The future role of the German automotive industry in autonomous private transport –

A conceptual approach for analyzing the interplay of the manufacturing and ICT sectors in innovation systems and its implications for the German economy

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Abstract

This dissertation examines the current and future roles of the automotive industry in the development and provision of autonomous driving from an innovation system perspective. It focuses on the interaction between the automotive and ICT sectors, incorporating sectoral and regional context factors. Based on the findings, four scenarios are developed for the German industry within the context of global market development for autonomous vehicles. In the final step, the economic implications of these scenarios are simulated up to the year 2050 using a macroeconomic simulation model (ISI-Macro). The thesis thus presents a novel approach for deriving prospective scenarios from an innovation system analysis and estimating their macroeconomic effects through a modeling exercise.

The dissertation combines sectoral, national, and technological innovation system approaches, explicitly focusing on the interaction between the two sectoral systems within a functional innovation system. The developed "integrated innovation system analysis" approach considers contextual factors in the development and dynamics of innovation systems, demonstrating how system interactions can be integrated into a functional innovation system analysis by selecting suitable indicators and by adding an additional function. The results provide insights into the structures of a new system developing around autonomous driving in Germany, the USA, and China, identifying factors that significantly influence the transformation of the affected value chains. In an adapted scenario-building process, findings from the innovation system analysis are translated into four prospective scenarios. These combine global market development scenarios for autonomous driving with scenarios for the positioning of the German automotive industry. As part of the macroeconomic modeling, the core characteristics of the scenarios are translated into quantitative impulses, estimating the possible effects on German GDP, value added, and employment up to 2050. The simulation accounts for the direct, indirect, and induced effects of the introduction of autonomous driving on 72 economic sectors in Germany. The potential differences in GDP, based on the varying positions of the German automotive industry, reach up to 4.75% in an ambitiously evolving global market. The analysis highlights the widespread impact of developments in the automotive industry on various sectors in the German economy.

Kurzzusammenfassung

In der Dissertation wird die aktuelle und zukünftige Rolle der Automobilindustrie bei der Entwicklung und Bereitstellung des autonomen Fahrens aus einer Innovationssystemperspektive analysiert. Der Fokus liegt dabei auf dem Zusammenspiel zwischen den Automobil- und IKT-Sektoren und dem Einbezug sektoraler und regionaler Kontextfaktoren. Auf Basis der Ergebnisse werden vier Szenarien für die deutsche Industrie im Kontext der globalen Marktentwicklung für autonome Fahrzeuge entwickelt. In einem abschließenden Schritt werden die ökonomischen Implikationen, die sich aus den zentralen Merkmalen der vier Szenarien ergeben, mit einem makroökonomischen Simulationsmodell (ISI-Macro) bis zum Jahr 2050 simuliert. Die Arbeit stellt somit einen neuen Ansatz vor, mit dem prospektive Szenarien aus einer Innovationssystemanalyse abgeleitet und deren makroökonomische Effekte modellbasiert abgeschätzt werden können.

Hierzu kombiniert die Dissertation sektorale, nationale und technologische Innovationssystemansätze und widmet sich explizit der Interaktion der beiden beteiligten sektoralen Systeme innerhalb eines funktionalen Innovationssystems. Der entwickelte Ansatz einer „integrated innovation system analysis" berücksichtigt Kontextfaktoren in der Entwicklung und Dynamik von Innovationssystemen und zeigt eine Möglichkeit auf, wie die Analyse von System-Interaktionen durch die Auswahl geeigneter Indikatoren und das Hinzufügen einer zusätzlichen Funktion in eine funktionale Innovationssystemanalyse integriert werden kann. Die Ergebnisse liefern einen Einblick in die Muster und Strukturen des sich entwickelnden Systems rund um das autonome Fahren in Deutschland, USA und China und erlauben die Identifikation von Faktoren, die die Transformation der betroffenen Wertschöpfungsketten maßgeblich beeinflussen. In einem adaptierten Prozess der Szenarien-Bildung werden die Erkenntnisse aus der Innovationssystemanalyse in vier Zukunftsszenarien übersetzt. Dabei werden globale Marktentwicklungsszenarien in Hinblick auf das autonome Fahren mit Szenarien zur Positionierung der deutschen Automobilindustrie kombiniert. Im Rahmen der makroökonomischen Modellierung werden die Kerncharakteristika der Szenarien in quantitative Impulse überführt und schließlich die möglichen Auswirkungen der Szenarien auf das BIP bzw. die Wertschöpfung und die Beschäftigung in Deutschland bis 2050 abgeschätzt. Die Simulation berücksichtigt direkte, indirekte und induzierte Effekte der Einführung des autonomen Fahrens auf 72 Wirtschaftszweige in Deutschland. Die aufgrund einer unterschiedlichen Positionierung der deutschen Automobilindustrie möglichen Unterschiede im BIP erreichen in einem sich ambitioniert entwickelnden globalen Markt bis zu 4,75 %. Die Analyse verdeutlicht die weitreichenden Auswirkungen, die die Entwicklungen in der Automobilindustrie auf verschiedene Sektoren der deutschen Wirtschaft haben.

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AI	Artificial Intelligence
AV	Autonomous Vehicles
AV TEST	Automated Vehicle Transparency and Engagement for Safe Testing
AVIA	Autonomous Vehicle Industry Association
AVT	Autonomous Vehicle Tester
B2B	Business-to-Business
B2C	Business-to-Consumer
BMDV	Bundesministerium für Digitales und Verkehr
C2C	Consumer-to-Consumer
CES	Consumer Electronics Show
CGE	Computable general equilibrium
CLD	Causal-loop-diagram
CPC	Cooperative Patent Classification
DARPA	Defense Advanced Research Projects Agency
EASME	EU Executive Agency for SMEs
EMS	Electronics Manufacturing Services
ERC	European Research Council
EUIPO	European Union intellectual property office
EUIPO	European Union Intellectual Property Office
FTE	Full Time Equivalents
GCC	Global Commodity Chains
GDP	Gross Domestic Product
GPN	Global Production Networks
GPS	Global Positioning System
GVA	Gross Value Added
GVC	Global Value Chain
HD	High-definition
ICT	Information and Communication Technologies
IOT	Input-Output Table
IoT	Internet of Things
IPC	International Patent Classification
LiDAR	Light Detection And Ranging
M&A	Mergers and Acquisitions
MLP	Multi-Level Perspective
MRIO	Multi-Regional Input Output
NACE	Nomenclature generale des Activites economiques dans les Communautes europeennes / European Classification of Economic Activities
NAFTA	North American Free-Trade Area

NPM	National Platform Future of Mobility
NSI	National System of Innovation
ODM	Original Design Manufacturer
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PATSTAT	EPO Worldwide Patent Statistical Database
Pkm	Passenger kilometers
R&D	Research and Development
R&I	Research and Innovation
RoW	Rest of World
SOC	System on a Chip
SME	Small and Medium Enterprise/Small and Mid-sized Enterprise
SSI	Sectoral System of Innovation
TIS	Technological Innovation System
UN	United Nations
VDA	Verband der Automobilindustrie (association of the automotive industry)
VIN	Vehicle Identification Number
Vkm	Vehicle kilometers
WIOD	World Input-Output database

1 Introduction

The automotive industry faces a fundamental digital transformation, as digitization will not only change the vehicle itself, including components, technologies, functionalities, resource needs, production processes and global production networks, but also has the potential to change the whole mobility system and automotive value chains. This includes the large-scale diffusion of autonomous vehicles as well as the servitization of mobility. The development of autonomous vehicle technologies and their application play a central role in that transformation. Not only the automotive industry itself, but also newcomers from other industrial backgrounds are engaged in the development and application of these technologies. While many of the technologies are still in the development stage, the future diffusion of autonomous vehicles is expected to induce a restructuring of global mobility supply and demand. The configuration of the future industrial network providing autonomous vehicles, services and accompanying business models, and of the related value chains remains unclear. So do the patterns of usage by customers, the regional distribution of global markets and the timeline of technological development milestones and implementation.

The current phase in the innovation process of autonomous vehicles is characterized by high dynamics and activities of both industrial players and governments, since the successful deployment of autonomous vehicles promises economic gains. Especially in countries like Germany, where the established automotive industry is a major contributor to value added and employment (Bundesministerium für Wirtschaft und Klimaschutz 2022), incumbent automotive firms stand under pressure to maintain their role in technological leadership and to secure market shares. The export-oriented German automotive industry faces competition in the domestic as well as international markets, specifically with players from the US and China. Governments have put autonomous driving on their agenda not only to prepare the domestic mobility system for the future but also to foster domestic innovation, industrial success and economic prosperity.

The development of autonomous driving differs in certain ways from past innovations in the automotive industry for three reasons. Firstly, a large amount of cross-sectoral technologies and concepts need to be integrated: Due to the increasing role of digital components and software solutions in the development of autonomous driving, a new set of actors has entered the mobility field, especially players from the information and communication (ICT) industry. Their competences in the area of digital technologies can, to some extent, be considered complementary to the traditional automotive key competences. Value added within vehicles is likely to increasingly consist of digital components, and established production chains may change accordingly. The automotive and ICT industries increasingly interact and have common interfaces.

Secondly, autonomous vehicles may encourage the transformation from product- to service-driven mobility markets: Without the need for an (active) human driver, new opportunities in terms of the creation of flexible mobility systems and in-car activities arise. These are accompanied by various new business opportunities and revenue pools. In both fields, the business models will be service-oriented. The sale of transportation might increasingly replace the sale of vehicles, while infotainment offers in autonomous vehicles will likely open up as a new market. The development of successful business models that meet individual needs will heavily depend on the collection and evaluation of user data, as can be observed in current digital business models. Platform-based services will increasingly be established in the mobility market, which are usually accompanied by shifts in and concentration of power among supplying actors (Alvarez León and Aoyama 2022).

Thirdly, the need for testing fields, new approval procedures and updated regulatory frameworks establishes a new kind of interaction between industry and society: In contrast to other purely or mostly technological innovations, the development and implementation of autonomous vehicles and related mobility services do not only depend on industrial players, but, to a larger extent, on the interplay with political and societal bodies and actors. The development and implementation of autonomous driving thus entail large changes to the established structures of the automotive industry and the mobility system.

The thesis is directed at assessing the potential effects of the introduction of autonomous driving on the role of the automotive industry and its value chains, especially in Germany, as well as the resulting impacts on the Germany economy. The thesis is thus divided into two parts: First, an integrated analysis of the innovation system[1] and second, a scenario-building and economic assessment. In the first part, the innovation system analysis has to consider the entrance of ICT players into the mobility field as one of the main determinants of change. Furthermore both the automotive and the ICT industry have to be considered in a broader context, including factors such as institutions, infrastructure and society, as well as the geographical location. All of this requires the use of a systemic framework, which goes beyond a single technological, sectoral or national innovation system heuristic and that accounts for the interplay between the automotive and ICT industries. In the second part, the effects within the innovation systems have to be assessed within a macroeconomic framework. Therefore the findings from the integrated innovation system analysis are translated into scenarios that are subsequently quantified and studied in a macroeconomic simulation.

In the first part, the dissertation combines the analysis of the technological innovation system on autonomous driving with the sectoral perspective of the two involved sectors and the national perspective of the most relevant countries in the field: Germany, USA and China. Furthermore, it integrates the evaluation of the interaction of the two sectoral systems as the determining dynamic that may shape the implementation of the technology and thus the transformation of the value chain. A mixed methods approach is applied that uses quantitative data from a variety of structured (vehicle sales, multi-regional input-output data, patents, bibliometric data, employment data, company databases) and unstructured sources (company websites, acceptance studies) and combines them with the results of a qualitative literature review and the evaluation of other text types. The latter cover company websites, government publications and websites, and press articles. The thesis sheds light on and structurally evaluates the current activities of different players from both the automotive and the ICT sector in Germany, USA and China. The leading research questions are:

1. What are the key characteristics of the automotive and ICT sectors that may influence their participation in the development of autonomous driving?
2. Are there any differences in the activity of the automotive and ICT sectors and different countries in the development and provision of autonomous driving?

[1] A shorter version of the integrated innovation system analysis has already been published in Grimm and Walz 2024, which includes the formulated research questions 2. and 3. Parts of the literature review (introduction to section 2 and section 2.1), the description of the conceptual approach (section 3.2.1), the sectoral and functional innovation system analysis (chapters 4 and 5), including several figures, the analysis of interactions and the intermediate results (chapter 6) and the conclusions (section 9.3) appear in the published paper. Passages of the text thus contain identical wordings. Author statements: Anna Grimm: Conceptualization; Methodology; Data curation; Formal analysis; Investigation; Resources; Visualization; Roles/Writing - original draft; Writing - review & editing. Rainer Walz: Conceptualization; Supervision; Validation; Writing - review & editing.

3. What are the main factors and how may they influence the potential reconfiguration of value chains and the division of tasks between the automotive and the ICT sectors? What does that imply for the national industrial landscapes?

In the second part of the thesis, four scenarios are derived in a scenario-building process. The process builds on the integrated innovation system analysis and specifically the identification of factors influencing the reconfiguration of value chains developed in response to the third research question. The scenarios assess the fourth research question:

4. How could the future autonomous driving market develop up to 2050 and which strategies of the German automotive industry are imaginable?

