	x	x	x	x	x		11	16
	Computation Management												x				1	12
	Disaster Management			x													1	2
	Risk Management	x															1	5
	Economic Requirments	x	x		x	x		x	x	x	x	x	x	x	x		12	x

Table 7.1: Evaluation system requirements

8 Discussion

This Chapter critically discusses the results and limitations of the research. For this, the research questions are reflected in Chapter 8.1 with regard to the work´s findings. After that, the societal relevance of this work is discussed. Lastly, Chapter 8.3 discusses future research and limitations.

8.1. Reflection on the Research Questions

This thesis presented a design science approach aligned with system engineering principles exploring how a future robust and interoperable European vehicular communication network can be designed based on requirements. For this, the following sub-research questions are answered and reflected. Further, these findings are combined to answer the main research question.

SQ1: What is the complexity in which a future European vehicular communication network will be developed?

A mission and stakeholder analysis is conducted to understand the complexity of a vehicular communication network. To determine the context of the complexity, the European and Dutch VCN-related strategies, visions, and communication documents were analyzed to define the problem and impact space. Based on this, the stakeholder analysis identifies relevant VCN stakeholders and discusses their roles, tasks, and needs. In addition, the stakeholders are placed in relation to each other, relationships are explored, and conflicting/common interests are highlighted. This approach was followed in order to encompass the complexity of a defined system through an understanding of the stakeholders and thus to be able to determine the implications.
The mission analysis shows a convergence of the European and Dutch visions for a VCN. Furthermore, the Netherlands can be classified as a pioneer within the EU, and five overlapping main objectives have been derived. Within the problem space defined by the objectives, 18 key stakeholders have been identified, and a stakeholder classification is proposed to cope with the complexity. This classification contains the categories of policymakers, infrastructure network providers, commercial/institutional users, and private users. Based on this identification, a complexity mapping 4-layer stakeholder model is presented, which categorizes the interrelationships with respect to the geographical scope of a VCN (international, European, national, regional/local). Hereby, the respective layer defines its impact on the system according to the stakeholder compositions on a layer. Furthermore, stakeholders are simultaneously impacting different layers. Thus additional dynamic complexity influencing the layers´ impact is identified. Another result contributing to this subquestion is a power-interest grid for the European and national scope which explores the complex interrelationships in finer granularity. The result of this breakdown shows that many stakeholders are simultaneously in a powerful position, hence, individuals in the VCN context can have an impact on the system. However, this also necessitates a joint approach of heterogeneous stakeholders, as their impact is otherwise too fragile and can be disrupted by individual interests. Lastly, the analysis of stakeholder clashes and challenges reveals a highly complex interplay of interests among and within stakeholder groups that must be aligned to find compromises in conflicts such as business case finding, investment responsibility, commitment, or data sharing.
From these results, a dynamic environment can be concluded in which VCN development can not be addressed on a single layer. Thus, system thinking for each layer by considering the needs around their geographical scope is crucial to establish an impact successfully. Furthermore, the interconnections and dependencies of stakeholders on and between layers suggest that development can only occur through co-evolutionary cooperative development. Also, the classification and interview findings imply that the user is decoupled in the decision and design process. This must be viewed critically since the foreseen VCN benefits are not directly apparent to the user. Through these findings and implications,

the relevance of the understood stakeholder needs can be identified and translated into system requirements. An essential finding of sub-question one for the future VCN is that a multi-disciplinary approach is essential for system design so that participating stakeholders can design effectively and in a feasible context.

SQ2: What are the system requirements of a robust and interoperable vehicular communication network, considering the socio-technical aspects?

To identify and assess requirements for a future VCN, a combined strategy is chosen. Hereby, 57 documents (Scientific publications, governmental documents, industry communications) representing state of the art are analyzed. After that, the insights are aligned with the stakeholder needs and mission objectives and complemented/validated by exploratory interview insights. Based on this, a structuring of the VCN requirements from the system integrator perspective of Rijkswaterstraat is proposed to guide design and decision-making processes. According to the assessment of the requirements, fundamental relationships and challenges have been highlighted and explored to generate an understanding of the design process of a VCN.
The requirement elicitation resulted in 33 conceptual requirements and subsystems that are emphasized as the state-of-art for a multi-disciplinary perspective. Within these requirements, a clear focus on system architecture design elements and a lack of social and institutional reflection is identified. Another observation of the analysis is that requirements such as safety or security are reflected individually. Further, to the best of our knowledge, a system perspective analyzing the interrelationships or defining requirements between the technical and institutional subsystems is absent. When aligning the stakeholder analysis, the identified needs and objectives are mostly in agreement with the state of the art. However, the alignment has synthesized two issues that need more attention. On the one hand, the decoupling of end-users can be clearly established in requirements since only 7 out of 33 requirements can be linked to the primal needs of the users. In addition, a mismatch between the need for social acceptance and the focus of requirements within the publications is observed. This issue was further reinforced by the agreement and emphasis of all 15 interview partners on the importance of acceptance. The summary of the expert interviews is another result that identifies enablers and barriers in the VCN context and clusters them by institutional, social, and technical character. These insights are synthesized knowledge that can serve as a basis for requirement-based engineering for the VCN beyond this work. Two significant results of the exploratory alignment symbolize the current focal points of VCN development. While the experts mostly agree on the technical feasibility, human and social criteria are far more critical in the discussion and development. This reflection differs from the focus of current publications, which focus on technicalities. Thus, this fundamental coherence shows the necessity to focus more on the system´s complexity and interdependencies rather than technical efficiency. Another system requirement identified by the expert interviews is the absence of public-private business cases that align the industry's business objectives with public institutions such as the EU or the government of the Netherlands. In addition to this, a system requirement structure is proposed that combines the institutional, social, technical, and economic subsystems. From this structure, it is clear that the subsystems can be broken down, however, due to the dependencies of the individual requirements, a multi-disciplinary approach to the realization and integration of a VCN is necessary.
The exemplary exorcising of the relationships from the privacy-preserving, robustness, and interoperability requirements implies that an island design of a subcomponent is not feasible. Therefore, The system perspective is critical from the perspective of VCN integration. Accordingly, the realization of the island reflection (e.g., safety-security) of current publications is to be seen critically, and a demand for the perspective between the requirements is implied. Now that the requirements are identified, and the system perspective is understood, the impact and relevancy of it can be evaluated.

SQ3: How feasible are the complexity abstraction and system requirements regarding granularity, understandability, and correctness?

To answer the third question, the findings of Chapter 5.2 and 6 are evaluated with 15 VCN experts of different domains. Hereby, the four-layer stakeholder complexity model is iterated and evaluated on understandability, granularity, and correctness to identify the impact of the system perspective on the stakeholder complexity. Furthermore, the system requirement structure is evaluated on the correctness and level of granularity to guide a multidisciplinary approach to designing a VCN. The evaluation of these stakeholder interrelationships results in the validation of the complex component of the VCN system and its implications for the design. Moreover, by the affirmation of the expert interviews, a need and high relevance for such a complex abstraction that guides understanding a VCN can be derived. The system analysis based on this system thinking was likewise positively affirmed by the experts as a foundation for a multidisciplinary view of the VCN system. However, another result of the evaluation is that there is a mismatch of focal points in the discussion about the design and development of VCN. Whereas the literature focuses on technicalities in the system architecture design, the interview partner highlights the importance of the human and social components in the system by addressing social acceptance and stakeholder cooperation as one of their critical requirements. Hence, this inconsistent overlap can be interpreted as a missing system thinking that aligns the technical and social subsystems. Therefore, the provided systems perspective is a valuable addition to the VCN community as a multidisciplinary integration approach.

Main Research Question: What are fundamental socio-technical factors to consider in a future European vehicular communication network design?

As all subquestions are discussed, the implications can be translated into the answer to the main research questions. For this, the problem decomposition in Chapter 1.3 is used as a way to answer the question.

I conclude that socio-technical reflection on system attributes such as interoperability plays a critical role in designing a future VCN. In addition, to realize these overarching objectives, VCN stakeholders must cooperate closely and find common objectives to build a business case that can be implemented on a national/European scale. Further, harmonizing the VCN approach in terms of standards, data format, and VCN functionalities is recommended. Thus, to solve the question's first sub-component, stakeholder complexity must be understood so that a consensus can be developed in the decision-making process, which paths the way of implementing the attributes robust and interoperable.
The realization of the VCN design itself must adhere to the identified stakeholder concerns and needs. It is recommended to separate the needs and decisions into the geographical scope, to understand the goals and impact of the respective layer. Nevertheless, decisions and designing efforts must be aware of the dynamics of different VCN levels in order to design VCN subsystems and subsequently the second sub-component effectively.
Hereby, the VCN should be based on identified future requirements, representing the question's third subcomponent. I conclude that these requirements must reflect and incorporate the multidisciplinary character of the system. Thus, considering the technical, social, institutional, and economic subsystems is recommended. Moreover, I argue that the interrelationships between these subsystems must be understood as they resemble a critical component of the system that aligns different stakeholder perspectives.
Ultimately, I recommend focusing on social components and socio-technical interactions to successfully design a VCN and come closer to its realization.

8.2. Reflection on Societal Relevance

To assess the societal relevance of this research´s results, the identified overlap of assessment criteria among scholars by Bornmann (2013) is used. Bornmann (2013) distinguishes into following impact subcategories:

8.2.1. Social Impact

Bornmann (2013) refers to the social impact of research by contributing to approaches that deal with social issues, policy-making, or public debates. The introduction of VCN encompasses a broad spectrum of social impacts for Europe. On the one hand, such networks are deeply rooted in the original ITS idea of improving road safety and traffic flow, which is society serving functionality and the interest of the institutional side. With the inclusion of advanced use cases, such as cooperative driving, the economic component is added to the VCN discussion. On the other hand, the system remains a concept and has not been implemented on a large scale, partly due to the lack of consensus in the political and economic arena. This thesis helps to contribute to unifying the understanding of the complexity of the system, hence, finding a compromise among the interest. The results of this thesis are relevant not only relevant for political and economic decision-makers by enhancing their perception of the system but also for developers of VCN functionalities by adhering to the proposed socio-technical requirements in their developments. In addition, this work contributes to policy-making and its debate by synthesizing the critical and previously neglected interrelationships between the social and technical subsystems.