Finally, the potential implications of the scenarios for the German economy are estimated for the timeframe 2025 - 2050. The macroeconomic simulation builds on the translation of the scenarios into quantitative impulses and the attribution of economic activity to different industries. The simulation model ISI-Macro (Sievers and Pfaff 2019) is used in order to assess direct, indirect and induced effects from two different positioning options of the German industry in two distinct trajectories of market development. The analysis answers the last research question:

5. How do different industrial strategies of the German automotive industry influence the overall German economy until 2050? What effects can be expected in terms of the development of gross domestic product, value added and employment?

The thesis contributes to the existing literature in several ways. First, sectoral, technological and regional perspectives on innovation systems are combined in a joint analysis. Second, the interaction of the two involved sectoral systems is explicitly analyzed. The thesis presents a novel way of integrating the analysis of interactions through the selection of suitable indicators and an additional function, and develops an integrated innovation system approach. Third, it is assessed whether and how an innovation system approach is suitable to answer questions on the transformation of value chains due to the emergence of a new technology. The systemic perspective has the potential to enrich the analysis of industrial and value chain dynamics through the explicit consideration of influential factors outside industries. Fourth, a comprehensive analysis of the current status and potential future development of autonomous driving is conducted. It provides insights into patterns and structures of the evolving system. Fifth, the performed scenario-building process develops an approach of translating findings from an innovation system analysis into the formulation of prospective scenarios. Finally, the economic modelling quantifies the potential effects of the scenarios on the German economy until 2050. The simulation is novel to the extent that it considers direct, indirect, induced effects from the provision of autonomous driving on 72 industries and is built on scenarios resulting from an integrated innovation system analysis.

The thesis is structured as follows. In chapter 2, a review of the relevant literature is conducted. Chapter 3 introduces the conceptual approach that contains the developed integrated innovation system approach and the link to methods of scenario-building and macroeconomic modelling. Chapter 4 describes the key characteristics of the automotive and ICT sectors. The functional analysis of the autonomous driving innovation system is presented in chapter 5. Chapter 6 summarizes the identified system interactions and reviews the main intermediary findings. In chapter 7, four scenarios are built that present different pathways of the German industrial development in the provision of autonomous driving in different framework conditions. These scenarios' implications on the German economy are simulated in chapter 8. Chapter 9 concludes.

2 Literature review[2]

The available literature on autonomous driving has increased immensely over the past few decades, with the majority of scientific publications relating to many technological sub-fields of autonomous vehicles, such as sensor technology or motion planning (Mora et al. 2020). A growing body of literature however deals with the societal and economic impacts of autonomous driving. To name a few examples, one field is transport research in which effects of autonomous vehicles on traffic flows (Levy and Haddad 2022; Gueriau and Dusparic 2020; Kolarova et al. 2019; Ongel et al. 2019; Levin and Boyles 2015), urban planning (Fayyaz et al. 2022; Lee et al. 2022; Shatu and Kamruzzaman 2022; Agriesti et al. 2020; Nogués et al. 2020) and mobility behavior (Liljamo et al. 2021; Saeed et al. 2020; Acheampong and Cugurullo 2019; Pakusch et al. 2018; Zmud and Sener 2017) are covered. Empirical studies, such as surveys, assess the current state of the public acceptance of autonomous vehicles and potential usage patterns (Xiao and Goulias 2022; Othman 2021; Nastjuk et al. 2020; Motamedi et al. 2020).

Potential business models that may accompany the introduction of autonomous vehicles are generally analyzed from an economic perspective (Alochet et al. 2021; Cavazza et al. 2019; Yun et al. 2016). Some contributions assess the economic effects on certain regions (Alonso et al. 2020), often using established methods such as input-output analysis (Jun et al. 2022). The studies show the complex effects that arise from the implementation of autonomous vehicles, since not only the industries producing autonomous vehicles are affected but also almost all other industries that rely on the transport sector in order to carry out their operations. Studies on the economic implications from an industrial dynamics point of view have long been underrepresented in the scientific literature (Alvarez León and Aoyama 2022). Many studies on the current state and future of autonomous driving can be characterized as gray literature (Deloitte 2022, 2019a, 2017; Hofstätter et al. 2020; McKinsey & Company 2019a; KPMG 2019). Effects are mostly estimated by identifying a set of influencing and influenced parameters, where variations in parameters are often consolidated into different scenarios. Many of the studies, however, can be considered rather restricted, since the interrelations between influencing factors are hardly considered.

While a lot of the publications in transport, economic and business research deal with the future implementation and potentials of autonomous vehicles, the current and past development phase of autonomous vehicles has been studied in the field of innovation research. Examples are the use of patent citations in order to study knowledge development and diffusion (Meng et al. 2019) or improved indicators to capture the emergence of the technology of autonomous vehicles and related technological topics (Woo et al. 2021). The approaches partly relate to the concepts of innovation systems. For instance, Meng et al. (2019) use parts of the concept of technological innovation systems (TIS) by focusing on the processes of knowledge development and diffusion. Existing work mainly focuses on one or a small set of indicators in order to explain distinct developments or interrelations in the field of autonomous driving and lacks the consideration of a full set of influencing factors from a systemic perspective.

The literature on innovation systems provides heuristics to comprehensively analyze the innovation processes. Usually, studies in the field have the goal to identify challenges and obstacles that hinder the development or diffusion of an innovation in order to provide policy a general recommendation

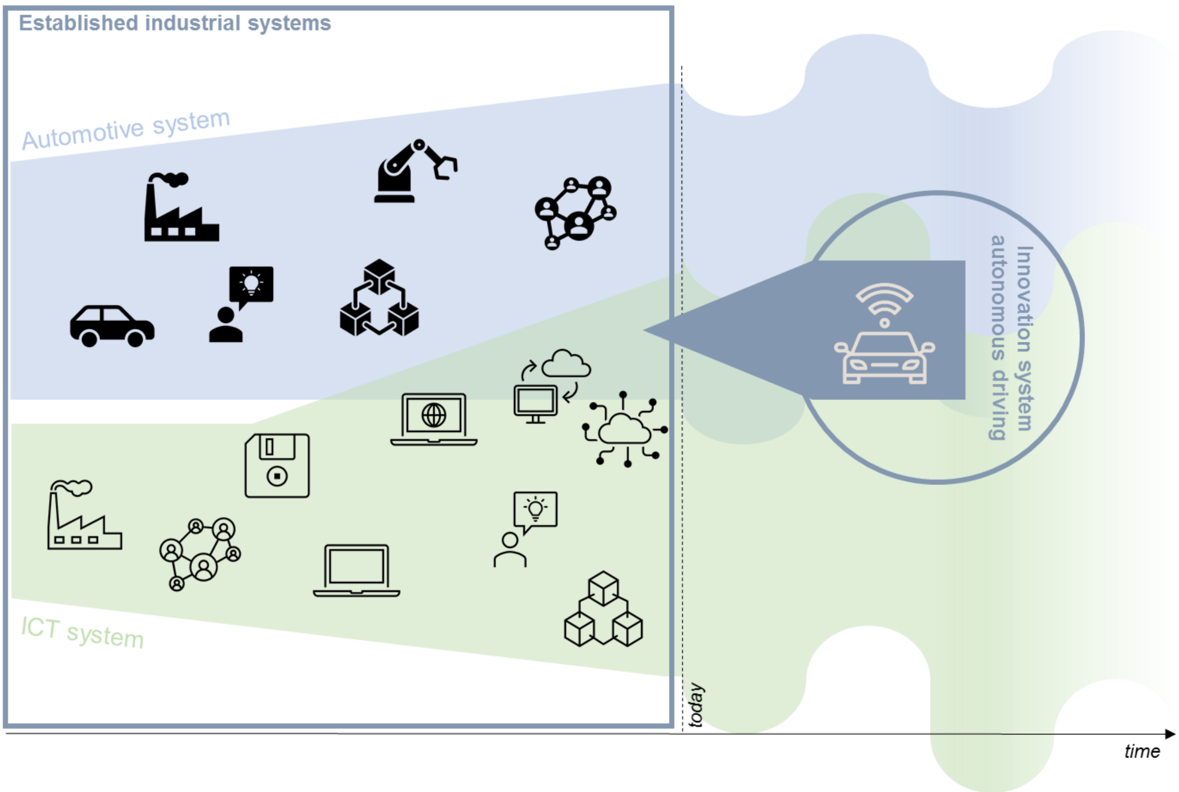
[2] Parts of the introduction have been published in Grimm and Walz 2024.

to overcome these obstacles. Innovation systems are delineated in different dimensions, along sectoral, national, regional or technological borders (Lundvall 1992; Carlsson et al. 2002; Malerba 2002; Hekkert et al. 2007). The different approaches have gained wide acceptance and numerous applications have been published. The topic of autonomous vehicles, to the best knowledge of the author, has not yet appeared in a comprehensive innovation system analysis, despite the analysis of the national innovation system of autonomous trucks in Sweden (Engholm et al. 2020).

The innovation system approach is based on an evolutionary understanding of technological development trajectories (Nelson 1994; Breschi and Malerba 1997) and follows the understanding of the co-evolution of industrial, institutional and societal structures as prominently addressed by Geels (2002) with the multi-level perspective (MLP). Innovation system research usually focuses on the innovation process, taking into account themes such as learning processes, institutions, market formation or legitimacy for the new solutions, thereby expanding the solely technological innovation dimension (Malerba 2002; Hekkert et al. 2007). The approaches thus have the potential to grasp the complex interrelations and implications that the development of autonomous vehicles induces and improve the understanding of the current processes in depth.

However, newly developed technologies do not only need to be developed but also, at some point, be produced on a large scale. In the case of autonomous vehicles, parts of the established vehicle production and distribution networks of the automotive industry need to be reconfigured and may be pressured by new market entrants. Even though autonomous vehicles are not yet produced for the public market, leaders in the innovation process are expected to be leaders in the future mobility market. The understanding of the innovation system of autonomous vehicles, which lies in the overlap between the participating automotive and ICT systems, thus plays a crucial role in order to assess potential future developments in the industrial structure of vehicle production (Figure 1).

Figure 1: Overview of the basic understanding of the automotive/ICT interplay



Source: Own representation

The question of future leadership and value chain configuration in the provision of autonomous mobility increases in complexity since not only the automotive industry itself, but also actors from the ICT and electronics[3] industry field engage in the field of autonomous vehicle technology development and start to position themselves as mobility providers (Alvarez León and Aoyama 2022). In the past, the automotive and ICT industries evolved separately and built their own distinct systems of production and innovation (Figure 1). Eventually the systems have become more and more intertwined. While in the beginning it might have been simple buyer-supplier relations that connected actors from the two systems, the automotive industry, like many other industries, increasingly based their operations on ICT solutions. In the course of the ongoing digitization, that integration has grown for both, operations and products. From telephone, internet communication and software solutions to automation of production steps, cloud services and digital interfaces and solutions in vehicles, the ICT industry has for long been both, operations enabler and component supplier to the automotive industry. In the case of autonomous vehicle development, that division of roles might change and will heavily influence the evolution of the two industrial systems. The two systems have been established over a long period of time and the established networks, operations and structures will probably influence the direction of change, the capabilities, and in a competing situation also the starting positions of actors regarding autonomous vehicle development.

The interplay between the automotive industry and the ICT industry is thus central to the future industrial landscape providing autonomous vehicles. On one hand, the sectoral background influences the participation in the innovation process of autonomous driving, on the other hand the future economic performance of certain countries such as Germany, depends on what role actors from the automotive and ICT industries will play in providing autonomous mobility. As autonomous vehicles may challenge the established automotive industry and present large business opportunities for newcomer firms, the technological development is also supported by governments through funding programs. The future implementation requires partly profound changes in traffic regulation and vehicle approval, thus the political body and governments are heavily involved in the current process. National or regional standard-setting and regulation may, in the case of autonomous vehicles, also function as a measure of innovation policy. Differences are observable between nations concerning the status of regulation, innovation policies, and industrial strategies.

In its simplest core, the future mobility market will be determined by a currently unknown supply of products and services and an unknown demand from customers. The demand side develops on the global level, different types of markets evolve and customers develop their preferences. On the supply side, the performance in the innovation process of the technology, the success in the development of suitable business models, the ability to offer products and services on a large scale and the meeting of demand are crucial. Not only industrial actors, but institutions, governments and societal factors play a role.

In the following, the relevant literature streams are reviewed for both parts of the thesis. Section 2.1 displays the literature relevant for the development of the conceptual approach in the integrated innovation system analysis. Literature on scenario-building and economic assessment and modelling is presented in section 2.2.

[3] ICT solutions mostly depend on the related hardware as e.g. chips, sensors or computers to be carried out. For reasons of simplicity and better readability in the paper, these hardware components are considered to be part of the "ICT systems", while it is acknowledged that in industrial classifications, the products would rather be assigned to the electronics industry.

2.1 Innovation system analysis[4]

2.1.1 Innovation systems

Different approaches to analyzing innovation systems exist. The selection on which to use is strongly connected to the research question in focus, while at the same time, the concepts partly overlap (Carlsson et al. 2002).

The national system of innovation (NSI) approach was introduced in early publications of the scholars Freeman, Nelson and Lundvall (Freeman 1988; Freeman 1995; Lundvall 1988, 1992; Nelson 1988). Their studies, as well as more recent contributions, use the concept of NSI in order to explicitly take into account the national characteristics of innovation systems. The focus often lies on the role of domestic institutions, such as universities or government bodies as well as their activities in the fields of research and development (R&D) and policies. Furthermore, other actors or organizations such as firms or individuals and the relation between all the components on the national level are included in the analysis. The approach is used, for instance, in the comparison of the performance of nations in a certain innovation field, such as photovoltaic (Vasseur et al. 2013). Due to its delineation along national borders and focus on the functioning of the system of a nation, application is also found in applied studies funded by national governments and institutions (Kuhlmann and Arnold 2001).