The Council of the EU announced on June 8, 2023, stating that they have reached a provisional agreement to revise the existing regulation. In this statement, the Council highlights the critical issues addressed in this endeavor, including interoperability, privacy, and a harmonized approach. This initiative confirms the significance of socio-technical considerations and underscores the relevance of this work. (Council of the EU, 2023)

8.2.2. Environmental Impact

VCN research contributes to the transition toward sustainable road mobility (Barth et al., 2015). VCN applications are anticipated to improve the traffic flow, thus, contribute to emission reduction by less start-stop traffic and traffic jams. This can positively influence the impact of transportation on climate change. However, the investment and operating emissions must be weighed against the benefits. Our results contribute to this transition by providing a multidisciplinary starting point for integrating an intelligent infrastructure. Furthermore, the enhanced understanding of fundamental socio-technical VCN properties can guide European commitment and finding compromises regarding VCN infrastructure decisions. Therefore, this work contributes to sustainable development goal 9, dealing with resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation (United Nations, 2023).

8.2.3. Economic Impact

The economic impact is defined by Bornmann (2013) as the economic capital of a society which can be broken down into all cost and value-creating contributions (e.g., governmental investments). Hereby, the results of this work could contribute positively on a governmental, business, and private level. For the EU and member states, the findings can directly be used to make better decisions through a deeper understanding of the complex stakeholder structures. Thus, these actors could avoid creating an unwanted costly infrastructure system legacy that further divides interests and discussion. Furthermore, pointing out the missing public-private business case can be used by institutional stakeholders to allocate resources and work on the value creation of a VCN to assess and improve the economic impact of such as system. This could also contribute to the system's economic level as a finding of this work is that institutional stakeholders have to cooperate closely with the industry. The contribution at the private level of this work is indirect. If the results help to introduce a VCN, costs for consumers can be reduced through the traffic-enhanced and fuel-reducing applications of a VCN. Further, the enhanced safety would reduce the risk of vehicle accidents and, subsequently, the associated private cost. Thus, the economic impact on this level is rather created by the system itself, to whose introduction this work could contribute.

8.3. Limitations and Further Research

The results of this thesis are subject to limitations. Firstly, the stakeholder analysis is limited by the scope of this work. Therefore stakeholder needs and tasks are based on the information they publish about themselves, complemented by scientific literature. To enhance this analysis, validation of the needs should be done. Furthermore, this also applies to the role of stakeholders. In this context, critical attention must be paid to whether the real role corresponds to the self-portrayal presented. Related to the proposed 4-level complexity mapping, the applicability is limited and can be iterated by a deeper analysis. An instance of this is complexity reduction, where nuances can get lost in translation due to flawed stakeholder analysis. Therefore, it may be that individual actors in the stakeholder groups have increased influence at one level and even beyond. Hereby, the vehicle manufacturer Volkswagen can be an example, which could have an influence on the European level due to its economic size.
Considering the system analysis, the scope is only set to a socio-technical system perspective on a VCN. Thus the applicability to other domains must be evaluated. A limitation to this is that the literature about the system view on VCNs is limited and less developed than the technical perspective. Hence, the findings of the work need further elaboration and validation to be scientifically sound as they are

mainly not based on prior work. In this context, the literature for the requirement synthesis is oriented towards this perspective. Therefore, not all viewpoints within the system are incorporated. Moreover, due to the scope of this work, not all relationships and conflicts among the requirements have been explored, resembling further research potential. Another limitation is that economic requirements are neglected in the literature review for scoping reasons.
Nevertheless, economic aspects are incorporated through the input of the interviews, which are also a subject of limitations. The reliance on accuracy in the answers can differ, as interview partners have different experiences, emotional strains, and backgrounds. In addition, the validity of the answers is affected by the bias of their domain. Thus a broader audience reviewing the findings is recommended. Furthermore, each country can have different approaches and opinions due to the heterogeneity in Europe. Thus this work is limited to the Dutch and German perspectives, as the interview partners are mainly from these countries.

Besides research potential that focuses on the limitations of this work, several unexplored areas emerged from this work. Firstly, the role of consumer associations such as NCAP can be explored in the context of the 4-layer stakeholder complexity model. By evaluating products and services, interesting socio-dynamic interactions can occur in the model, and additional influencing factors can be determined. In particular, the impact on industry acceptance of the inclusion of VCN functionalities in such a consumer association test is novel and can be scientifically elaborated. In addition, such social interactions and reactions are also highlighted by the interviews as decisive, therefore, resemble a future research direction as little work has been done yet.
The proposed system requirement structure would benefit from applying it to a VCN research or development project to understand its impact on the incorporated domains. Hereby, translating the socio-technical concerns into architecture for a designed artifact is particularly interesting. Another research gap that emerges from the system analysis is the lack of system thinking represented in the VCN community. Exploring this perspective can be crucial for realizing a VCN; hence, more attention toward integrating these aspects is recommended. In addition to the absence of the system perspective, a lack of institutional reflection on VCN developments can be identified, which also resembles a potential direction research can head. Lastly, it is highlighted that the synthesized insights are biased by the Western Europe perspective of the Netherlands and Germany. Hence a comparison of social interaction, technical limitations, and the interactions between the social and technical subsystems in other EU countries can generate valuable insights contributing to the realization of a VCN. Also, comparing these aspects to VCN approaches in different economic zones such as China, the US, or Japan might lead to implications for cross-contextual policy-making and implementation recommendations.

9
Conclusion

This work addresses the socio-technical nature of vehicular communication networks. The aim was to develop a multidisciplinary view and approach to this topic and to highlight the interdisciplinary interrelationships. For this, Peffers's design science methodology extended by system engineering techniques was applied to transform the system's complexity into design artifacts. Based on this approach, a comprehensive mission analysis is provided to synthesize the objectives of the decision-makers in the system. After that, an extensive stakeholder analysis is presented, which categorizes the stakeholder groups, decomposes the complexity by a proposed 4-layer model, and analyzes the interactions, roles, and power structures. Through this understanding, a system requirement analysis from the socio-technical system perspective is performed by analyzing 57 articles and conducting 15 expert interviews. Through this process, insights guiding the development of future vehicular communication networks are generated, and the following research problem of this thesis is addressed:

Main Research Question: What are fundamental socio-technical factors to consider in a future European vehicular communication network design?

In order to successfully design such a large-scale infrastructure project, attention to socio-technical interrelationships is essential. The systematic complexity of the system must be a central element in the process. Further, technical requirements such as interoperability and robustness must be incorporated into the system addressing the institutional, ethical, and economic influences. Thus, socio-technical considerations for system components are decisive for the design of a VCN. Due to the increased number of stakeholders with influence and interest, the codependency of institutional and economic stakeholders is identified and directly related to the chicken-egg problem of communicating infrastructure and connected vehicles. Therefore, substantial challenges of legal certainty, stakeholder cooperation, and responsibility allocation must be solved first before the large-scale technical implementation can start.

The following Chapters highlight the contributions and proposals that are concluded by addressing the research problem. First, Chapter 9.1 presents the scientific contributions to the research problem resembling the results. Next, stakeholder recommendations are given based on the outcome of this work in Chapter 9.2. Lastly, Chapter 9.3 provides an outlook and impact of this thesis.

9.1. Contributions of the Work

The scientific contributions of this work are separated into contributions towards the domain in Chapter 9.1.1 and methodological contributions to design science in Chapter 9.1.2.

9.1.1. Contributions to the Vehicular Communication Network Development

The main research contributions to the VCN discussion can be distinguished into three points.
Firstly, a layered stakeholder complexity mapping is contributed to the understanding of VCN development. Currently, most work focuses on the technicalities or functionalities of subsystems without following a stakeholder-based approach. Thus, this work provides an understanding of these developments, where to categorize their impact, and how to adjust it to the stakeholder needs. Moreover, to the best of our knowledge, this work is the first to break down the stakeholder complexity over the regional scope to draw the dynamic constellations in a VCN. This understanding of relationships contributes to the positioning and cooperation of decision-makers as it helps to comprehend and align the cross-geographic objectives. The proposed stakeholder model is applicable in Figure 5.2
Secondly, this work resembles an approach of integrating the socio-technical system perspective on a complex, large-scale infrastructure project. In contrast to other works, the system view reflects on

the processes and requirements between the social and technical subsystems rather than highlighting the components within one of these systems. By this, impacts and focal points to tackle the system integration of the heterogeneous stakeholder interests are aggregated, which is an important addition to technological integration efforts. This integrated perspective is proposed in Figure 6.3.
Lastly, this work compares scientific focus, stakeholder needs and objectives, and expert insights, highlighting the mismatch and alignment of requirements. Hence, a valuable contribution to the VCN research community for adjustment and further research is presented. The outcome of this comparison is presented in Table 7.1.

9.1.2. Contribution to the Methodological Research

The main methodological contributions of this work can be distinguished into two points.
On the one hand, the Peffers et al. (2007) design science research framework is aligned with systems engineering ISO standards translating a scientific approach into a practical approach. Hereby, systems engineering methods and processes are applied to the framework as a methodological addition to ensuring a scientific but industry-relevant design.
On the other hand, the design science research framework is used as a potential approach to cope with the complexity of a VCN system. To the best of our knowledge, no efforts have been made to develop knowledge about the system´s complexity that VCN stakeholders can use to design solutions for their field problems. Thus, the introduction of a systems perspective and the iterative framework resembles a novel addition to the VCN community.

9.2. Stakeholder Recommendations

In order to implement the added value of the contributions, recommendations to four key stakeholders (policy makers, vehicle manufacturers, network providers, and research institutions) are given.

9.2.1. Policy Makers

According to this work's findings, policymakers, specifically the EU, play a critical role in decision-making and designing a future VCN. Thus, the EU should become more aware of its decisive role and allocate resources toward the challenge of unifying the approach and objectives. For this, considering the business objectives of the system owners (vehicle manufacturers, network operators, IT road infrastructure providers) is recommended to find a shared pool of interest. A potential approach to ensuring this is to extensively focus on organizing the cooperation in a structured and central way. The interviews showed that the VCN development lacks a common vision and easily visible organizational structure for the heterogeneous actors. Thus, a target-oriented approach has yet to be initiated. Only an overarching institution such as the EU can play the directing role, hence, taking responsibility is recommended. In addition, the orientation of such a lead must have a long-term scope and an adaptive manner as the development and deployment of a VCN have a surpassing temporal scope than the legislative period.
Another recommendation to policymakers is to involve industry more and earlier in the decision-making process, including the creation of a regulatory framework. This can be critically reflected since policy must be shaped according to ethical principles for the good of the public and not according to industrial desires. However, it can be deduced from the stakeholder analysis that the citizen lack interest in the anticipated features. This results in the absence of a VCN market pull as vehicle manufacturers and service operators are not sufficiently incentivized to commit to a technology that users do not perceive as value-generating. Here, the policymakers must understand the game theory aspects of the anticipated VCN applications.
Individual users are not interested in taking the initially longer travel route to improve the common road safety or travel time, even though this decision can lead to a higher travel time if everyone follows the initial recommendation. This exemplifies that a VCN system might be an institutional lead market push where the EU must take the initiative.
Another recommendation in this context is to focus on these fundamental aspects as a policymaker and not to approach every sub-detail as a problem owner. VCN needs to be addressed at different levels, and the policymaker should work closely with the implementing party but not work on the content before the general direction is defined. Thus, a layered approach is recommended, and the presented complexity reduction from Chapter 5.2 can be taken as a starting point.

9.2.2. Vehicle Manufacturers

The OEMs emerged from the analysis as an entity to be convinced. However, their responsibility for collaborative design and development cannot be removed. In order to maintain technical progress against the competition, these stakeholders must actively participate in the transformation and, above all, embrace it. Therefore, three recommendations can be derived from this work.

Firstly, identify and start implementing VCN applications that can be rolled out on a regional scale with a potential upscaling. This can help to solve the chicken-egg problem of a waiting infrastructure for connected vehicles and vice versa. The critical response that this represents a risk since selecting the wrong technology leads to loss can also be framed as an opportunity. Due to early implementation, one can be a leader in the design of the VCN and position oneself in an economically beneficial way by actively influencing developments.

In this context, the second recommendation is that OEM must assume that VCN components will be heterogeneous and that no harmonized approach will be present in the EU. Due to geographical and political diversity, a unified approach to national infrastructures in Europe is complicated. Therefore, waiting for a homogeneous infrastructure or data pool is unrealistic, resulting in wasted resources if focused on the neverending discussion to unify technology. Allocating these resources instead to value-creating aspects such as embracing heterogeneity and mastering this requirement is recommended. Not only would this drive the development of the VCN, but also be beneficial for the economic development of the respective company.

Lastly, I recommend understanding and leveraging the position at the national level. Due to the power shift in favor of vehicle manufacturers (Chapter 5.3), a strong initiative in the topic of implementation is possible as decision-makers at the national level are more agile and influenceable. Here, the OEMs can clearly communicate technical developments so that the institutional infrastructure expansion has a technical reference point, and the chicken-egg problem is thus addressed.

9.2.3. Network Operators

Due to the increasingly connected society and technological advances such as 5G, the relevance of network operators for the VCN is increasing. This fact has already arrived in the industry, and increased cooperation exists between vehicle manufacturers, IT road infrastructure operators, and network operators. Hence, co-development can be identified. To advance this development triangle, I recommend that network operators bundle their wireless communication expertise and elaborate intensely on VCN business cases for the vehicle manufacturer. Conceivable is an approach such as the example of Vodafone in the greater Munich area (INT12). Going in advance by providing the physical infrastructure but also the data system can incentivize the vehicle manufacturers to commit to the VCN.

The second recommendation that can be made is to systematically integrate the mobility data from the national access points (NAPCORE) into your own offering. Hereby, the main interoperability requirement represents a significant business potential for network operators. Therefore, they can enhance their service offering and generate value by alleviating the concerns of OEMs. Further, a certain level of quality threshold can be determined by this actor, as operators can advise the national data points towards a unified quality standard or function as a data filter for the users.

9.2.4. Research Institutions

This work has shown that more emphasis should be placed on the fundamental requirements of VCN development. Scientific contributions focus on corner cases or experimental research and not on system integration and complex multidisciplinary interrelationships. However, this is one of the fundamental components of the system, which is why a mismatch of research direction and need is identified by the problem owner. Therefore, the recommendation can be made that the systems and socio-technical perspective need more attention and research effort in order to contribute to the fundamental socio-technical challenges of the VCN.

Another recommendation that can be given is to relate the security perspective to safety. Research can and may focus on aspects, but the bridge from security to safety must always be built in the VCN context, despite focusing on one of the two. The analysis in Chapter 6 showed that this is not always the case. However, this is critical because security has a direct and massive impact on human health on the road. Thus, it is recommended that at least implications on the corresponding requirement are discussed in order to conduct functional and valid research in the VCN cosmos. This is further reinforced by the standard of functional security in the automotive industry (ISO 26262).

9.3. Future Outlook

This final chapter of the thesis gives an outlook on implications and future work. To do this, one paragraph highlights the baseline situation prior to this work. Then, a paragraph outlines the short-term outlook for the implications and findings of this work. Finally, a long-term outlook is provided, including the role of this work in moving forward.

Prior this work To our knowledge, no efforts are made to reflect VCNs on socio-technical properties. Moreover, there are various disagreements between stakeholders and approaches in the VCN cosmos (see ITS-G5 and c-V2X and the disagreement on regulations). These complexities and interrelationships are untouched, and discussions instead revolve around technicalities. Thus, fundamental issues shaping the boundaries of solutions are not set.

Short-term outlook The basis for setting up stakeholder cooperation in a European VCN can be assisted through the proposed stakeholder model and the increased understanding of complexity. Thus, developing stakeholder strategies and decision-making rounds can be derived more effectively through further research and subsequently achieve a higher stakeholder acceptance rate.
Furthermore, the findings of this work indicate that more socio-technical reflection is needed in the VCN domain, which is highlighted by Table 7.1. Scholars can explore this perspective and contribute the VCN cosmos by elaborating on its socio-technical dimension.
Ultimately, forming a European regulatory framework can be formulated as a short-term outlook of this work. Both the stakeholder analysis and the system requirement analysis generate insights into the needs and requirements of the system as a whole. These insights can guide the development of such an intervention as they represent the most critical stakeholders in the system. At the time of the thesis, the non-binding regulatory framework was the delegated ITS regulation.

On the 8th of June, 2023, the Council of the EU released a statement that they provisionally agreed on revising this regulation. Hereby, the statement addresses the highlighted critical issues in this work, such as interoperability, privacy, and the harmonized approach. Thus, this initiative validates this work's relevancy and importance of socio-technical considerations. (Council of the EU, 2023)

Long-term outlook This work can be classified as the initial building block of the socio-technical consideration of the VCN in the long term. Once the right regulatory framework and cooperation basis have been established in the system, refined and extended results of this perspective can guide the implementation of a VCN. Thus, scholars are encouraged to think more outside of the technical subsystem.
Furthermore, this thesis touches on the interrelationship of economic considerations concerning the interactions between the social and technical VCN subsystems. In terms of implementation, research in this direction is attractive, especially the financial impact of the European approach compared to the American or Chinese approach.
Lastly, this work catches an abstraction of a highly dynamic stakeholder system that is under the influence of emerging events, such as the Ukraine-Russia conflict (Costa & Barbé, 2023). Thus, the validity of the 4-layer stakeholder model must be examined over time. A power shift within the systems by political discourse or emergent events can create dynamics impacting the VCN cosmos and the socio-technical considerations, which can be subject of future research.

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A
Appendix A

A.1. ISO Alignment with the Research Approach

In order to apply the design science research approach in a meaningful way, systems engineering ISO standards are used as a methodology for this work. ISO/IEC/IEEE 1528 system life cycle approach is chosen as the foundation of this report structure and content as it contains the basics of systems and requirement engineering. Figure A.1 shows the system life cycle approach and focus of this work. Moreover, ISO/IEC/IEEE 29148:2018 complementary information to the aforementioned standard is used for refinement. Due to the complex nature of a VCN, the systems of systems standards ISO/IEC/IEEE 21839 and ISO/IEC/IEEE 21840 are applicable to the VCN and provide additional input to the foundation of this work. Table A.1 summarizes the relevant standards.

Table A.1: Relevant ISO standards

Standard	Description	Contribution to this work
ISO/IEC/IEEE 15288:2015	This International Standard establishes a common framework of process descriptions for describing the life cycle of systems created by humans. It defines a set of processes and associated terminology from an engineering viewpoint. These processes can be applied at any level in the hierarchy of a system's structure.	This standard guides the process of this work and elaborates on the necessary steps to be taken. Further, it lays the foundation for the structure of this document.
ISO/IEC/IEEE 29148:2018	This International Standard provides guidelines for applying the requirements and requirements-related processes described in ISO/IEC/IEEE 15288.	This standard provides higher detail on the steps to be taken in each subchapter. Further, it defines the principle of recursion of chapter 6.
ISO/IEC/IEEE 21839:2019	This document provides a set of critical system of systems considerations to be addressed at key points in the life cycle of the system of interest. The considerations and life cycle model align with those which are already defined in ISO/IEC/IEEE 15288	It complements the systems of systems perspective in the process.
ISO/IEC/IEEE 21840:2019	This document provides guidance on the application of processes in ISO/IEC/IEEE 15288 to systems of systems	Complements the systems of systems perspective in the process.

As the scope of this work is limited and the VCN is in an early development stage, the focus relies on the first three technical subprocesses as highlighted in Figure A.1. These subprocesses lead to the elicitation of system requirements which are transformable into an effective system. For this, the mission of a VCN is analyzed from the institutional perspective in Chapter 4. After that, a stakeholder analysis is provided in Chapter 5.2 resembling the second subprocess. Hereby, a system of interest is defined. Based on these findings, a system analysis with respect to ISO 21839 elicits and defines VCN requirements in Chapter 6. Hereby, the recursion of the system of interest is the focus of the chapter, as the VCN is a system of systems, and findings can be transposed to the architecture. For this, the analyses' outputs are used as inputs and starting points for the recursive complex system. This bottom-up principle is done to achieve a higher level of system detail and apply the generated results to system function. The alignment of the applied ISO norm processes with the document structure and Peffers et al. (2007) design science research approach are highlighted in Figure A.2. As indicated by the figure, the iterative character of Peffers et al. (2007) design cycle is also part of the standardized process. Thus, a substantial overlap can be identified.