The sectoral perspective on innovation systems suggests that the characteristics of innovation processes are dependent on the features of the sector or industry in focus (Breschi and Malerba 1997; Malerba 2002; Malhotra et al. 2019). The conceptual framework of sectoral systems of innovation (SSI) systematizes the development of a sector in more depth (Malerba 2002). It defines the system components, namely products, agents, knowledge base, technologies, inputs, demands, institutions and various types of market and non-market interactions. “Sectoral systems may prove a useful tool in various respects: for a descriptive analysis of sectors, for a full understanding of their working, dynamics and transformation, for the identification of the factors affecting the performance and competitiveness of firms and countries and finally for the development of new public policy proposals” (Malerba 2002, p. 261). The approach has been used widely in order to analyze the development of sectoral systems such as the automotive industry (Ibusuki et al. 2020) and has been refined in different ways (Hansen et al. 2018). While the delineation of national systems of innovation along geographic borders can be considered straightforward, the delineation of sectoral systems lies, to some extent, in the hands of the applicants.

An early introduction to a concept of technological systems has been made by Carlsson and Stankiewicz (1991), who build on the understanding of technological change as a main driver for economic growth. A technological system does not necessarily follow national or sectoral boundaries but is defined as "a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology" (Carlsson and Stankiewicz 1991, p. 93).

Both, Hekkert et al. (2007) as well as Bergek et al. (2008) link the concept of innovation systems with a technological focus and introduce the well-established TIS framework. Hekkert et al. (2007) describe the innovation process as a combination of software, hardware and orgware. Their proposed TIS approach is meant to fill in on the shortcoming of traditional innovation system approaches

[4] Parts of the section have been published in Grimm and Walz 2024.

that focus on institutions on a macro level and leave the micro level of entrepreneurs rather unstudied. Instead of describing actors, they suggest the description of activities that result in the technological change under consideration. Using a functions approach enables applicants to trace the dynamic developments within a TIS and allows for the comparison of the functioning of different innovation systems. Bergek et al. (2008) point out that scientific studies on the functioning of innovation systems and their insights are partly hard to translate into practical guidelines. The authors thus propose a framework of analysis of technological innovation systems for policy makers. They argue that an applied approach to TIS and a clear operationalization of the functions in a TIS might also help to integrate quantitative analysis in order to explain the systems' functioning and to identify components and patterns. Furthermore it might help to conduct a linkage of conceptual ideas with indicators on the macro as well as the micro-level. The framework of TIS provides the tools to deepen the understanding of technological innovation processes, and in particular, to identify weaknesses in order to derive recommendation for action, e.g. for policy makers to support the development of a favorable technology. While the application itself is not limited to that notion (Köhler et al. 2020), the framework is very well established in the field of sustainability studies (Nevzorova 2022; Ulmanen and Bergek 2021; Kao et al. 2019).

The delineation of an innovation system can present a challenge and also plays a central role in the context of TIS. Hekkert et al. (2007) argue that a TIS overlaps with different national as well as sectoral innovation systems, which goes along the understanding of Carlsson and Stankiewicz (1991) of the spread of technological systems. Bergek et al. (2015) argue that activities and the interdependence within a TIS are well studied while the systematic delineation of a TIS can still be improved. Carlsson et al. (2002) mentioned a similar issue when studying technological systems. While concepts for systematic delineations, as introduced e.g. by Markard and Truffer (2008), might provide orientation, the definition of the TIS in focus remains a critical issue when applying the framework. Furthermore, it has been increasingly acknowledged that the functioning of a TIS may also be influenced by factors "outside" of a TIS (Bergek et al. 2015). The authors identify "different types of relevant interactions that cross TIS boundaries and can give rise to coupled dynamics between a TIS and various contextual structures" (Bergek et al. 2015, p. 53). They distinguish between external links, which mostly influence the TIS, not the other way around, and structural couplings. Contextual structures can be clustered into (1) surrounding and related TISs, thus TIS-TIS interactions, (2) pre-existing infrastructures describing the starting-point, which can be related to the regional or sectoral context, and (3) the resources by which the TIS is influenced while evolving, such as political support and financing opportunities.

The literature on innovation systems usually has a strong focus on analyzing and explaining historic or actual configurations and characteristics of systems as well as their development up to the present. The identified dynamics, malfunctions, opportunities and challenges are then transferred into recommendation for different actors in the system in order to improve the systems' functioning and efficiency. The three central concepts of innovation systems, namely NSI, SSI, and TIS have been shortly introduced above. It also has been stated that the different concepts of innovation systems partly overlap. Depending on the research question, the intensity and importance of an explicit consideration of the overlap may vary. Markard and Truffer (2008) integrate the perspectives of national, sectoral and technological systems and display how the concepts are strongly interlinked. Generally, they suggest that the process of defining the system of interest can follow two basic concepts: descriptive (which suits the purpose of the research question) or conceptual delineation (which suggests exogenous system borders that can be determined empirically).

2.1.2 System interaction

The discussion on the development and implementation of autonomous vehicles has been heated and in parts pins the innovative power to players from the ICT industry such as Google's daughter Waymo, due to their competencies in the field of digital solutions, such as data processing or artificial intelligence. Some have even built scenarios in which the automotive industry will lose their direct contact to the customers and downgrade to being hardware suppliers to the ICT-giants (Deloitte 2017). Other scenarios picture varying configurations of cooperation between different players along the value chain. In contrast, some studies show an increase in the number of cooperations and partnerships among firms in the field of autonomous vehicles and new mobility solutions (Hofstätter et al. 2020). The discussion shows that the types of interaction between different players are versatile. Furthermore, they can have a large influence on the innovation process and technologies itself, on the way the future mobility system will be configured and on the distribution of roles and success of the automotive and ICT industries. The relevance of system interactions for the transformation of systems has increasingly been acknowledged in the conceptual literature.

System interaction can be observed and is crucial in the reconfiguration of different infrastructure sectors (Hiteva and Watson 2019), the acceleration of sustainability transitions (Andersen and Geels 2023), but also with regard to the co-evolution of infrastructure and technology as in the case of electricity, transport, and heating-systems (Rosenbloom 2019). In addition, interconnections between sustainability transitions and industrial transformation that affect e.g. employment on different sectoral levels have been identified (Andersen et al. 2020). The authors describe the need of an integrated viewpoint with the explicit analysis of global value chains (GVC), such that the consideration of developments in one sector in relation to the upstream as well as downstream sectors is ensured. Interaction can take place on different levels or among different system components. While Rosenbloom (2019) focuses on actors, Malhotra et al. (2019) study inter-sectoral learning processes on the example of three clean energy technologies, since these help to understand the "dynamics of industry formation for emerging technologies" (Malhotra et al. 2019, p. 464). The authors suggest that a stronger integration of TIS approaches with concepts of SSI would be useful to understand developments. The call for expanded analyses that put a special focus on multi-system interactions has also been made by Rosenbloom (2020). The author argues that simplified typologies, e.g. the characterization by competition, symbiosis, integration and spill-over, as suggested by Raven and Verbong (2007), may provide a good starting point to grasp the inter-system dynamics. The aim of the analysis, however, should not only be to cluster or characterize the interactions but to study their complexity. Furthermore, a holistic viewpoint on system interaction should be taken, without limiting the perspective on e.g. regime-regime interactions between multiple systems. Most of the interactions "manifest most prominently among particular material and social elements (e.g., firms and industry associations) in specific contexts (e.g., markets and policy debate)" (Rosenbloom 2020, p. 338).

2.1.3 Structures, value chains and markets

As stated in the introductory paragraphs of the methodological approach and displayed in Figure 1, the further development of the automotive and ICT systems is dependent not only on the innovation systems' functioning but also on the established structures of the sectoral systems. One channel is the indirect influence on the future industrial and systemic configuration, meaning the sectoral context factors that influence the participation in the innovation systems. The other channel, referred to here, is the direct impact. Both the automotive and ICT system are long established and have built complex production networks around the globe. For the future mobility system, autonomous vehicle technology not only needs to function in prototypes but has to be produced on a large scale and requires smooth implementation and operation. The firms' backgrounds and the power distribution may influence what patterns and principles a newly established production will follow. The functioning and dynamics in production networks have been studied in the GVC literature (see e.g. Gandenberger et al. 2021 for an overview). The increasing international fragmentation of production processes in the second half of the 20th century has been reflected in the growing body of scientific literature in the field. In the beginning, researchers focused on "global commodity chains" (GCC) (Bair 2009; Gereffi and Korzeniewicz 1994). The term and perspective was soon replaced by the more comprehensive understanding and analysis of "global value chains" (Ponte et al. 2019; Gereffi et al. 2001), that still prevails. GVC are studied in different disciplines. For instance, the international economics literature studies the efficiency of the contractual organization of outsourcing and offshoring activities, as well as on geographical shifts in international trade. International business research focuses on the firm level and the identification of competitive advantages through GVC. The realization of these competitive advantages and the organization of actors along GVC is often linked to the study of governance structures in GVC (Gereffi et al. 2005). Besides GVC, the concept of "global production networks" (GPN) evolved, which claims to take a more systematic perspective and understands value creation as a network rather than a chain (Coe and Yeung 2015; Yeung and Coe 2015). Often, the term of GVC is used as a synonym for all three concepts.

Much research on the GVC of the automotive industry has been conducted with focus on the dynamics of upgrading and catching-up of less industrialized countries along the automotive value chain (Lu et al. 2015; Pavlínek and Zenka 2011; Wang and Kimble 2011; Humphrey and Memedovic 2003; Sturgeon and van Biesebroeck 2011; Humphrey and Memedovic 2003). Quantitative studies on trading patterns and relationships in automotive value chains use databases such as multi-regional input-output tables or trade statistics (Frigant and Zumpe 2017; Timmer et al. 2015). The literature on GVC does not show a lot of interfaces to other literature streams and can be considered rather homogeneous (Jurowetzki et al. 2018). With regard to innovation systems, some attempts have been made in order to combine the perspectives with the viewpoint of global value chains. Scholars thereby study, whether the participation in (automotive) value chains may positively affect the innovation systems of especially less industrialized countries (Swati Mehta 2021; Jurowetzki et al. 2018; Lema et al. 2018).

2.2 Scenarios and economic assessment

The introduction of new technologies, players or framework conditions is usually accompanied by high levels of uncertainty. In order to assess the possible outcomes of such developments, which are mostly dependent on the complex co-evolution of different factors, scenario methodologies are seen as a suitable tool (see e.g. Walz et al. 2019) to determine the range of possible outcomes. Scenarios are developed qualitatively, quantitatively or as a combination. The analysis can differ with regard to the studied time horizon, the complexity of the scenario definitions themselves as well as the assessment of the potential reaction of the economy to the scenarios. For instance, Sievers et al. (2019) analyze the employment effects of sustainable transport by translating qualitative narratives into quantitative scenarios by deriving assumptions on the development of indicators, such as investments in certain technologies, travelled kilometers or export numbers. The outcomes for the German economy are assessed through a modelling approach, where demand impulses are implemented in an input-output analysis.

The future of the automotive industry has been studied on a global, general level as well as for the German case. The overall trends of digitization, environmental concerns, trade policies, and their implications for the economic performance of the automotive industry – thus the firm perspective – have been analyzed in studies of the large consultancies and organizations (e.g. McKinsey & Company 2023, 2019b; Deloitte 2018, 2019b; pwc 2017-2018; European Climate Foundation 2018;

Alonso Raposo et al. 2018). These studies predict possible outcomes up to the year 2050, partly qualitatively in the form of chances and risks for the relevant players in the field, and partly quantitatively in the form of sales numbers, revenues or employment. The potential development paths, suggested by the authors give an impression of which components are influencing the overall development of the mobility market. They differ in their characteristics, combinations and exogenous developments such as global sales trends or the openness of the demand side to new services. At their core, they all describe and focus on the same area of tension around digital services. The quantitative estimates vary in magnitude, while the increasing importance of this field is obvious. The sets of scenarios and recommendations for action illustrate the uncertainties regarding the size of future markets and the division of revenues between automotive manufacturers and ICT players.

A lot of studies solely focus on the role of electrification. Within this research field, the market developments for electrified cars are predicted for different regions as well as globally (e.g. International Energy Agency 2018), socio-economic outcomes and governmental influences are estimated (Lutsey et al. 2018; European Climate Foundation 2018; Schade et al. 2012; Bauer et al. 2018) and recommendations are given on a firm or regional level (Bauer et al. 2015; UBS 2017). Due to the strong role of Germany in global automotive markets, several studies focus on developments from the German perspective (Schade et al. 2012; Bauer et al. 2018; DLR et al. 2019).

The studies mentioned above work with scenarios and forecasts or projections. They differ in the degree of detail in which the scenario-building process is described. Often, high and low ambition scenarios are used, in order to open up the widest plausible derivation in scenarios. Other scenarios are tied to certain assumptions such as the implemented policy measures, the velocity of a technology's diffusion or the adaptation rate of users (e.g. Alonso Raposo et al. 2018). The mentioned studies mostly aim at the derivation of the quantitative impacts that certain future development pathways may have on selected industries or sectors. In the following, literature on the methodology of scenario-building and macroeconomic modelling is reviewed.