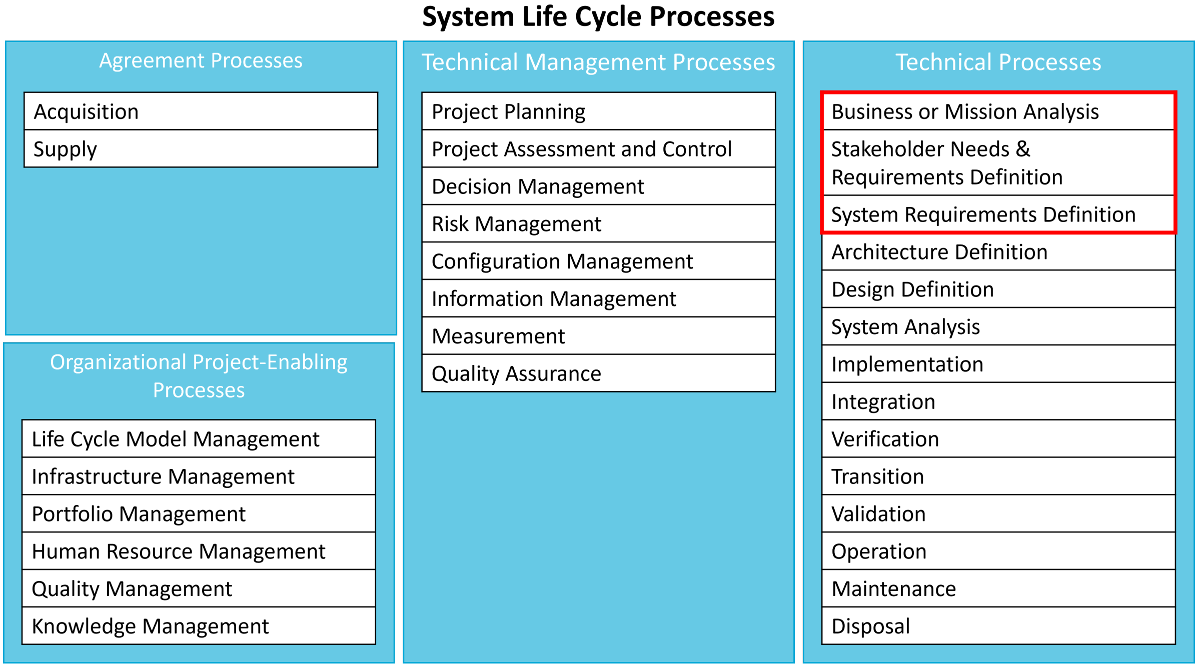

Figure A.1: Applied system life cycle processes of this work

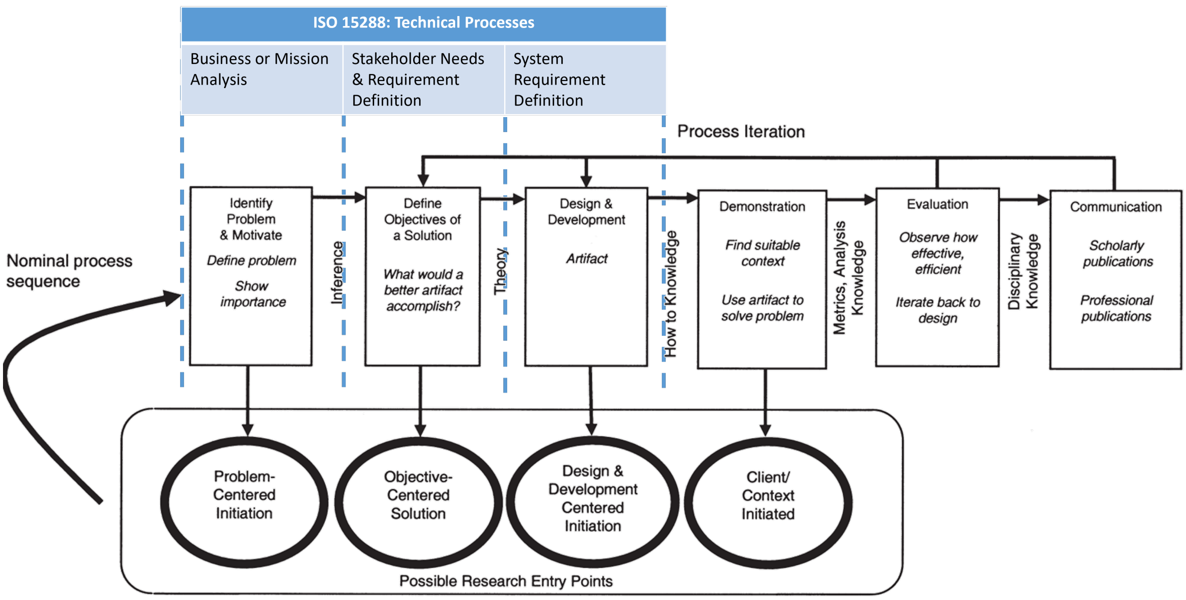

Figure A.2: ISO 15288 alignment with the design cycle

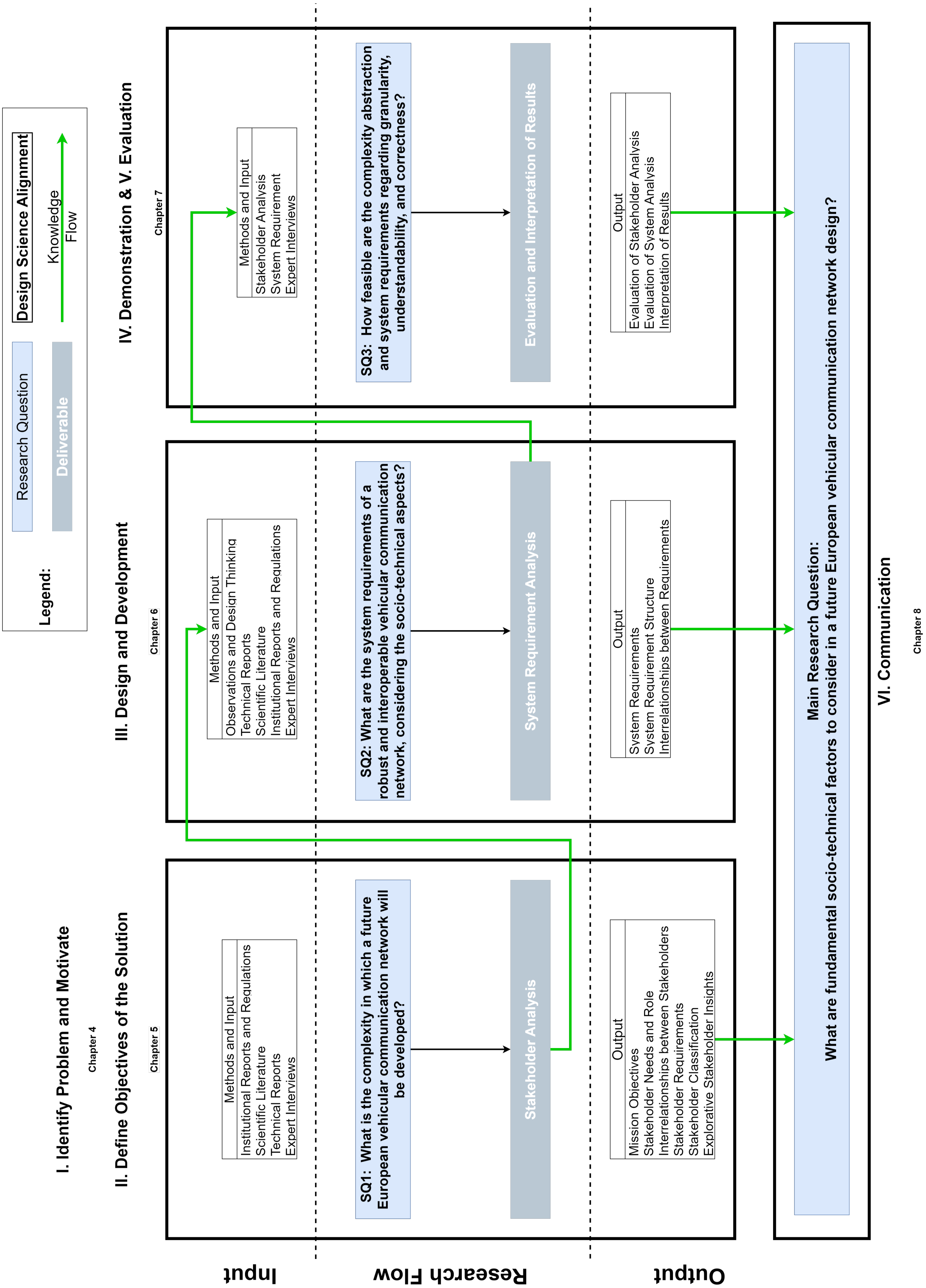

Figure A.3: Research framework (Enlarged)

B
Appendix B

What is your role and your industry?
What is your connection to VCN/ITS/VANET/IoV?
How many years of experience?
What is your institution's role in realizing the infrastructure for an ITS? (Developing, executing, deciding …)
What is your institution´s interest in the system?
Do you have clashing goals/strategic partners with other stakeholders?
Are you missing the initiative/contribution of other actors?
Is the current ITS/telecommunications regulation sufficient to develop a future VCN infrastructure?
Are the Dutch or European regulations stricter?
What are social/institutional barriers/enablers for a future VCN?
What are technical enablers/barriers for a future VCN?
Do you think V2V and V2I limitations are hindering the deployment of VCN?
Is the upcoming industry standard of C-V2X superior to ITS-G5?
Is the allocated Frequency Band sufficient for ITS-G5/ C-V2X?
Should the infrastructure adapt to self-driving cars or should the cars adapt to our current road system?
Do you think relevant governmental institutions or commercial companies should take the lead in developing/deploying a VCN?
Are missing standards hindering your institution´s progress?
Is legal uncertainty hindering your progress?
Do you see net neutrality or the EECC as a barrier for commercial VCN? (Infotainment functions)
Do you have any main requirements you would like to emphasize for a future VCN?
Do you have concerns about deploying a large-scale multifunctional VCN on the highway?

Table B.1: Interview question list

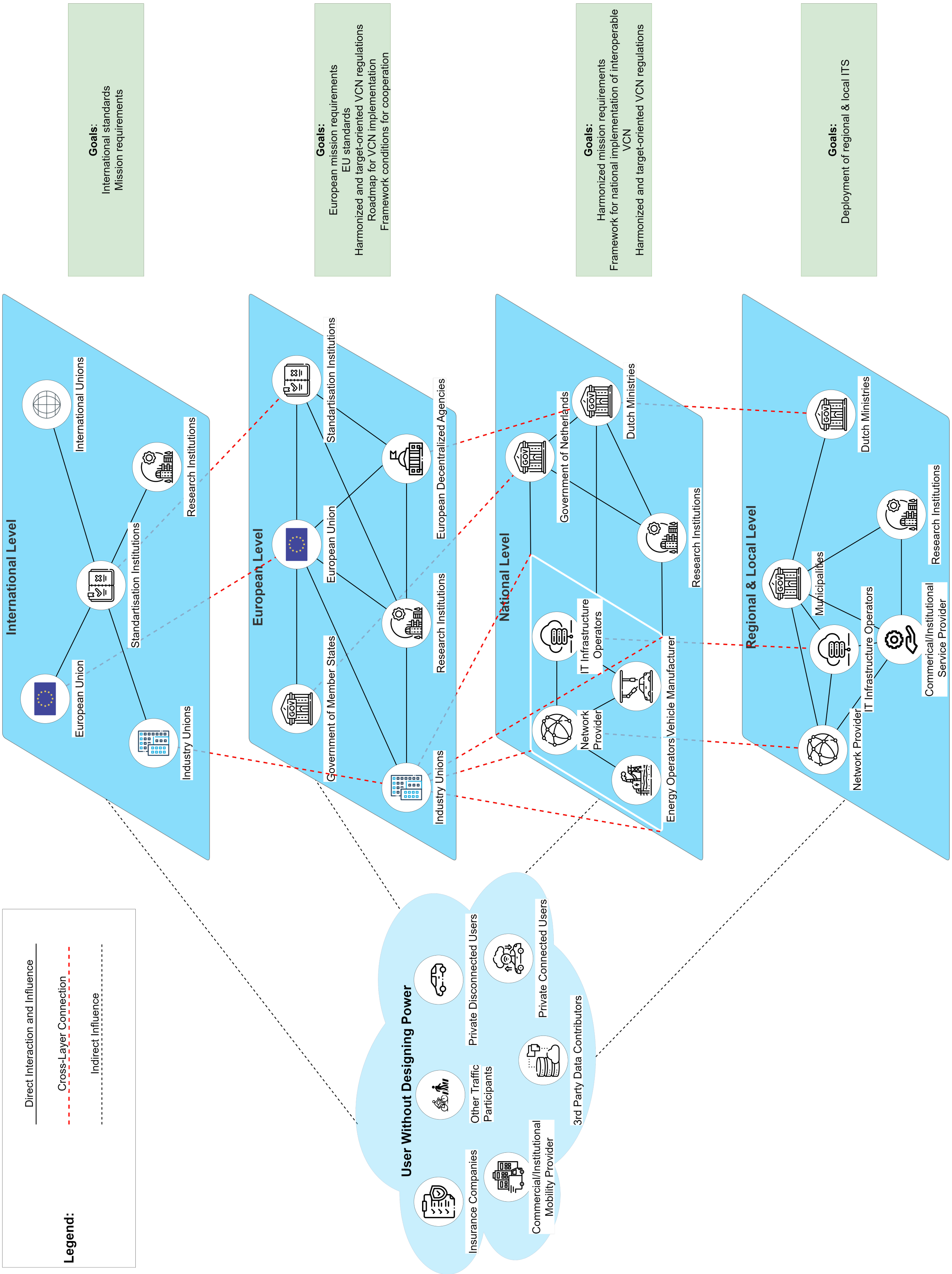

Figure B.1: 4-Layer stakeholder complexity model (Enlarged)

Table B.2: Stakeholder taxonomy description

Category	Actor	Description	Role
Policymakers	International Unions	This category includes all stakeholders with an international character who are not based in the EU and have an interest/influence on the future vehicular communication network or technology developments. These stakeholders are mostly economic key players such as USA, China, and associations such as the UN or G7.	International Unions contribute and decide international technical and social standards for a vehicle communication network. Furthermore, discussions among these players shape mission requirements for the development of a VCN.
	European Union	The EU is a political and economic association with significant interest in a European interoperable VCN. Through their role, they contribute to the mission requirements of a future large-scale VCN. Previous Initiatives of the Union are the European eCall system, which automatically contacts emergency services in the event of a serious accident, and the Cooperative Intelligent Transport Systems (C-ITS) framework, which enables vehicles and infrastructure to communicate with each other to improve traffic flow and safety. This actor splits himself up into the decision-making organs responsible for the regulations and agencies which are assisting the legislative organs	The EU has the role to develop and provide VCN policies and guidelines for its member states. Further, this stakeholder is responsible for the effective coordination and funding of research focusing on the development of a future VCN such as HORIZON 2020. Furthermore, it shapes the development by formulating mission requirments.
	Countries	The term countries refer to the individual countries within the EU. Due to their membership, EU guidelines and regulations are legally binding. However, each country is different in terms of the institutional constellation, needs, IT infrastructure or deployment capabilities, thus, an individual reflection for a national implementation has to be done. Moreover, this stakeholder group is a multilayered social construct, where responsibilities and tasks are divided differently among the ministries or institutions within the national member state.	Member states contribute to the decision-making within the EU. Furthermore, they have the responsibility to implement the Union's decisions within their own country. Member states also guide and restrict the development of a VCN in their own country by national regulations and mission objectives.
	Standardisation Institutions	This stakeholder contains institutions responsible for the development of technical standards. Furthermore, this actor can be decomposed by regional locations as VCNs are of interest to most global powers. Due to this, the VCN development is decentralised and standards ensure interoperability, minimum functionality, and common understanding. On a global level, key players for a VCN are ISO, IEC and IEEE. Related to the EU scope of a VCN, CEN, CENELEC or ETSI can be considered as relevant stakeholders of this cluster. It should be noted that standards are developed collaboratively and transparently by industry experts, government regulators, and other stakeholders. Moreover, depending on the hierarchical level of the institutions the standards are built up on each other.	The role of standardization institutions is to develop and propose technical standards that guide the VCN conceptualisation, deployment and promote the interoperability and compatibility of ITS solutions, while also ensuring the safety and security of these technologies.
	Industry Unions	Industry unions are all associations of interest groups from the industry to represent their interests in a collective form in an institutional environment. Their aim is primarily to influence the standardization decisions and regulations of future VCNs at the international and European levels. Industry unions are usually formed within a specific sector such as automotive or telecommunications. Relevant VCN unions are example 5GAA AECC or ITU. These players are also characterized by the fact that they publish white papers and policy recommendations in order to exert influence.	Industry Unions advocate for their members by representing their interests and opinion in an institutional environment.

Table B.2: Stakeholder taxonomy description

Category	Actor	Description	Role
Infrastructure Network Provider	Network Providers	This stakeholder group contains communication and internet network providers. These providers can be separated into three tiers. Kurose and Ross (2022) provides an overview of the responsibilities and structure of the internet network providers. In the context of VCNs Tier-3 providers are the most relevant, due to their proximity to the end users. In the Netherlands, Vodafone, t-mobile or kpn can be identified as a network operator.	The role of network operators is to design, build, and operate the communication networks according to the corresponding decisions, regulations and user needs. Moreover, they are responsible for ensuring the continuity, security, and reliability of the communication networks.
	IT Road Infrastructure Operators	IT road infrastructure operators are the authorities responsible for the ITS operation. Since this is critical infrastructure, it is usually done by an institutional authority. In the case of the Netherlands, Rijkswaterstraat and the associated ndw data point can be seen as the IT Infrastructure Operator. In specific cases, a third-party company can take over this role under specific legal terms. This stakeholder typically contributes to the policy goals set by the rule-makers. Further, their main interest is to sustain a high level of safety on the roads as the operators often are responsible for the road network itself.	The role of IT infrastructure operators is to operate and maintain the IT systems on the road network.
	Energy Operators	Energy operators are all the companies that are responsible for the energy supply of a country. For reference, Eneco, Essent or Vattenfall can be identified in the Netherlands. This stakeholder group has an interest to operate a stable and economic network. As a future VCN in the EU might install RSUs or ITS components in remote locations, and technology such as 5G consumes energy, cooperation is essential for VCN design and deployment. Therefore, the needs and existing infrastructure must be taken into account while designing.	Energy Operators inherit a rather constraining role in the future VCN system. They design, build, and operate the energy infrastructure that supports the operation of ITS technologies.
	IT Technology Suppliers	This cluster is composed of companies contributing technology to a future VCN system. These companies are characterized by being a supplier to other stakeholders and free of responsibility to operate the system. An example for the network operator would be Huawei, as they provide the perator with the technological components for 5G communication. Another example could be NXP as they supply RSUs to the IT infrastructure operator. This cluster represents essential actors for the system, as they drive technological development and provide a technical framework. Their interest in the system is economic.	Technology providers are providing and developing the technical components for the realisation of a future VCN.
Infrastructure Network Provider/ Commerical and Institutional Users	Vehicle Manufacturers	Vehicle manufacturers refer to all Original Equipment Manufacturers (OEMs) in the automotive industry. This stakeholder group have significant power over the future VCN system as they are the actors that need to be convinced of the validity and value of the system in order to adopt the technology. Further, they have a certain amount of interest in the system as they are an executing stakeholder in the case of regulations. In addition to their described responsibility, vehicle manufacturers are potential commercial VCN users as service offerings through a VCN are conceivable.	The role of the manufacturers is to implement the necessary technology in their vehicles to allow the functionalities of a future VCN.
Infrastructure Network Provider/ Commerical and Institutional Users/ Rulemakers	Research Institutions	Research Institutions are Universities and research companies such as TNO or Frauenhofer. These Stakeholders contribute on various levels to the development and deployment of a future VCN through their research. Their Interest in the system is mainly scientific, thus, economic factors are less relevant.	Research Institutions have a versatile role in the ITS development and deployment. Depending on the geographical level of the ITS system they take part in policy and standardization decision-making by consulting and researching, technical development/research, or project implementation.