2.2.1 Scenario-building

Scenario-building or development itself has evolved as a methodology in the field of foresight or future studies (Slaughter 2009). Besides the application in quantitative simulations, qualitative scenarios have been used in order to guide the assessment of potential future developments and to reduce uncertainty by providing a structured approach to the thinking about the future. Such prospective processes need to be distinguished from forecasting methods (Jouvenel 2000). First, they include several dimensions, second, they integrate the "long-term dimension, past and future", and lastly, prospective processes allow and explicitly consider breakdowns such as technological breakthroughs (Jouvenel 2000). There exist various techniques for developing scenarios, according to the context and problem that they are applied in (Bishop et al. 2007).

Scenario planning methods emerged in the corporate field with the aim to make better strategic decisions (e.g. Schoemaker 1995). Especially the company Shell is known for applying scenario planning methods (Wilkinson and Kupers 2013), that are now a common tool in corporate decision making processes. Also, scenario-building and planning has been increasingly used in policy-making, policy consultation and as a policy analysis tool (Moniz 2005; Volkery and Ribeiro 2009). Scenario-building is one step in a scenario planning process. A scenario planning process usually goes beyond deriving pictures of the future, but includes the development of strategies or the implementation of measures (Bishop et al. 2007).

Scenarios, which build the base for decision making, should meet the following requirements, according to the European Foresight Platform (2023):

1. Scenarios need to be plausible. That means, they should only include developments that lie within the scope of what seems plausible. Otherwise, implausible developments are assessed that are unlikely to provide useful insights on the future.
2. Scenarios need to be consistent. A formulated scenario should not contain any contradictions between the scenario-components and follow a sound logic or storyline.
3. Scenarios need to be useful in the decision-making process. This means that the scenarios should be built with focus on the in issue in question.

The building of plausible, consistent and useful scenarios departs from the definition of the problem under study, and proceeds with the identification of the driving factors and the study of the cross-influence of factors. The identification of factors is usually carried out in expert workshops, using interviews or other forms of collaboration. After the definition, data on the factors needs to be collected, hypothesis on the alternative development of factors need to be formulated and alternative developments of factors can be combined into scenarios. The further processing into decisions or strategies is left to the applicant. The insights thereby are not only drawn from the final scenarios, but especially from carrying out the process (Jouvenel 2000).

2.2.2 Model-based macroeconomic impact assessment

Macroeconomic effects from the diffusion of technologies on the overall economy have been prominently estimated in the context of sustainability transformations (Walz and Schleich 2009). Mostly, model-based macroeconomic impact assessments are applied to the ex-ante estimation of effects of the introduction of policies, technologies or more complex transformations on a national economy or geographical region (e.g. Sievers and Pfaff 2019, Weitzel et al. 2023). The macroeconomic effects from trends influencing the automotive industry have been studied in the context of the decarbonization of the transport sector. Especially the implications from the electrification of the powertrain have been assessed on the national and international level, using macroeconomic modelling (Lutsey et al. 2018; European Climate Foundation 2018; Schade et al. 2012; Bauer et al. 2018). Macroeconomic modeling of sustainability transformations shows that innovation is a key driver of the cost of the transformation and thus of the related economic development (Mercure et al. 2019). The authors thus argue that approaches in the field of sustainability transformations can be suitable for the evaluation of other innovation and structural changes, too. The potential long-term macroeconomic effects resulting from shifting competition in the automotive industry in the provision of autonomous vehicles have not yet been subject to a macroeconomic modelling exercise.

In the field of model-based macroeconomic impact assessments of sustainability measures, different types of models are applied. Modeling approaches can be distinguished by their underlying understanding of the economy (equilibrium/supply-led versus non-equilibrium/demand-led) (Mercure et al. 2019; West 1995) and by their perspective on technological effects on the economy and their level of detail in portraying these effects (top-down versus bottom-up) (Walz and Schleich 2009). It has been shown that the choice of modeling approach, which is usually based on principle differences regarding the applied economic theory, can considerably influence the scale of economic effects (e.g. Mercure et al. 2019; Pollitt et al. 2015). These differences are explained in more detail below.

Equilibrium or supply-led approaches follow a neoclassical economic school of thought (Mercure et al. 2019), where optimization models are used to estimate economic outcomes. The key assumptions are that prices clear markets and production factors are fully exploited to generate the supply that meets demand, resulting in a market equilibrium. The equilibrium is reached over time through agents that maximize utility. Thereby, rational decisions are assumed that also apply to investment decisions in a balanced capital market, which includes crowding-out effects. The volume of production is determined by the factors capital, labor and productivity. Thus, changes in the volume of production are driven by changes in these factors. The implementation of scenarios and reflection of the real-word effects are implemented as deviations from the former equilibrium and the optimization procedure, carried out in the model, yields a new equilibrium. Different types of supply-oriented optimization approaches to macroeconomic models exist, distinguished by their respective underlying assumptions (optimal growth, general equilibrium, partial equilibrium) (Mercure et al. 2019). The well-known computable general equilibrium (CGE) models belong to this group of modelling approaches (e.g. Standardi et al. 2023).

Non-equilibrium or demand-led approaches mostly follow a (post-)Schumpeterian or (post-) Keynesian understanding of the economy, which is considered to be in dynamic change (Mercure et al. 2019). This change can be induced by entrepreneurial activity and agents show heterogeneous behavior. Investments are not limited and crowding-out effects are not necessarily considered. Markets thus do not have to reach equilibrium and future development trajectories are simulated rather than optimized from different starting points. The comparison of different scenarios thus describes different trajectories and parallel evolutions without a normative component. Mercure et al. (2019) summarize the difference in the philosophy of non-equilibrium and equilibrium approaches as the following: non-equilibrium models provide a description of "what agents are observed to do", while equilibrium models provide recommendations by identifying the configurations or strategies that are best for the agents in the future. Non-equilibrium or demand-oriented simulation includes approaches such as macro-econometric, Systems Dynamics, agent-based or input-output models. Macro-econometric and input-output models usually consider static relations since they are calibrated on historical data (Walz and Schleich 2009). Input-output models use national input-output tables (IOT) provided by national statistical offices (Statistisches Bundesamt 2019b) as well as international data (e.g. Timmer et al. 2015; Stadler K. et al. 2018). They display the interconnection of industries by providing information on the intermediate inputs that are traded between the industries. The usage of input-output tables allows for the analysis of direct effects of changes in final demand in the directly affected industries, but also the assessment of indirect effects in the upstream industries that provide intermediate inputs (Leontief 1936). Effects can be measured in terms of gross value added (GVA) or employment. Input-output models are simulation models that project ex-ante the development of input-output tables and the respective changes in final demand. Endogenous effects from the changes in demand, such as shifts in competitiveness or changes in production factors are neglected in basic forms of input-output analysis.

Next to the economic school of thought, another distinguishing characteristic of modelling approaches is their perspective. In energy system modelling, but also in other contexts, effects can be estimated using a top-down or a bottom-up approach (Grauwe 2010; Walz and Schleich 2009; Böhringer and Rutherford 2008; Herbst et al. 2012). Top-down models choose an aggregated perspective of a regional or national economy and simulate effects based on economic growth, changes in prices or demographics (Herbst et al. 2012). Technological change is normally not considered. Bottom-up models, in contrast, explicitly estimate the effects of changing technologies. Thereby, they include the assessment of economic indicators such as investment or operation and maintenance cost of technologies but generally fall short on the estimation of the impact on the overall economy. Bottom-up models are considered to be especially advantageous for modelling the impact of technologies that have not yet been introduced (Walz and Schleich 2009). When studying the effects of (partly) technology-based transformations, non-equilibrium models are often combined with bottom-up technology- or sector-specific models (Hartwig et al. 2017; Doll et al. 2019; Sievers et al. 2023).

3 Conceptual approach

3.1 Research gap

The future role of the automotive industry in Germany, the entering of new players in emerging ICT branches of the wider automotive industry and the connected potential changes in industrial leadership can have huge implications for the performance of the German economy. Various trends influence the automotive industry and imply complex developments. A comprehensive understanding of the current and potential future state of the industry requires the conceptualization of industrial dynamics and a transfer into their probable evolutionary paths. In particular, it has to be taken into account that it is not only the development within one sectoral system which matters in this case; parts of the ICT industry and the automotive industry are moving closer together. The identification of the characteristics and dynamics of this convergence plays an essential role in assessing potential changes of the industrial structure in Germany.

The state of the art literature describes future as well as past developments in the automotive industry, suggests approaches to build an understanding of innovation systems and to conceptualize industry dynamics, and presents methods to assess the future implications through scenario techniques and simulation. Each of the literature groups has its distinct shortcomings, which can, however, be considered complementary. Studies on the trends in the automotive industry point out the whole system of potential interactions and structural change in the automotive industry but lack macroeconomic assessments or conceptual frameworks of analysis. Literature on systems of innovation presents approaches to gain a comprehensive understanding of innovation processes, allowing for different viewpoints such as the national, sectoral or technological. It deals with the underlying dynamics and presents concepts to structure and identify system drivers within one sector rather than analyze its inter-sectoral interfaces or interactions. Furthermore, innovation system approaches focus on explaining historic developments with only few attempts to draw conclusions on future evolution or to link observed relationships with a quantitative database. The role of system interaction is increasingly considered in the literature, but leaves room for further exploration. Global value chain studies use an economic database and conduct comprehensive and quantitative analyses of industrial linkages and developments but fall short on predictions or concepts to explain the drivers of identified changes. The literature on scenario-building and modelling shows that many studies approach estimations on future developments by using qualitative and quantitative scenarios. However, the role of ICT players in the automotive field and resulting economic impacts have hardly been assessed using a systematic scenario-building methodology and by considering market dynamics.

In consequence, two central research gaps arise that need to be filled in order to answer the research questions, posed in the introduction (chapter 1). First, there is the need to build a sound conceptual basis, which accounts for the interplay between sectors in the field of autonomous driving and the implications the interactions can have on the respective sectoral systems and their value chains. The gray literature on the future automotive industry includes thoughts on both sectors, but lacks a framework to conceptualize the described industry dynamics. In the literature on sectoral systems, sectoral differences in economic development, as e.g. differing innovation cycles are increasingly recognized (e.g. Malerba and Nelson, 2012) but their interplay is not yet analyzed for one industrial evolution, induced by a new technology. When new technologies are pursued by new actors in the economic structure, incumbent firms might have more time to adjust to the new technology. In the ongoing developments in the automotive industry, however, large firms of different sectors with a high amount of capital enter the development process. Partly, they invest more than the traditional automobile manufacturers, which makes them an even bigger and especially quickly evolving threat. This type of entering firms and its implication on the conceptual framework has not yet been studied in detail.

Second, there is the need to transfer the conceptual basis into a sound prospective approach of future scenario development. In addition to typical scenario approaches (development of storyline, interactive approaches), the scenarios need to be derived based on a sound conceptual basis, which accounts for the industrial dynamics' complexity. Furthermore, the scenarios need to be transformed into economic impulses so that they can be further analyzed with macroeconomic models with regard to employment and GDP. The gray literature on the future of the automotive industry rarely links its considerations on actual as well as future industry dynamics with macroeconomic numbers or provides concrete scenarios on a country level. Conceptual studies on innovation systems reveal valuable insights on drivers of industrial development in different competing countries. However, they generally look at historic examples for an ex-post identification of enabling factors for industrial change, rather than possible future outcomes. Additionally, they rarely express the links in economic terms. Input-output studies in the field are concrete in economic terms as in the development of export numbers or GDP but also rather display the development in the past than predict future structures and macroeconomic developments. When conducting macroeconomic modelling for the automotive industry, a more precise analysis on the relevant industrial sectors providing products or services in the field of digitized transport, besides the automotive industry, is needed in order to draw conclusions on the inter-industrial dynamics (see first attempts in Sievers et al., 2019).

3.2 Research design

The objective of the theses is to assess the potential role of the German automotive industry in the provision of future transportation, taking an evolutionary economic point of view, and to identify key chances and risks. Different concepts of innovation systems and the analysis of system interaction are used to study recent developments and to transfer the identified underlying business and economic dynamics into scenarios for the future. The conceptual analysis is paired with computational approaches from the field of input-output analysis to study global value chains in the automotive industries and to link the conceptual insights with quantitative evidence. A special interest lies in the tension between the manufacturing automotive industry, including its development towards system providers, and the potential new players entering the market by offering transport services. Finally, by using macroeconomic modelling, possible outcomes in a set of scenarios for the German automotive industry are estimated.

Figure 2 gives an schematic overview of the conceptual approach, chosen in the thesis. In the first part, an integrated innovation system analysis on autonomous driving, the automotive and ICT sectors and central countries aims at building an understanding of the current state of autonomous driving development. Identified key factors that influence value chain reconfiguration and affect the sectoral and national industrial landscape are used in the scenario-building process that leads to the second part of the thesis. Qualitative scenarios are developed for the German industry. These scenarios are translated into quantitative impulses and a macroeconomic simulation model is used in order to assess quantitatively possible implications for the German economy up to 2050. In the following, the conceptual approach and research desgin are described in more detail.

Figure 2: Schematic conceptual approach

Source: Own representation

3.2.1 Integrated innovation system analysis[5]

The aim of the first part of the thesis is to assess the current and future roles of the automotive and ICT systems in the provision of autonomous driving and draw conclusions on the potential configuration of the corresponding value chain. The analysis is based on the key assumption that there is a strong linkage between the participation of actors and systems in the innovation process of a product or service and the future role in the providing markets or value chains. The conceptual approach is required to match the characteristics of autonomous driving development by

- offering a broad and systematic understanding of the current innovation process and the engaging sectors,
- taking a broader point of view than just the industrial perspective and including e.g. political and societal elements,
- explicitly accounting for the interfaces and interactions between automotive and ICT sectors in developing and providing autonomous driving,
- assessing pursued business models and shifts in value chain configurations.