Table B.2: Stakeholder taxonomy description

Category	Actor	Description	Role
Commerical and Institutional Users	Commercial and Institutional Service Providers	Commercial and Institutional Service Providers are using the VCN Infrastructure to provide the traffic participants of the VCN with services that enable ITS functions and platforms. This cluster consists of road authorities, 3rd party service providers or vehicle manufacturers, and other instances offering ITS-related end-user applications. As these services enable the potential of a VCN their needs and requirements must be considered while designing and deploying such a large-scale infrastructure project.	This stakeholder has the role to use the VCN infrastructure to offer ITS services.
	Commercial and Institutional Mobility Providers	Commercial and Institutional Mobility Providers are traffic participants who offer mobility services to private and commercial customers. This includes MaaS companies such as greenwheels, but also public road transport operators.	Active users of the VCN. Their user behaviour and needs shape the VCN.
	Insurance Companies	The insurance companies category refers to the stakeholder vehicle insurance companies. These insurance companies have a great interest in the developments in the VCN sector, as the application can create new or omit business models for them. This player has no influence on the developments of the future VCN.	Insurance companies have no active role in the system but are heavily impacted.
	Data Contributors	This stakeholder category includes all commercial 3rd party companies that contribute data in some form to the VCN. For example, companies that collect real-time data through mapping services (Google order tom-tom) and then sell it. This also includes other commercial companies that share data about their facilities with the VCN, such as charging infrastructure providers. Their interest in the system is mostly economic.	Active users of and contributors to the VCN.
Private Users	Connected Vehicle Users	Connected Vehicle Users are the private users of the VCN. Due to their central role in the system, a future VCN must adapt the functionalities to the needs of the users and also the behaviour.	Active users of the VCN. Their user behaviour and needs shape the VCN.
	Disconnected Vehicle Users	Disconnected Vehicle Users are those vehicles that cannot communicate to other vechiles or the infrastructure via a wireless communication technology	These stakeholders do not have an active role in the system, but attention to their needs is essential as they are in close contact with the future VCN.
	Other Road Traffic Participants	This Cluster of actors contains all road participants who are not in the other private user groups. This includes for instance cyclists or pedestrians.	These stakeholders do not have an active role in the system, but attention to their needs is essential as they are in close contact with the future VCN.

Table B.3: Stakeholder needs

Actor	Role	Tasks	Needs	Need Identifier	Source
Government of Netherlands	Member states contribute to the decision-making within the EU. Furthermore, they have the responsibility to implement the Union's decisions within their own country. Member states also guide and restrict the development of a VCN in their own country by national regulations and mission objectives.	Set the regulatory framework for VCN. Communicate national VCN vision/mission. Provide funding for deployment and development. Advocate national interests in the EU regarding VCNs. Adopt the EU regulations and mission requirements for the nation.	Smooth introduction of cooperative ITS systems and autonomous driving applications. Adhering to the EU Regulations and Values. Road safety. Increasing Competitiveness of the Netherlands.	SN1	(Government of the Netherlands, n.d.-a, n.d.-b)
Dutch Ministry: Rijkswaterstraat	VCN IT Road Infrastructure Provider. Rijkswaterstraat is a ministry but also the IT road infrastructure operator of the system. Therefore a double role can be identified as an advisor and enforcer for the policymakers as well as a technical implementer /operator of the system.	Operate and maintain the road network. Traffic management. Report to the government Modifying infrastructure Traffic data management Advise the Government of the Netherlands	Improving the quality of life, access and mobility in a clean, safe and sustainable environment. Creating an efficient network of roads. Security and safety of road network. Sustainable mobility.	SN2	(Rijkswaterstaat, n.d.-a, n.d.-b, n.d.-c, n.d.-d, n.d.-e, 2022)
Dutch Ministry: Economic Affairs and Climate Policy	Development and implementation of policies related to sustainable economic growth, energy transition, digitalization and climate change, thus,influence potential VCN regulations. In addition, the ministry specifies the regulatory framework for enterprises to act on the Dutch market and is responsible for administrative tasks such as frequency band allocation.	Consumer Protection. Policy making/advising. Administrative tasks and facilitating budget. Facilitates cooperation. Facilitates innovation and research. Central access point for government information and services in the area of innovation, export and financing	A competitive business-friendly climate. Fostering sustainability and innovation.	SN3	(Ministry of Economic Affairs and Climate, n.d.-a, n.d.-b, 2022; Netherlands Enterprise Agency, 2022)

Table B.3: Stakeholder needs

Actor	Role	Tasks	Needs	Need Identifier	Source
Dutch Ministry: Ministry of Justice and Security	Responsible for maintaining the rule of law in the Netherlands,	Classifying VCN and application risks. Enforcing Dutch security regulations (Wbni und Bbni). Analysing and reducing identified threats. Providing surveillance and protection for persons, property, services and events, as well as for vital sectors. Expanding and strengthening cyber security. Making property, persons, structures and networks more resistant to threats. Ensuring effective crisis management and crisis communication.	Protect national interests, identify threats and strengthen resilience. Cyber resilience of the government, (VCN) businesses and civil society organisations. Secure and innovative digital products and services. Countering cyber threats posed by states and criminals.	SN4	(Ministry of Justice and Security, n.d.-a, n.d.-b, n.d.-c)
EU: Commision	The EU has the role to develop and provide VCN policies and guidelines for its member states. Further, this stakeholder is responsible for the effective coordination and funding of research focusing on the development of a future VCN such as HORIZON 2020. Furthermore, it shapes the development by formulating mission requirements.	Establish investment structure, regulatory framework, international cooperation, coordination, harmonizing and providing security-certificates for C-ITS services in its member states. Set incentives and mission requirements through political initiatives.	Putting people and their rights at the centre of the digital transformation. Supporting solidarity and inclusion. Ensuring freedom of choice online. Fostering participation in the digital public space. Increasing the safety, security and empowerment of individuals. Promoting the sustainability of the digital future.	SN5	(European Commission, n.d.-a, n.d.-b, 2021a; Frötscher et al., 2022)
EU Decentralized Agencies: BEREC	Contributes to EU policies regarding electronic communication	BEREC issues guidelines on several topics and delivers opinions, recommendations, common positions, best practices and methodologies. In addition, BEREC reports on technical matters and keeps registers, lists or databases.	Fostering the independent, consistent and high-quality regulation of digital markets (including VCN) for the benefit of Europe and its citizens. Connectivity and access to, and the take-up of, very high-capacity networks. Competition and efficient investment in the communication market. Development of the internal communication market.	SN6	(BEREC, n.d., 2019, 2020)

Table B.3: Stakeholder needs

Actor	Role	Tasks	Needs	Need Identifier	Source
EU Decentralized Agencies: ENISA	Contributes to EU policies on the topic of cyber security	Identification of cyber risks. Support digital security standards. Reflection on emerging technologies. Security incident investigation. Contribute to EU policy.	A resilient VCN Infrastructure. A connected economy. Digitally secure applications for the citizens. Secure communication.	SN7	(ENISA, n.d.)
EU Decentralized Agencies: EIT	Support research and entrepreneurship on VCN topics	Invest in strategic areas to accelerate the market uptake and scaling of research-based digital technologies. Support start-ups in the VCN domain.	A VCN should enable sustainable economic growth and job creation. Promoting and strengthening cooperation among leading business, education and research organisations.	SN8	(European Institute of Innovation and Technology, n.d.; European Parliament, 2021)
Research Institutions	Research Institutions have a versatile role in VCN development and deployment. Depending on the geographical level of the VCN system, they take part in policy and standardization decision-making by consulting and researching, technical development/ research, or project implementation.	Developing new technologies and applications. Conducting research and analysis. Providing education and training. Facilitating collaboration. Contribute to standards. Assist in policymaking.	Advancing and disseminating knowledge. Fostering innovation and entrepreneurship. Serve and improve society. Develop and advise morally.	SN9	(Intarakumnerd & Goto, 2018; Tseng, 2012)
Network Provider	The role of network operators is to design, build, and operate the communication networks according to the corresponding decisions, regulations and user needs. Moreover, they are responsible for ensuring continuity, security, and reliabilityof the communication networks.	Development and deployment of communication infrastructure. Operate the communication infrastructure. Establish business cases with the stakeholders.	A VCN needs to be reliable and economical. High capacity utilization. Leverage & expand the superior network. Simplify & streamline the operating model.	SN10	(Frötscher et al., 2022; KPN, 2021; Vodafone, 2020)
Energy Operators	Energy Operators inherit a rather constraining role in the future VCN system. They design, build, and operate the energy infrastructure that supports the operation of ITS technologies.	Provide reliable energy supply. Construct supply infrastructure.	High capacity utilisation. Energy-saving VCN technology components. Respect the system legacy of the current infrastructure. No imbalance in the load system.	SN11	(Eneco, n.d.; E.ON, n.d.)

Table B.3: Stakeholder needs

Actor	Role	Tasks	Needs	Need Identifier	Source
Vehicle Manufacturer	The role of the manufacturers is to implement the necessary technology in their vehicles to allow the functionalities of a future VCN.	Develop and implement technologies for connected vehicles. Cooperate with stakeholders to achieve co-development.	Increased perceived comfort in travelling. Increase in safety. Increase customer satisfaction. Reliable VCN-based services. Opportunity to develop and be competitive. Increase revenue. High level of trust and quality for the external data. Legal certainty and harmonized regulations/standards.	SN12	(Frötscher et al., 2022; Hamad-neh et al., 2022)
IT Infrastructure Operator	In the Dutch case, the operator is Rijkswaterstraat. See above.	In the Dutch case, the operator is Rijkswaterstraat. See above.	In the Dutch case, the operator is Rijkswaterstraat. See above.	SN13	x
Private Users	Active and passive users of the VCN	Using and participating in the VCN.	Safe and secure communication for the applications. Full connectivity for the services of their choice. Privacy-preserving communication and data usage. Cross-border usability of the VCN services. VCN application must improve the convenience for the users.	SN14	(Lee et al., 2022; Pfleging et al., 2016; Shaheen & Finson, 2013)
Commerical and Institutional Users	Active Users of the VCN with an economic interest	Using and participating in the VCN.	Safe and secure communication for the applications. Full connectivity for the services of their choice. Privacy-preserving communication and data usage. Cross-border usability of the VCN services. VCN application must improve the convenience for the users. A VCN should create business opportunitiesand generate business value.	SN15	(Lee et al., 2022; Pfleging et al., 2016; Shaheen & Finson, 2013)
Standardisation institute	The role of standardization institutions is to develop and propose technical standards that guide the VCN conceptualisation, deployment and promote the interoperability and compatibility of ITS solutions, while also ensuring the safety and security of these technologies.	Drafting, reviewing, voting and publication of standards. Research new technologies. Education about standards.	Inclusiveness of VCN technology. Equitable economic VCN development Advance VCN innovation. Enhance safety to achieve a sustainable future. Services must ensure the safety, efficiency, reliability and interoperability of VCN.	SN16	(IEC, 2018, 2022; ISO, 2021)

Table B.3: Stakeholder needs

Actor	Role	Tasks	Needs	Need Identifier	Source
Industry Unions	Industry Unions advocate for their members by representing their interests and opinion in an institutional environment.	Advocate to policymakers. Supporting industry innovation. Contributing to standards. Deployment and development, testing of member technology. Enable Cooperation among members.	Inclusiveness and addressing societal mobility needs in a VCN. Overcome road accidents and increase safety (vision zero). Increase traffic efficiency/sustainability by using smart solutions. Keep the cost low for users and the environment Powerful, reliable, robust and mature safety-related solutions. Consider system legacy. Cross-border (worldwide) harmonisation and promotion of C-ITS	SN17	(5GAA, n.d.; AECC, n.d.; Car2Car, n.d.)