It is widely acknowledged by scholars that technological innovation has the potential to initiate a co-evolution of industrial structure as well as of the institutional environment (e.g. Dosi 1982, Nelson 1994, Geels 2002). In its core, the research approach is built around a basic evolutionary understanding of the transformation of the automotive industry due to an ongoing technological innovation process. The conceptual approach departs from an innovation system perspective on the development of autonomous vehicle technology and its implementation.

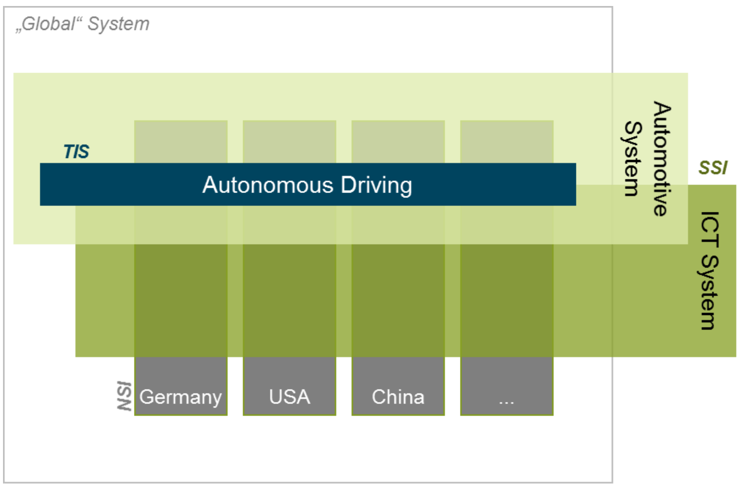
Looking at the case of autonomous driving, research and development (R&D) is carried out in many different locations around the globe, partly in different intensities. Furthermore, not only players from the automotive but also from other sectoral origins, especially from the ICT sector, conduct R&D on autonomous driving. Thus, there are all three, a national, a sectoral as well as a technological dimension to the topic. In turn, depending on the focus of the (sub-) research questions one could consider all the concepts of innovation systems suitable in order to conduct an analysis. In the following, central arguments for the suitability of each of the different concepts to the research topic autonomous driving are listed:

[5] Parts of the section have been published in Grimm and Walz 2024.

- National system of innovation
  - national environment can relate to e.g. differing culture, financing options or structure of the workforce, that in turn can influence the development of ideas and firms
  - national regulation plays an important role in terms of testing fields for autonomous driving, so do national funding and innovation fostering programs
  - interest in comparing different national systems and their performance in R&D processes
  - national governments are interested in the support of domestic players from industry or research, thus policy recommendation from the national point of view valuable
- Sectoral system of innovation
  - sectoral perspective does not consider national borders which suits global networks in both, the automotive as well as ICT sector
  - potential differences in the approach of players to develop autonomous driving, based on their individual sectoral backgrounds, which makes a comparison interesting
  - sectoral perspective puts a special focus on the industrial system
- Technological innovation system
  - technological perspective suits the topic of digitized mobility, especially autonomous driving, as a complex technology
  - focus on the technology helps to draw boundaries to other technologies the sectors provide and to build a targeted analysis
  - analysis along the TIS functions accounts for dynamics in the field

In case of autonomous driving, the relevant innovation system is considered to be in the overlap of the three perspectives (Figure 3). Due to the strong integration in global networks and complex entanglements of automotive and ICT firms with their international subsidiaries, partners and suppliers, a purely national perspective seems inappropriate. A sole focus on the sectoral systems of automotive and ICT sectors does not suit the strong technology-related focus and provides a rather static description of the existing system components. Lastly, a strict focus on the technological innovation system might neglect relevant national as well as sectoral characteristics. In order to study the transformation of the of the industrial landscape providing autonomous driving, approaches from the different concepts of innovation systems have to be combined while restricting the degree of complexity and keeping the feasibility in mind.

Figure 3: Mapping of the relevant systems and approaches

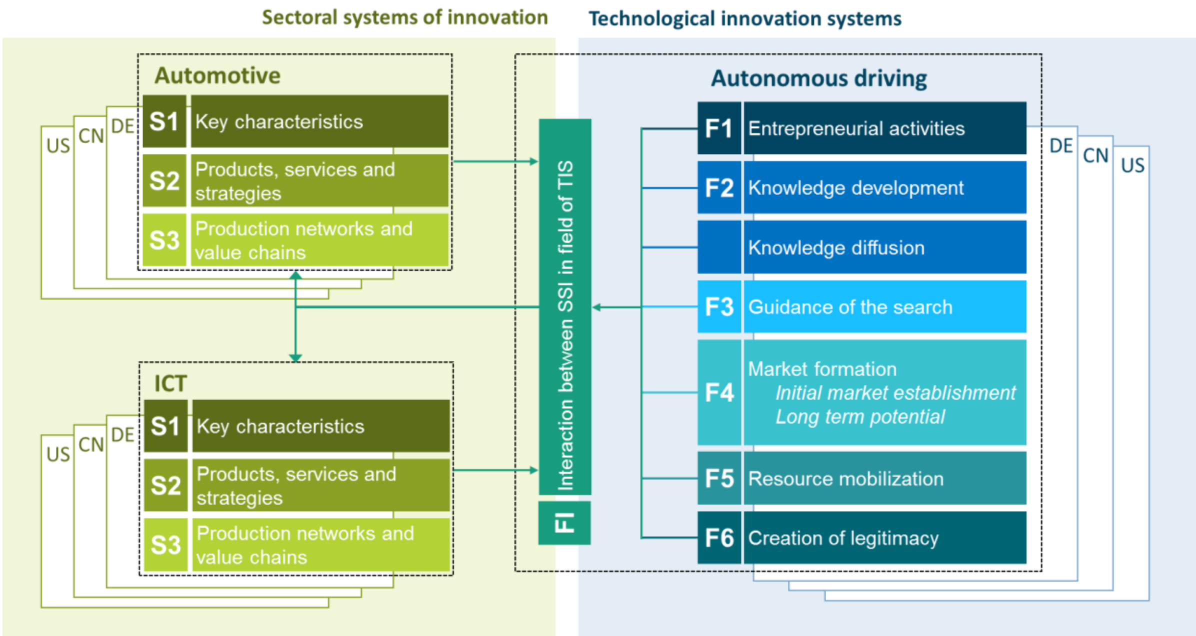


Source: Own representation following Markard and Truffer (2008)

Within the thesis, the development of autonomous vehicles is understood as a technological innovation system with actors and other system components from different sectoral as well as national origins. One central hypothesis is that the sectoral systems' configurations as well as differing national contexts will have an influence on how the actors participate in the innovation system, which is of utmost interest in the field of autonomous driving. The relevance or existence of the influence of the context factors on concepts such as TIS has been stated and analyzed (Ulmanen and Bergek 2021; Nevzorova 2022). Following the argument of influencing context factors, in the following analysis, the national as well as sectoral dimensions are considered as such context factors.

The functions of a TIS were initially chosen in order to organize the collection of information. Within the proposed functions of Hekkert et al. (2007) (entrepreneurial activities, knowledge development, knowledge diffusion in and through networks, guidance of the search, market formation, resources mobilization, and creation of legitimacy) it was explicitly accounted for sectoral and national specifics by choosing indicators that allowed for a distinct analysis along sectoral and national borders. Despite accounting for contextual factors, it was concluded that the gathered information was not sufficient in order to fully grasp the dynamics of system change in context of the development and implementation of autonomous vehicles. Thus, the conceptual approach was altered and an integrated functional innovation system approach was developed. An overview of the considered aspects is displayed in Figure 4.

Figure 4: Overview of analyzed sectoral aspects and adapted functions of innovation system



Source: Own representation, published in Grimm and Walz (2024)

First of all, a distinct analysis of the automotive and ICT sectors is conducted (green boxes on the left in Figure 4). The sectoral context is important in order to understand the participation of actors in the innovation process, and it is even more crucial when assessing future value chain configuration. The ability to produce and offer services on a large scale may rely on existing production capacities, production networks and industrial structures. The analysis of already established know-how and production systems of the participating automotive and ICT sectors on the one hand and current dynamics and activities in the innovation process of autonomous vehicles and related services on the other hand may indicate potential pathways.

The sectoral context is understood as information on the actors, networks, institutions and typical patterns. The sectoral analysis covers three fields, that are derived from the building blocks of a SSI as proposed by Malerba (2002) (see left side of Figure 4). One analysis each is conducted for the automotive (section 4.1) and the ICT sector (section 4.2) in chapter 4. The first sections of the sectoral analyses (sections 4.1.1 and 4.2.1 cover the key characteristics (S1). A basic understanding of the sectoral systems, including the display of key figures, and the delineation for further analysis is built. The second sections (4.1.2 and 4.2.2) describe examples from the industries on typical products, established and emerging services and firm strategies (S2). The third sections (4.1.3 and 4.2.3) map the principles of the industries' production networks and conduct an analysis of the international structure of the manufacturing industries and their inputs on a quantitative basis (S3).

Ensuing the prepended sectoral analysis, a functional analysis of the innovation system of autonomous driving is conducted in chapter 5. The analysis is based on an altered set of the TIS functions to match the research subject (blue boxes on the right of Figure 4). The functions of knowledge development and knowledge diffusion are integrated. Through the preliminary analysis of the case of autonomous vehicles, strong interactions between the two functions were identified. Especially the industrial R&D strategies contain e.g. investment in knowhow and mergers with and acquisitions of other firms, which can be considered as a way of generation knowledge for firms but also a path of knowledge diffusion in the network.

Throughout the analysis of the functions, it is explicitly assessed what roles the actors, networks or institutions from the automotive and the ICT sector take on. The focus lies on identifying similarities and differences. In the functional as well as in the sectoral analysis, a mixed methods approach is chosen that combines quantitative data and methods with qualitative literature reviews and the evaluation of other text types. The selection of indicators is based on the suggestions in the literature (Hekkert et al. 2007; Bergek et al. 2008; Vasseur et al. 2013; deGrazia et al. 2019; Dziallas and Blind 2019; Grupp 1994). The used data and methods are indicated and described within the sections. Table 1 provides an overview of the used methods and data. The table contains information on the data sources and a short description of their application, and indicates in which function the data is used. For instance, descriptive data from employment statistics or company databases was used. A patent analysis on patent applications in the field of autonomous driving was conducted. Furthermore, the international entanglements of the automotive and ICT value chains were assessed based on a multi-regional input-output database. Literature reviews from scientific sources were made for instance with regard to the acceptance of autonomous driving. In many cases, other sources such as company websites, government publications, websites, press articles as well as non-scientific studies were used. The last column indicates, in which part of the integrated innovation system analysis the data and methods are used (see Figure 4 for explanation of the abbreviations).

The usage of gray literature and web-sources is needed in order to provide up-to-date information on the development process of autonomous driving. However, the development of autonomous driving is currently very dynamic. Regularly, new partnerships are announced, established cooperations are terminated and individual business strategies change. Since the analysis was conducted in the beginning of 2022, some exemplary information may be already outdated. To the best knowledge of the authors, only a small number of examples is affected. The observed, overall tendencies in the positioning of actors and restructuring of value chains and the progress in the development of autonomous driving hold nevertheless.

Table 1: Overview of used methods and data sources

Method	Data source	Description	Utilization
MRIO - analysis	WIOD database (Timmer et al. 2015)	Calculation of regional origins of intermediates into the motor vehicle and ICT industries	S3
Patent analysis	PATSTAT	Autonomous and assisted driving technology patents (see Sievers and Grimm (2022)), 2005 - 2018 at EPO Considered patent classes: components for recording the vehicle environment, data processing and analysis, and decision-making mechanisms, vehicle handling, e.g. control of automated driving maneuvers, communication technologies for data transmission, networking and cooperation between vehicles, and intelligent traffic systems and infrastructures Requirement: titles or abstracts contain the words car/vehicle/driving in combination with autonomous/V2X/connected or surrounding/environment/assist* Final database: 14.025 patents, published 2005-2018.	F1, F2
Bibliometric analysis	SCOPUS	Search for publication that include the keywords vehicle-to-vehicle, or autonomous/self-driving/driverless (driving)/vehicle/car/automobile and exclude publications on underwater/marine/railway vehicles Final database: 9.656 publications, published 2005-2021.	F2
Literature review	Scientific journals	Papers on specifics of the autonomous driving innovation system (functions), sectoral activities and principles, geographical spread	All functions (F2, F4, F6)
	Company websites, press releases	Relevant industrial players from automotive and ICT sectors (e.g. Table A 1)	All functions (F2, F4)
	Gray literature	Studies by think tanks, applied research institutes, consultancies, unions, associations	All functions
	Newspaper articles and journals	Information on current activities of players from automotive and ICT sectors, activities in different countries	All functions
	Government and legal documents	Regulation of autonomous vehicles and its implementation	F3
Additional methods	Transport and automotive market data; ICT market data	Market size of automotive manufacturing, global production, car sales etc.; ICT spending, new market potentials, startup funding	S1, S2
	Company database (Crunchbase 2022)	Identification of companies active in field of autonomous vehicles, all registered foundations until 2021	F1, F5
	Disengagement reports California (California DMV 2022)	Information on disengagement of autonomous systems in test drives by all operators, testing autonomous vehicles in California	F3
	OECD employment data, ILOSTAT (OECD 2022; ILOSTAT 2022b)	Graduates by field, employment by economic activity	F5

Source: Own representation, published in Grimm and Walz (2024)

The sectoral and functional innovation system analysis enlarges the understanding of the current state of the innovation system or systems related to autonomous driving. However, it does not sufficiently allow for a translation of the findings towards the impact the innovation might have on the transformation of the mobility value chain. The reconfiguration of the value chain materializes through activities of and elements such as actors, institutions, or business models that actually form that value chain and which, in this case, originate from the automotive and ICT sectoral systems. In the literature, it is stated that the interaction of systems' components can be considered a source of change (Hiteva and Watson 2019) and system interactions may impact the dynamics of transformation and transition pathways (Moallemi and Malekpour 2018; Breitschopf et al. 2023). Alvarez León and Aoyama (2022) suggest the process of market capture to be a dynamic process or interaction between actors from the automotive and ICT industries that shapes industrial dynamics. The interaction of the automotive and ICT industries within the development of autonomous driving is thus understood as the determining dynamic that may shape the implementation of the technology and thus the transformation of the value chain. Therefore, an additional function of "sectoral interaction" (FI) was included in the analysis that leaves room for a cross-functional analysis of relevant sectoral interactions (see center of Figure 4). The interactions in focus here are the ones that take place between elements of the automotive and ICT systems and are referred to as sectoral interactions. The analysis of interactions is described in section 6.1 and builds on the insights from the functional analysis in chapter 5. Following the argument of Rosenbloom (2020), the goal was not so much to identify and classify all sectoral interactions but rather to study the interactions that are relevant with regard to the assessment of industrial dynamics. The analysis of interactions follows the framework of Breitschopf et al. (2023) and builds on their case study on the automotive and ICT systems.

The analysis of the innovation system of autonomous driving within the thesis thus integrates three parts: the sectoral system analysis of the automotive and ICT sectoral systems, the functional innovation system analysis of autonomous driving, including the consideration of sectoral and national contextual factors, and the analysis of sectoral interactions. The approach is referred to as an integrated innovation system analysis.

3.2.2 Scenario-building approach

The insights from the integrated innovation system analysis in chapters 4-6 are transferred into the building of scenarios for the German industry in chapter 7, as indicated in Figure 2. The scenario-building process follows the fundamental steps as described by Jouvenel (2000) (see section 2.2.1 for a description of the scenario-building procedure). First, the objective and setting of the scenario-building process is defined (section 7.1). Second, the driving factors for future development are identified, described and their interrelations are studied (section 7.2). At this point, no new data on the factors is collected. The driving factors and their potential alternative developments are drawn from the innovation system analysis in sections 4-6, which provides a lot of information and data on the various aspects. After the list of central driving factors is set, the alternative developments per factor are combined into scenarios (see Bertelsmann Stiftung (2016) for an example) (section 7.3). The explicit quantification of the scenario characteristics is carried out in section 8, which also includes the discussion of the scenarios' implications.

The applied procedure slightly differs from a 'classic' scenario process in two ways. First, the scenario-building process is heavily intertwined with the preceding integrated innovation systems analysis. Scenario-building or prospective borrows "heavily from systems analysis" and "invites us to consider phenomena on the basis of a study of all the factors and their interrelations" (Jouvenel 2000, p. 42). The three different perspectives in the integrated innovation system analysis systemically described the phenomena of autonomous driving and its industrial implications and are considered to have built a sound basis for the scenario development process: The sectoral innovation system analysis described the automotive and ICT sectors and the key characteristics of the industries' functioning. The functional innovation system analysis provided insights on the status quo of autonomous driving and allowed for the derivation of the factors that are responsible for the success of the technological development and of the factors that drive the division of the markets between the automotive and ICT industries. The analysis of the interactions between the systems displayed how the engagement and strategies of one sectoral system might affect the other system and what types of relationships could prevail. The factors for the scenarios are thus drawn from the results of the integrated innovation system analysis. Such an approach entails the risk of subjectivity of the results. This risk is met in two ways. The interrelations between the factors has been studied extensively through an interrelation-matrix and by developing a causal-loop-diagram (CLD). An iterative process between the derivation of the list of factors, the definition of the interrelation-matrix and the development of the CLD has been carried out that yielded several rounds of adaptation in all three documents. Furthermore, the final list of factors and scenarios has been discussed in three focused discussions with experts from the transport, industrial innovation and industrial dynamics and macroeconomic impact-assessment fields (see Annex Table A 2 for details on experts and their expertise).

The second deviation from most existing scenarios lies is the definition of two levels of scenarios that are combined. The identified factors in section 7.2 can be divided into two groups: factors that determine the engagement of the German industry and factors that describe the overall market development in terms of the diffusion of the technology and global economic relations, which lie beyond the influence of individual industry players. The development of market framework factors might in some cases heavily influence the outcome of the scenario. At the same time, varying both, market framework factors and industry engagement factors between two scenarios would complicate the tracing of the influence. Therefore, two scenarios on the market framework conditions are built from the sub-group of factors by combining their alternative developments. Furthermore, two scenarios on the engagement of the German industry are developed, based on the other sub-group of factors. The cross combination of the two sets of two scenarios each then yields four scenarios in total.

The scenarios explore potential combinations of alternative developments. The following step in the thesis aims at the assessment of the implications that the scenarios may present for the German economy. Therefore, in section 8 (see Figure 2) the key characteristics of the derived scenarios are quantified and a simulation of the related economic developments and effects is conducted. The methodological approach is outlined in the following section.

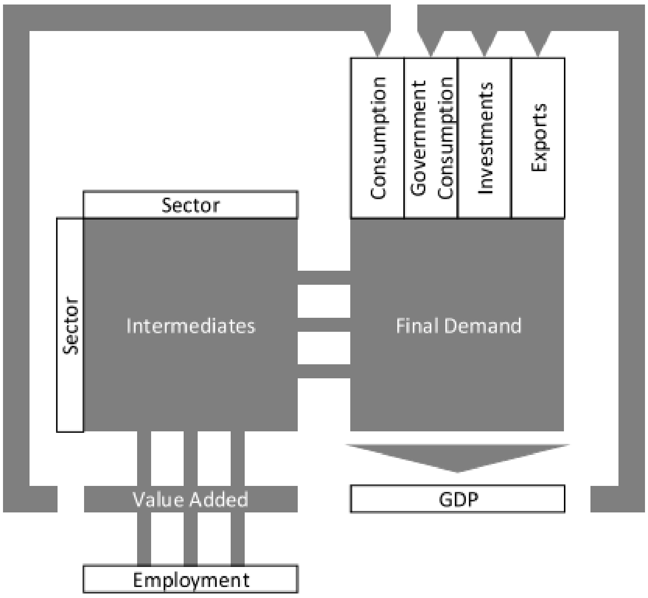
3.2.3 Model-based macroeconomic simulation

Autonomous driving can be considered a disruptive technology that has the potential to change the industrial landscape that provides street-bound mobility, including the automotive industry itself as well the demand for mobility and suitable business models. The established automotive industry in Germany has played and is still playing a major role in the domestic economy since it contributes a large fraction of GDP and employment. Next to the value added and employment generated by the German automotive industry itself, the industry is also responsible for the demand of intermediate inputs from other industries and additional economic activity in Germany. According to calculations of the federal statistical office of Germany, around 1.75 million employees in Germany were connected to the automotive industry in 2016, while only 880 000 worked in the automotive industry itself (Statistisches Bundesamt 2019a). The success of the German automotive industry is a fundamental building block to prosperity and available income in Germany.

Thus, the model-based macroeconomic assessment approach should explicitly consider the introduction of the new autonomous driving technology, account for the directly and indirectly affected industrial branches in Germany, and consider the implications of the industry being a major determinant of German income flows. As outlined in section 2.2.2, bottom-up approaches are suitable to map the introduction of new technologies over time. In order to assess the economic implications on the aggregate level, a combination with a macro-economic model is needed. This approach is common in macroeconomic impact assessments (see section 2.2.2). While usually technology- or sector-specific models provide the bottom-up impulses to the macroeconomic modelling, within the thesis the bottom-up impulses are estimated based on the scenarios described in the previous section and developed in chapter 7. The scenarios themselves result from the integrated innovation system analysis. The macroeconomic modelling approach should therefore reflect the evolutionary understanding of the innovation process. Mercure et al. (2019) suggest that evolutionary economics, transitions theory and technology innovation systems are clustered into the post-Schumpeterian school of thought, which follows a non-equilibrium or demand-led understanding of the economy. Therefore, a demand-led modelling approach is considered suitable.

The macroeconomic analysis is carried out using ISI-Macro (Sievers and Pfaff 2019), a dynamic macroeconomic simulation model implemented in System Dynamics that is designed to evaluate mid- and long-term effects of technology deployment scenarios. "The main focus of ISI-Macro is to determine high resolution sectoral impact in the economy arising from demand-side changes" (Sievers and Pfaff 2019, p. 3). Figure 5 provides a reduced illustration of the model ISI-Macro. The model is built around a macroeconomic core containing IOT (see gray box "Intermediates" in Figure 5 on the left) at a high resolution (72 sectors) (Statistisches Bundesamt 2022) and allows for projections until 2050. The input-output core of the model allows for the consideration of both, direct and indirect effects and is hence suited to assess the economic effects through the automotive industry's interconnections in the German economy.

Figure 5: Illustration of ISI-Macro



Source: Sievers and Pfaff (2019)

Within the model, final demand is calculated endogenously, driving sectoral production, which then determines the different components of Gross Value Added (GVA), namely wages, taxes, profits and write-offs and allows for the calculation of the Gross Domestic Product (GDP). ISI-Macro is a partly closed model, meaning that the listed components of GVA drive domestic demand, thereby closing the income cycle. Wages determine the private consumption, taxes influence the state budget, which in turn affects government consumption and private investment. Profits drive corporate investments in the economy. Sectoral production also determines the labor demand. ISI-Macro thus goes beyond open input-output analysis and especially the endogenous calculation of the consumption budget is therefore suitable to consider the role of the automotive industry to German income flows.

Several exogenous projections are used in order to determine long-term developments in the model. Domestic economic growth and labor productivity are implemented following the published economic framework data by Mendelevitch et al. (2022). The exogenously set development of labor productivity allows to meet labor demand according to the projected economic growth, despite demographic change. Projections on economic growth in OECD countries and China are used to update future development of exports (OECD 2021). Other parameters such as the import shares per sector or the intermediate input structure are held constant according to the embedded IOT of 2019.

In the application of ISI-Macro, scenarios are simulated by defining economic impulses per sector and final demand category (consumption, government consumption, investments, and exports). The implemented impulses represent shifts in final demand and directly influence the production of the selected sectors. Using the information on economic interconnections, given in the IOT, indirect effects in sectors that supply intermediate products to the directly affected sectors are assessed, too. Furthermore, induced effects are covered through the closing of the model, which is described above.

Within the thesis, the scenario characteristics, derived in chapter 7, are translated into final demand impulses, namely changes in consumption, investments and exports in section 8.1. The impulses are designed to only display the amount of production or service generation that is carried out in Germany. The model is hence adapted such that the impulses directly affect the domestic production while not considering potential changes in foreign production. The origins of intermediates that are used in the production of the given products are then considered according to the intermediate input structure given in the IOT.

Macroeconomic simulation in ISI-Macro allows for the assessment of direct, indirect and induced economic effects that result from changes in final demand. Its strength lies in the fine granularity of displayed sectors, which allows for a detailed analysis of structural changes. On the other hand, ISI-Macro is characterized by a focus on the demand side, since production factors are not limited. Price effects can only roughly be estimated and the substitution of products is not modelled endogenously. Furthermore, the focus on the domestic production does not allow for a detailed assessment of foreign trade relations.

ISI-Macro is, however, well suited to assess the potential economic implications that result from the developed scenarios. In a country like Germany, where the automotive industry is one of the large drivers of economic prosperity, the calculation not only of direct and indirect, but also of induced effects is crucial. The economic implications of the transformation of the industry do not only arise from the production of automotive products and its intermediates, but also from the general level of economic activity in Germany. Furthermore, the sectoral granularity allows for the differentiated perspective of classic automotive products and new components for autonomous driving.

4 The automotive and ICT sectoral systems[6]

The thesis concentrates on the interplay between the automotive and ICT sectors in the field of autonomous driving. As described in chapter 3, the sectoral context is considered a key determinant of actor participation and dynamics in the innovation system of autonomous driving. The following paragraphs in chapter 4 provide information and data on the actors, networks, institutions and typical patterns of the two sectors in focus.

In context of the systemic viewpoint that is taken in the thesis, the definition of Andersen et al. (2020) of a (focal) sector is followed: "A sector is a socio-technical system consisting of actors, institutions and technologies that generates a specific set of products (e.g. chemicals, cars or electronics) or services (e.g. energy supply or transportation) (Geels 2004). A sector may use several key technologies. A 'focal sector' is a sector in a state of transition. Sector boundaries correspond to substantial differences in the core competences (e.g. in engineering, electronics, or chemistry) needed to deliver the product or service." (Andersen et al. 2020, p. 348). In contrast, the term "industry" is used when referring to the industrial (sub-)systems, thus the firms that form the industry branch and produce the industries goods or provide services.