Table B.4: Interview insights: Stakeholder insights

	Stakeholder Insights
Common Points	Institutional actors and vehicle manufacturers/Technology providers (safety interest and economic interest) (INT2, INT3, INT4, INT6, INT7, INT10, INT11) Deadlock infrastructure cars chicken egg problem (INT1, INT6, INT11, INT12, INT13) Clashing interest among member states à failing ITS directive (INT6, INT7, INT8,. INT9) Industry associations have different interests (fight over frequency band allocation ITS-G5 vs. c-V2X) (INT5, INT14) Clashing Interest of Privacy from User and road authorities (switching identity for CCAM, Speeding ticket) (INT1, INT2)
Unique Points	Ministries are waiting on the Country or EU to commit and provide the budget and task (INT4)

C
Appendix C

Table C.1: Requirement description

Requirement	**Description**
Mission Requirements	Mission requirements are the overarching goals of the entire society. In this context, the requirements are characterized by a long-term time span and guiding technologically but also socially. In relation to the vehicle communication network and the scope, mission requirements are defined by the European Union and the national member states, whereby the member states mission requirements are in line with those of the Union. The purpose of these Mission requirements is to provide future systems and developments with a set of objectives they can contribute to.
Regulation: System Operation	System operation measurements summarize the regulatory requirements for operating a future vehicular communication network. This includes clear decisions about legal concerns such as ownership allocation of system parts among stakeholders, liability for unexpected occurrences or mistakes, broadband licensing, device placing restrictions, administrative prerequisites/tasks for operating stakeholders, or reporting and iteration requirements. A minimum set of these governance concerns is typically set out in European and national regulatory directives. An example of this is the European Electronic Communications Code Directive.
Regulation System Architecture	System operation measurements summarize the regulatory requirements for the architecture of a VCN, including software and hardware choices.
Standards	The Standards requirement defines the applicable standards that are incorporated in the VCN system. This incorporates the development, selection, and commitment to standards.
Stakeholder Cooperation	This requirement summarizes the efforts needed to bring the stakeholder together to cooperate. Furthermore, it addresses the collaboration, clashes, and trade-offs between the stakeholder.
Ethical Requirements	The ethical requirements summarize all ethical discussions that concern the VCN. These include topics such as responsible design, safe and secure design, fairness in the system, accountability in case of emergency, human trust, transparency, and the differentiated view of commercial and private users.
Social Acceptance	Social acceptance refers to the necessary willingness of stakeholders in the system and users to accept the technology and decisions affecting the VCN and, thus, in the best case, to cooperate.
Application Requirements	The application requirements summarize the requirements that arise from VCN applications (e.g., traffic management, autonomous driving, safety applications, or infotainment). Each of these applications creates a requirements tree, as it represents a subsystem. These requirements are the basis for the minimum required performance metrics of the network and, subsequently, the supporting infrastructure.
Robust	Robustness equals the degree of smallness in the variability of a system's function under various noise conditions (ISO16336). In the context of the VCN, the requirements of redundancy, availability, connectivity, interference design, and partly fail-safe design are represented by this cluster.
Safe	Safe defines the absence of physical harm to humans and objects(infrastructure, vehicle ...).
Adaptive	The adaptive requirement includes the ability of the VCN to respond to situations. This includes temporary data peaks due to human behavior. But also the ability to adapt to rapidly changing VCN applications. Thus, this requirement deals with the ability to deal with uncertainty and human behavior.
Secure	This requirement covers the security of the cyber-physical system. The aim is to ensure that the VCN is secure from digital threats, but also on enabling applications such as seamless authorizing.

Privacy Preserving	Under this requirement fall all efforts to ensure the privacy of users in the system architecture.
Efficient	Generally speaking, it is defined as the relationship between the result achieved and the resources used (ISO9000). Documents fall under this requirement if they state this as a requirement or are working on efficiency-enhancing applications or network architectures. This includes for instance protocol design, data filtering, network slicing, self-optimizing architectures, broadcasting, or resource sharing.
Effective/ Reliable	This requirement is defined as the need for the VCN system to provide sufficient resources to perform the applications as expected and reliably. This includes the considerations of high mobility requirements but also enabling network functions such as inter and intra-handover.
Resilient	This requirement describes the self-healing attribute of the VCN. Further, it includes the time to recover from an disruptive event.
Interoperability / Heterogeneity / System legacy	This requirement is one of the fundamental concepts of the VCN. It includes all requirements that relate to the heterogeneity of software, hardware, approaches, and actors. In addition, this technical requirement also refers to non-technical conditions as well as country heterogeneity due to for instance border crossings or the system legacy of the stakeholders.
Architecture Choice: Centralized/Decentralized	This requirement determines the choice of architecture for a VCN system. Here, everything is conceivable from centralized to decentralized or in between.
Comply With Standards	The system architecture must adhere to the standards.
Automation	This requirement includes all documents that aim to automate processes, improve automated processes or state this as a requirement for a VCN.
Spatial Differentiation	Spatial differentiation refers to the ability of the VCN to distinguish and classify geographical areas in terms of for instance local and global data.
Data Management System	The data management system defines the requirements for a system architecture that can cope with data issues.
Scalable	Scalability refers to the ability of a VCN to be extended physically and digitally on demand without disrupting the system.
Continuity of the Service	Network service continuity represents the ability of the VCN operation to maintain seamless connectivity and uninterrupted data transmission among different stakeholders involved in the VCN ecosystem. This Requirement is linked to the legal obligations as a network provider.
Trust and Control Management	This requirement contains the subsystem to ensure trusted communication in the VCN.
Change Management / System Update	Change management and system upgradability in ITS involve the systematic management of changes, updates, and upgrades to the system's hardware, software, and infrastructure components. This requirement emphasizes the need for flexible and scalable ITS solutions that can adapt to evolving technologies, regulatory requirements, and operational needs, while minimizing disruptions and maximizing system performance.
Monitoring	A VCN must be monitorable.
Data Management	The data management in the operation of a VCN includes the requirements to operate the data landscape of a VCN.
Maintenance	Maintenance in a VCN operation refers to the planned activities and processes aimed at preserving the functionality and performance of the system and its components. This affects the physical and cyber physical subsystem.
Communication Management	Under this requirement fall all the efforts that deal with the type of communication. This includes the attempt to establish hybrid communication paths or the distribution of data and communication in the VCN network.
Computation Management	Computation management in a VCN involves the allocation, utilization, and optimization of computational resources This includes processing power, memory, and storage, that handle the communication.
Disaster Management	This requirement defines disaster preparedness measures, including risk assessments, emergency response plans, and training programs, to ensure stakeholders are equipped to respond effectively in the event of a disaster.
Risk Management	Risk management in a VCN involves the systematic process of identifying, analyzing, evaluating, and mitigating risks that may impact the operation and performance of the system.