Sections 4.1 and 4.2 cover the automotive and ICT sector, respectively and are structured along three fields that are considered relevant to build the base for assessing the sectoral context in the analysis of the innovation system of autonomous driving in chapter 5. First of all, the key characteristics of each sector are presented which provide a basic understanding of the considered sectors for the following analysis. Furthermore, the systemic perspective on the sectoral components is introduced. Second, the section products, services and strategies covers examples from the industries on typical products as well as emerging services and gives further insights in related strategies. Third, the principles of the industries' production networks are described. The rather conceptual categorization is complemented by a quantitative analysis of the international structure of the manufacturing industries and their inputs.

4.1 The automotive sectoral system

4.1.1 Key characteristics

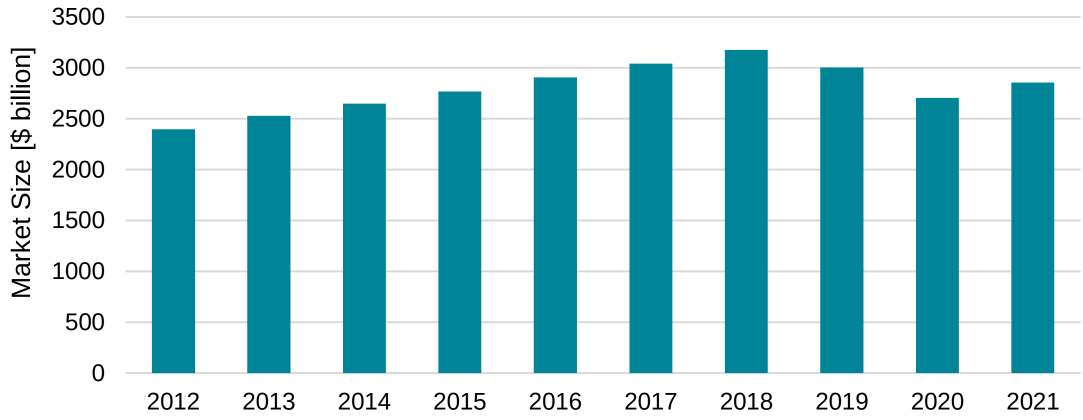
The automotive sector's roots lie in the invention and development of motorized vehicles. Nowadays, the automotive sector provides a large variety of passenger cars and larger vehicles as well as vehicles for freight transport and other special purposes. Besides the development and production of vehicles, other revenue streams are generated such as aftersales services (e.g. maintenance) or financial services (e.g. leasing contracts). Finally, most of the products and services serve the function to flexibly transport people or freight from one place to another using roads.

The automotive industry is one of the largest industries on a global scale. Based on the annual Forbes Global 2000 list and measured in sales of 2019, the automotive industry ranked fifth behind oil and gas, technology and communication, banking, and retailing (GlobalData 2019). Currently (2022), more than eight million people are directly employed in the automotive industry (IBISWorld 2022b), while many more are indirectly linked to the production of vehicles when working in one of the many supplier industries.

[6] Parts of the chapter have been published in Grimm and Walz 2024.

Figure 6 shows the development of the global automotive market size for the time period from 2012 - 2021. After global markets were characterized by steady growth after the 08/09 financial and economic crisis, (temporary) saturation might have been reached in 2018 at above 3 trillion $. The automotive market size shrunk in 2019 and even more in 2020 due to the COVID-19 pandemic. The year of 2021 shows signs of recovery, however, production has not yet reached pre-crisis value. The collapse of global value chains, semiconductor shortages as well as other resource deficits still slow down production and sales.

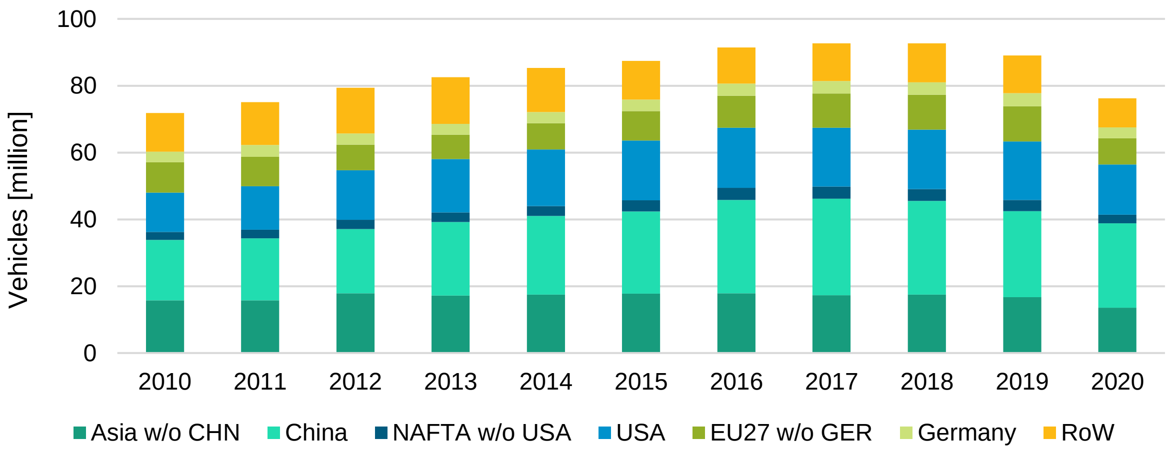
Figure 6: Market size of global car and automobile manufacturing (2021-2021)



Source: Own representation based on IBISWorld (2022a)

The trend in market size, measured in US $, matches the overall development of sales of passenger cars (Figure 7). However, sales of passenger car units grew only by 17% between 2012 and peak in 2018, while market size increased by 33% in the same period. The increase in global passenger car sales was to a large amount driven by the strong growth in the Chinese market of + 46%. While in 2012, China accounted for 52% of 56 million cars sold in Asia, in 2018 China accounted for 62% of 73 million car sales in all of Asia and overcompensated the decline of -2% in absolute car sales in other Asian countries. Between 2012 and 2018, European and NAFTA car sales increased as well, by 37% and 26%, respectively. The established automotive markets Germany (+12%) and USA (+20%) showed smaller growth.

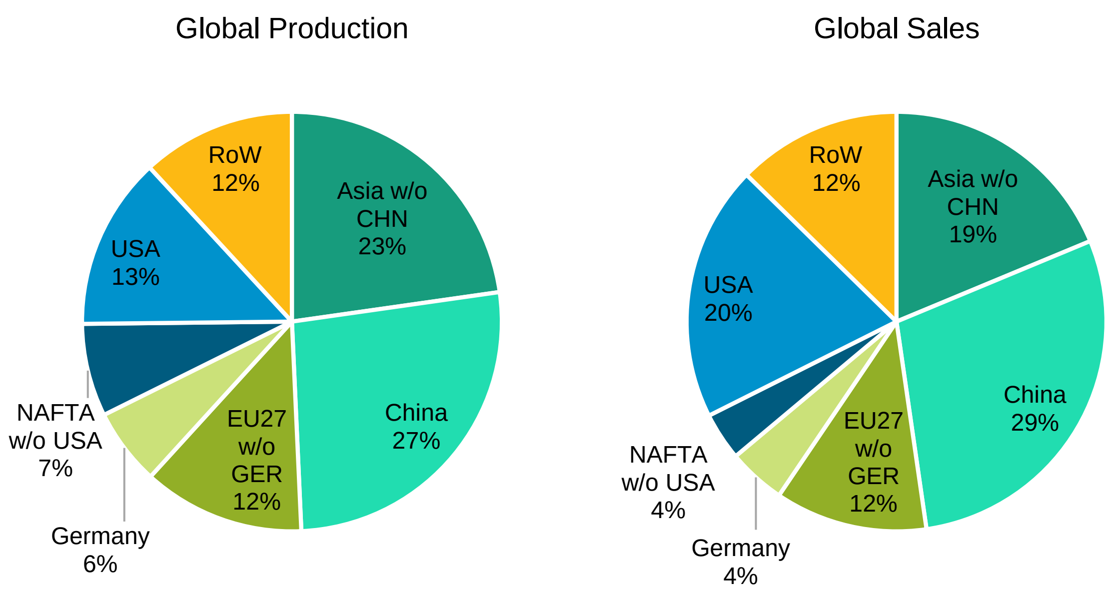
Figure 7: Global passenger car sales by region (2012-2020)



Source: Own representation based on ISI-Database

In the past 10 years Asia has been the largest single market for passenger cars, accounting for 48% of global passenger car sales in 2019 (Figure 7, or Figure 8 (right)). At the same time, Asia also hosted the largest car production in 2019, with even 50% of global production (Figure 8 (left)). Next to China that accounted for 27% of global car production alone, Japan, India and South Korea were large contributors in Asia. The NAFTA region is the second largest automotive manufacturing region, producing 20% of worldwide cars, followed by the European Union with 18%. The three regions cover 78% of both, global car production as well as global car sales.

Figure 8: Regional shares in global production and sales of passenger cars 2019[7]



Sources: Own representation based on ISI-Database (sales) and VDA (2022) (production)

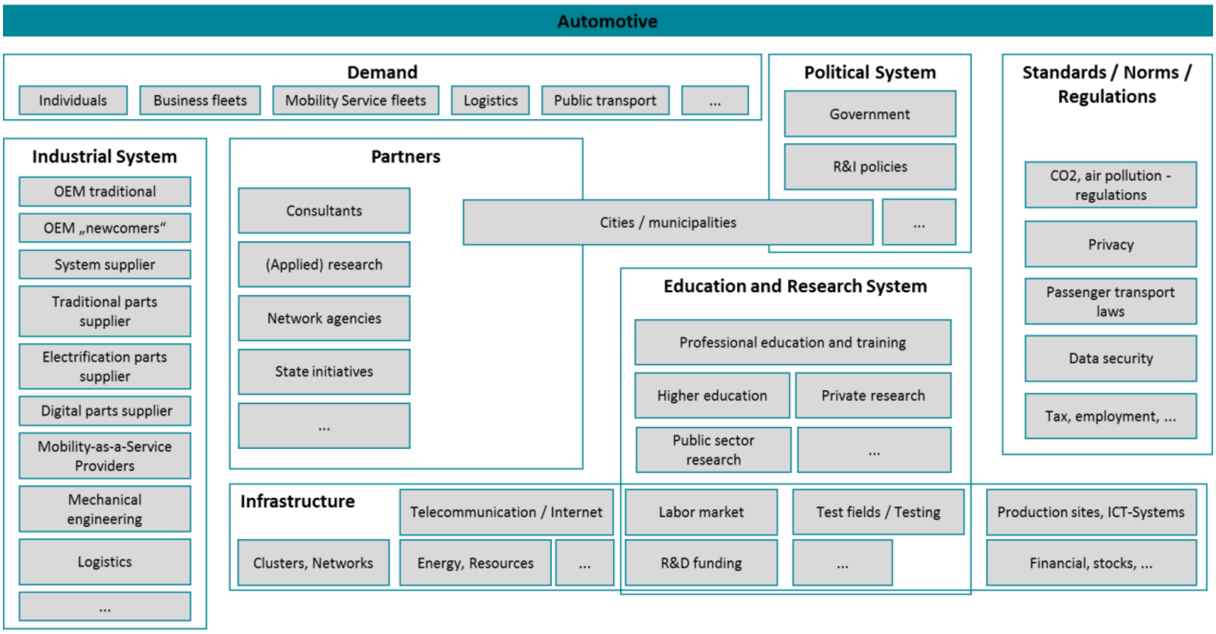
The location of production and sales does not necessarily match the origin of the vehicle brand. Car production is both, exported and imported as well as offshored. The latter is the case especially for German, US and Japanese vehicle manufacturers who started to expand across Asia, NAFTA and Europe in the early second half of the 20th century (Grimm and Pfaff 2022). Especially Chinese vehicle brands mostly supply the domestic market, however, foreign markets are increasingly targeted by Chinese automotive firms.

The presented figures focus on the production and sales of vehicles and thus implicitly on the automotive industry. However, the production and sales are embedded in a larger system, that is referred to as the automotive sectoral system, or shorter, the automotive sector. The automotive industry is considered a subsystem of that sectoral system. Figure 9 displays elements of the automotive sector (Figure 14 for the ICT sector). The turquoise and thinly framed boxes indicate the various subsystems of the sector, the smaller gray colored boxes within them display elements or components of the subsystems. These elements can be actor groups, institutions, infrastructures or subject areas. While each sector is unique, they also share common elements, especially in subsystems as e.g. the political system or regarding infrastructure: governments play a role in almost all sectoral system, while the patterns of course can differ, at the same time, operations in sectors always rely on certain aspects of infrastructure as e.g. functioning communication or energy networks. The schema is not encompassing regarding the in-depth description of a sector, but serves

[7] EU27 production includes production in EFTA states

as a first introduction of the systematic understanding of the automotive sector, and its components beyond the industrial subsystem. This understanding, especially of the differences and similarities between the automotive and ICT sectors, is crucial when moving towards the analysis of the innovation system of autonomous driving. Contextual factors that influence the dynamics in innovation systems and emerge from the sectoral background can be the specific technological knowhow of industrial actors, but also the established interplay between industrial actors and actors e.g. from the political subsystem or experience in certain regulatory frameworks.

Figure 9: Components of the automotive sectoral system



Source: Own representation following the display of Kuhlmann and Arnold (2001)

The automotive industry or industrial system basically consists of all firms that provide raw materials, manufacture parts, components or the vehicles themselves. Furthermore, accompanying fields as e.g. the specialized plant engineering, required for the production of the vehicle (components), or logistics play an important role.

On the demand side, the automotive industry is strongly entangled with actually all other sectors as one of the fundamental providers of transportation, offering business fleets for employees or vehicles for logistics organizations. Individuals that purchase cars and public transportation organizations are other important actors on the demand side.