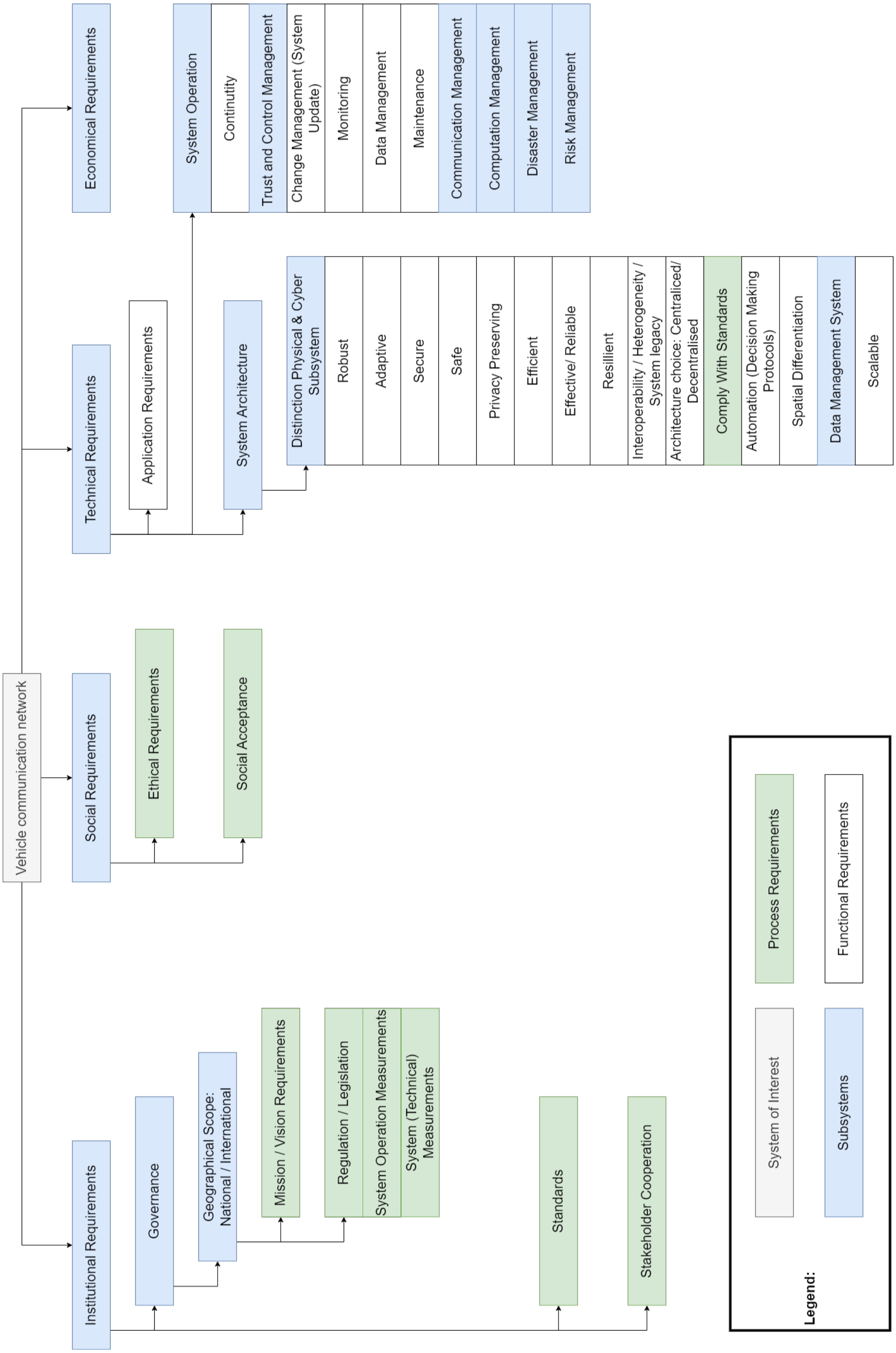

Figure C.1: System requirements structure (Enlarged)

Table C.2: Requirement analysis classification

Institutional: Government of Netherlands (7 Documents)	(Dutch Safety Board, 2019; Government of the Netherlands, 2017, 2022; Netherlands Enterprise Agency, 2022; RDW, n.d.; Rijkswaterstraat, 2022a, 2022b)
Institutional: European Union (12 Documents)	(EIT Urban Mobility, 2020; ENISA, 2021; Euopean Commission, 2021; European Commission, 2019, 2020a, 2022a, 2022b; European Commission et al., 2020; European ITS Platform, 2022; Frötscher et al., 2022; Government of the Netherlands, 2016; Secci, 2021)
Industry Association (7 Documents)	(5GAA, 2021, 2022; AECC, 2020, 2021; GSMA, 2019; ITU, 2021; NGMN Alliance, 2018)
Knowledge Institutions (31 Documents)	(Ahmed et al., 2022; Alén-Savikko, 2019; Arnesen et al., 2021; Bwalya, 2020; Canitez, 2021; França et al., 2021; Gilbert et al., 2022; Gschwendtner et al., 2021; Hamadneh et al., 2022; Hussain & Zeadally, 2018; Kaiwartya et al., 2016; Li et al., 2023; Lima et al., 2016; Mahmood, 2020; Marletto, 2019; Mishra et al., 2023; Musa et al., 2022; Renner et al., 2020; Roy et al., 2022; Sharma & Kaushik, 2022; Silva & Iqbal, 2019; Singh et al., 2020; Storck & Duarte-Figueiredo, 2019; Vermesan et al., 2021; Wan et al., 2021; Wang et al., 2020; Yaqoob et al., 2020; Zhang & Letaief, 2020; Zheng et al., 2016)

Table C.3: Requirement analysis (1)

Type	Requirement	(Rijkswaterstraat, 2022b)	(RDW, n.d.)	(Dutch Safety Board, 2019)	(Rijkswaterstraat, 2022a)	(Netherlands Enterprise Agency, 2022)	(Government of the Netherlands, 2022)	(Government of the Netherlands, 2017)	(European Commission et al., 2020)	(Euopean Commission, 2021)	(European Commission, 2022b)	(European Commission, 2022a)	(European Commission, 2020a)	(European Commission, 2019)	(Frötscher et al., 2022)	(European ITS Platform, 2022)	(Secci, 2021)	(EIT Urban Mobility, 2020)	(Government of the Netherlands, 2016)	(ENISA, 2021)
Institutional	Mission Requirements						x	x		x		x	x							
	Regulation: System Operation			x	x	x	x	x	x		x	x	x	x	x	x			x	
	Regulation System Architecture			x		x	x	x						x					x	x
	Standards					x		x	x				x		x	x		x		x
	Stakeholder Cooperation	x		x	x	x			x			x	x		x			x		x
Social	Ethical Requirements						x		x	x		x	x						x	
	Social Acceptance				x	x														
Technical: System Architecture	Application Requirements				x										x	x		x		
	Robust			x		x	x	x		x					x	x	x	x		
	Safe		x		x		x		x			x	x							x
	Adaptive	x																		
	Secure	x					x	x	x			x	x	x	x	x	x	x	x	x
	Privacy Preserving					x		x	x			x	x		x	x	x		x	x
	Efficient	x			x	x	x				x		x		x	x		x		
	Effective/ Reliable	x				x	x				x		x			x	x	x		
	Resilient									x		x	x			x	x			x
	Interoperability / Heterogeneity / System legacy				x	x					x	x	x	x	x	x		x		
	Architecture Choice: Centralized/Decentralized												x	x			x			
	Comply With Standards						x		x						x					
	Automation	x			x										x	x				
	Spatial Differentiation														x					
	Data Management System	x				x			x				x	x	x				x	
	Scalaable	x						x												
Technical: System Operation	Continuity of the Service	x				x	x					x	x					x		
	Trust and Control Management								x					x	x					x
	Change Management / System Update														x	x				
	Monitoring					x			x						x					x
	Data Management	x				x							x	x	x				x	
	Maintenance															x				
	Communication Management	x									x				x					
	Computation Management																			
	Disaster Management																			
	Risk Management					x									x					x

Table C.4: Requirement analysis (2)

Type	Requirement	(5GAA, 2022)	(AECC, 2021)	(AECC, 2020)	(NGMN Alliance, 2018)	(GSMA, 2019)	(ITU, 2021)	(5GAA, 2021)	(Erwin, 2016)	(Lima et al., 2016)	(Zheng et al., 2016)	(Marletto, 2019)	(Renner et al., 2020)	(Wang et al., 2020)	(Ahmed et al., 2022)	(Roy et al., 2022)	(Alén-Savikko, 2019)	(Li et al., 2023)	(Storck & Duarte-Figueiredo, 2019)	(Arnesen et al., 2021)
Institutional	Mission Requirements																			x
	Regulation: System Operation	x	x		x			x					x				x			
	Regulation System Architecture																			
	Standards	x		x		x	x	x					x	x						x
	Stakeholder Cooperation					x							x							
Social	Ethical Requirements				x				x					x	x					
	Social Acceptance				x								x		x					
Technical: System Architecture	Application Requirements	x												x				x		
	Robust		x	x	x	x			x	x				x				x		x
	Safe				x	x				x				x						x
	Adaptive		x	x	x	x			x					x				x		x
	Secure		x	x	x	x			x	x	x		x	x		x				
	Privacy Preserving		x		x				x	x	x		x	x						
	Efficient	x	x	x	x	x				x	x			x			x	x		x
	Effective/ Reliable	x	x	x	x	x		x		x				x			x	x		x
	Resilient		x							x										
	Interoperability / Heterogeneity / System legacy	x	x	x	x		x	x				x	x	x			x	x		x
	Architecture Choice: Centralized/Decentralized		x	x									x							
	Comply With Standards		x											x						
	Automation													x				x		
	Spatial Differentiation													x						
	Data Management System	x	x		x					x				x				x		x
	Scalable		x	x	x	x								x				x		
Technical: System Operation	Continuity of the Service		x	x																x
	Trust and Control Management		x		x				x	x				x						
	Change Management / System Update		x	x	x															
	Monitoring				x															
	Data Management	x	x		x									x				x		x
	Maintenance				x	x												x		
	Communication Management		x	x	x	x								x				x		
	Computation Management		x	x	x									x				x		
	Disaster Management									x										
	Risk Management								x											

Table C.5: Requirement analysis (3)

Type	Requirement	(Iqbal, 2018)	(Silva & Iqbal, 2019)	(Yaqoob et al., 2020)	(Bwalya, 2020)	(Singh et al., 2020)	(Kaiwartya et al., 2016)	(Vermesan et al., 2021)	(Wan et al., 2021)	(Mishra et al., 2023)	(França et al., 2021)	(Mahmood, 2020)	(Sharma & Kaushik, 2022)	(Zhang & Letaief, 2020)	(Musa et al., 2022)	(Hussain & Zeadally, 2018)	(Canitez, 2021)	(Gschwendtner et al., 2021)	(Hamadneh et al., 2022)	(Gilbert et al., 2022)
Institutional	Mission Requirements																			
	Regulation: System Operation	x	x									x				x	x	x	x	x
	Regulation System Architecture															x				
	Standards												x					x	x	
	Stakeholder Cooperation						x				x						x		x	
Social	Ethical Requirements	x	x			x										x		x		x
	Social Acceptance				x											x				
Technical: System Architecture	Application Requirements														x	x				x
	Robust			x		x	x	x	x		x		x		x	x			x	x
	Safe		x	x				x				x	x			x			x	x
	Adaptive														x			x		x
	Secure	x	x	x	x	x		x	x		x	x			x	x			x	
	Privacy Preserving	x	x	x	x	x	x	x			x	x	x		x	x		x	x	
	Efficient			x	x	x		x	x	x	x		x		x	x	x		x	x
	Effective/ Reliable		x	x	x	x	x	x	x		x	x	x		x	x		x		x
	Resilient							x												x
	Interoperability / Heterogeneity / System legacy			x			x	x				x	x		x				x	x
	Architecture Choice: Centralized/Decentralized											x			x					
	Comply With Standards																			
	Automation							x												
	Spatial Differentiation																			x
	Data Management System			x	x	x	x				x	x		x		x				
	Scalable			x		x	x	x			x				x					
Technical: System Operation	Continuity of the Service							x												
	Trust and Control Management						x	x					x		x	x				
	Change Management / System Update										x									
	Monitoring	x	x																	
	Data Management			x	x	x	x				x	x		x	x	x				
	Maintenance							x											x	
	Communication Management			x		x		x					x		x	x			x	
	Computation Management			x		x		x					x		x	x			x	
	Disaster Management							x												
	Risk Management																			x