Many partnerships between industrial actors and organizations outside the industrial subsystem are long established. Consultants with different areas of expertise engage in automotive companies in various fields: in the optimization of organization and production processes, the implementation of environmentally sustainable solutions and concepts, or in strategy development. Large consultancies often have their own automotive divisions, which are dedicated to consulting automotive companies along the value chain. Partnerships with (applied) research institutions aim at the joint development of new technologies, but also include e.g. professorships that are financed by automotive companies which represent an interrelation with the education and research system (e.g. (Audi AG 2022b). Cities or municipalities may act also as both, agents of the political system e.g. in the allocation of industrial areas, but also as partners e.g. in pilot projects.

The automotive industry stands in constant interaction with the political system on different levels. In countries like Germany, where the automotive industry plays an important role in national employment and economic status, even concepts like automotive summits with representatives of large companies, organizations and politics as the chancellor are carried out (Die Bundesregierung 2022). Dialogues between the political and industrial system cover, among other topics, existing or planned as well as lacking standards, norms and regulations. In the automotive sector, CO_2 regulation and fleet targets have been in the center of attention, however, also the relevance of privacy and data security in road-bound transportation and related regulation increase (Zander et al. 2020). Technological standards for vehicles and regulation in the admission process have for long been considered day-to-day business, but gain in importance due to new assisted driving functions that are safety-relevant.

The education and research system fulfills two major roles in the automotive sector. Firstly, besides specific partnerships with the automotive industry, basic research in vehicle construction but also in related fields as physics or computer sciences is carried out in e.g. universities. Secondly, research facilities also educate and train the required workforce for the automotive sector. That includes study programs at universities and colleges and further training in research institutions but also apprenticeships and professional development provided by other institutions. The educated workforce is relevant to the automotive industry and to governments and other organizations. The education and research system can be viewed overlapping with certain infrastructural fields. While the education system forms the workforce, labor markets and the geographical proximity to educational facilities are considered parts of the regional infrastructure. Other aspects which the functioning of a sectoral system is based on, are basic infrastructure networks to provide electricity or internet services as well as the access to financial markets. The interdependence with the digital infrastructure increases, when the functionality of automotive products such as connected vehicles relies on aspects as cellular networks. The automotive sector has evolved over decades and is strongly characterized by its regional automotive clusters and networks, where OEMs and suppliers work closely together in both production and development.

Testing activities of autonomous vehicles in real-world traffic present an illustrative example of the many interrelations between subsystems within a sectoral system. For automotive R&D, the existence of testing roads has always played an important role and lies in the intersection of infrastructure and research. When it comes to the testing of autonomous vehicles, the political system and regulatory system are also touched, since new regulatory frameworks are needed. Furthermore, cities or municipalities have to be included in the process of implementing pilot testing regions. The industry as well as research facilities test their technologies in test vehicles that in turn, might already be used by individuals and may influence their future demands.

While the basic understanding of the automotive sectoral system is important to retrace dynamics and patterns, some delineations are made. In the scope of the thesis, the focus lies on the components and especially actors in the automotive sector that are relevant to or engage in the fields of autonomous cars and small passenger vehicles as robotaxis rather than autonomous freight vehicles or autonomous buses.

4.1.2 Products, services and strategies

The core products of the manufacturing automotive industry are motorized vehicles for road-bound transport. For passenger transport that includes passenger cars and buses, for freight transport different sized trucks, and finally the automotive industry manufactures a range of special purpose vehicles. The OEMs and partly the large suppliers are well known, however they are only the head of large global production networks and value chains that supply the components, parts and raw materials. Section 4.1.2 presents the characteristics of the automotive production network to more detail.

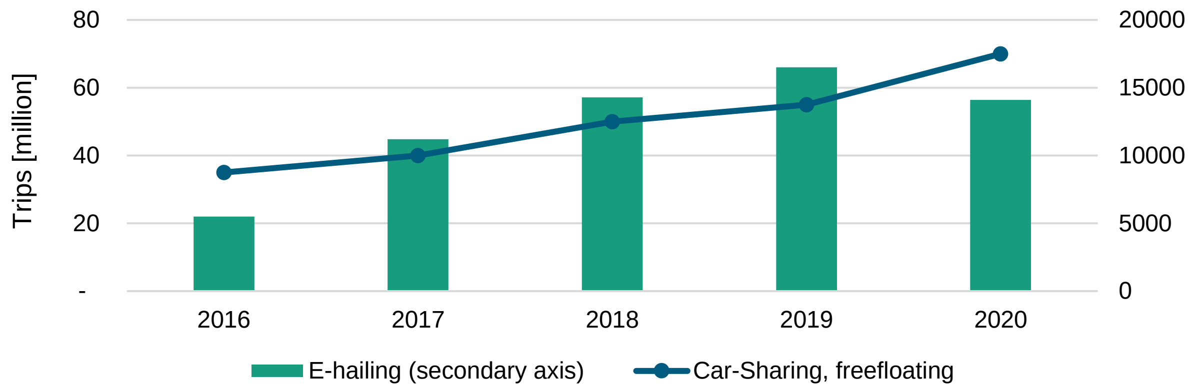
The automotive OEMs can be considered more homogeneous compared to the large ICT companies: They usually offer a rather similar core product portfolio and differentiate themselves e.g. by targeting different customer groups (e.g. premium cars vs. mass-production) and by realizing comparative advantages through cost and quality related optimization. Innovation in the automotive industry has for long been focused on the vehicles themselves, where the combustion engine was mostly in the center of technological innovation for the OEMs. The further development of components and systems within the vehicles is often carried out by suppliers or in R&D partnerships between OEMs and suppliers. The automotive industry is one of the largest investors in research and development, in the EU, for instance, it is even the biggest private investor in R&D (European Commission 2022).

Right now, the automotive industry is in a large transition phase due to the electrification of the power train. The substitution of the combustion engine with the electric powertrain and battery represents a major change to the key component of vehicles and entails shifts in production processes, value chains and relevant actors (Grimm and Pfaff 2022). Newcomers such as Tesla or Chinese OEMs, which focus on the production of electric vehicles, enter the market and change the competitive landscape in the automotive industry.

The traditional business model of OEMs is to sell vehicles to both, private customers as well as businesses or organizations, to provide spare parts for the aftermarket, and therefore to buy components and parts from their suppliers. Next to the manufacturing automotive industry itself, the broader automotive sector has always provided services. Traditional examples are repair and maintenance services and shops. In the past decades, an increasing diversification of the offers especially in service-oriented fields was observable. For automotive OEMs, one important growing field has been the provision of financial services to finance or lease vehicles. Furthermore, carsharing and ridehailing, or broader speaking, shared mobility or mobility services have gained relevance in for the traditional automotive industry, especially the OEMs. Besides private customer-oriented services, corporate services as fleet management or carpools for companies complement many portfolios.

Carsharing is the shared usage of vehicles, where cars can be rented mainly for short-term periods. Carsharing-concepts are either station-based, which means that one has to pick up and return the vehicles at the same place, which is usually a defined parking area, or they are freefloating, where the pick-up and parking can happen anywhere in a defined operating zone, which can be a city region. Ridehailing is comparable to traditional taxi services, where the booking process is carried out online. Ridehailing services can be combined with concepts such as ridepooling, where people share the vehicle for the entirety or parts of the trip. Both types of services experienced considerable growth through the diffusion of smartphones and thus the simplified access to the vehicles and rides through online platforms (Pfaff et al. 2022). Figure 10 displays the growth in the number of trips that are carried out through E-hailing (which can be considered synonymous to ridehailing and includes rides that are booked online, excluding pooled rides) on the secondary axes and freefloating carsharing on the primary axes. The provided figures cover the sum of trips carried out by the major global players. The figure shows the large difference in scale between the two service concepts and the growth rates. The number of carsharing trips grew by 57% between 2016 and 2019, from almost 40 million trips worldwide up to almost 60 million trips. E-hailing in contrast started at over 5 000 trips in 2016 and increased to more than 15 000 trips in 2019, a gain of 200%. In 2020, the number of carsharing trips increased further, while ridehailing shrunk due to COVID-19 restrictions (Wilhelm 2021).

Figure 10: Number of trips provided via E-hailing and Carsharing (global leading players)



Source: Own representation based on Heineke et al. (2021)

The potential market is growing and examples show that OEMs enter the field, mainly via in-house services rather than investing in mobility startups (Heineke et al. 2021). OEMs then usually use vehicles of their own brands, which gives them some cost advantage. One example are Mercedes-Benz and BMW who jointly run FREE NOW, a mobility service platform to book rides, access the carsharing fleet and to rent scooters and bikes (FREE NOW 2022). The service is concentrated on the European market, after it closed down its services in USA towards the end of 2020 (SHARE NOW 2022). Another example is Volkswagen's MOIA, a ridehailing service in Hamburg and Hanover that includes the pooling options in their services or Volkswagen's WeShare, a fully electric carsharing platform (MOIA 2022a). Ford partnered up with Flinkster, a German railway subsidiary, in providing carsharing services in Germany (Ford 2022b). Toyota runs its global mobility service platform KINTO that is present in different world regions with different concepts, e.g. in Europa it provides carsharing as explained above, in USA it provides a rental fleet for drivers that can use the vehicles for operating via the Uber platform (KINTO 2022a, 2022b). The Mobility-as-a-Service portfolios are often embedded in the new mobility strategies of OEMs, where the companies present their effort in leading into the modern, digital and sustainable mobility future.

The field is characterized by high dynamics within the past years and the present. Mercedes-Benz and BMW, for instance, both had their individual carsharing platforms. A few years back, they decided to partner up, in order to increase profitability, then they had to shut down the American market. The Volkswagen services are only offered in German cities and Toyota's KINTO concepts vary significantly among the different global regions. On the other hand, pure mobility platforms Uber, Lyft or DiDi are successful in many ridehailing markets (Fortune Business Insights 2022). It remains unclear, to what extent and in which form these private customer services will be provided by OEMs in the future.

4.1.3 Production networks and value chains

Production and sales networks in the automotive industry have evolved over decades and span around the globe to serve the demand of private individuals and different types of commercial customers. Vehicles are very complex products that require the production and assembly of parts from many different industries. The complexity has leaded to the establishment of fragmented production networks in which the OEMs outsource large parts of the value-added to suppliers. Table 2 summarizes actor types in the automotive production network (Table 3 does so for the ICT production network), in orientation to the key roles in a production network suggested by Yeung and Coe (2015).

Automotive OEMs, both, traditional companies as well as newcomers in the field of electric vehicles, are considered the lead firms. In a servitized mobility industry, mobility service providers, who sell trips instead of vehicles to customers, might take the role of lead firms. In case that mobility service providers are not the OEMs themselves, the upstream manufacturing steps, including the final assembly of vehicles by OEMs, would be pushed one stage up.

Table 2: Actor types in the automotive production network

Type	Automotive examples
Lead firms	- Product-oriented o OEM (traditional) o OEM (newcomer) - Service-oriented o Mobility service providers (new)
Strategic Partners	Large automotive suppliers that directly work with OEM (established automotive modules, modules for electrification, modules for digitization, chassis, …): Tier 0.5 and Tier 1 suppliers
Specialized suppliers (industry-specific)	Specific automotive parts that are often indirectly delivered to OEMs via Tier 0.5 / 1 suppliers: Tier 2 suppliers
Specialized suppliers (multi-industrial)	Many technologies and services that are used in automotive products, however also existent (or originated) in other industries (same level as Tier 2 suppliers) - Battery cells - Electronics - Specialized logistics - …
Generic suppliers	- Simple parts o Tier 3 suppliers - Raw material suppliers - …
Key customers	- Individuals - Companies (Business fleets) - Logistics

Source: Own representation following Yeung and Coe (2015)

In the classic automotive production network, OEMs are the lead firms and they work directly together with Tier 0.5 and Tier 1 suppliers. Tier 1 firms usually have their own design and R&D divisions and supply complex components. Tier 0.5 suppliers evolved out of Tier 1 supplier, when the OEMs increasingly outsourced the development and production of major systems. Tier 0.5 suppliers are responsible for the independent development and production of these full systems as e.g. the chassis, which are designed following the requirements of the OEMs. These suppliers are usually as global as the OEMs regarding their production sites and subsidiaries. Tier 1 and Tier 0.5 suppliers have the responsibility to manage their own production networks which supply them with parts and smaller components. These are Tier 2 suppliers, which can be clustered into the industry-specific suppliers that provide automotive parts, as well as the multi-industrial suppliers, mainly from other industries, that manufacture more universal products as e.g. battery cells, which are also relevant to other industries. The latter are not as dependent on the downstream automotive firms. Lastly, Tier 3 suppliers provide simple products and can be attributed to the category of generic suppliers, together with raw material suppliers or other suppliers to daily business operations of involved firms.

The OEMs and the suppliers along the value chain represent large and intertwined global production networks where intermediate inputs are sourced from abroad. As indicated in the description above, the value chain has many stages on which intermediates are traded. While the basic principles of OEM-supplier relations are observable among different regions, the degree of globalization in the production networks vary. Multi-regional input-output tables, as the world input-output database (WIOD), provide information on the interconnections of countries and their industries (Timmer et al. 2015). The data allows to extract information not only on which countries and respective industries supply a specific national industry, but also what indirect intermediates these direct intermediates themselves consist of. The WIOD contains data on 44 countries (including the region rest of the world (RoW)) and 56 industries, covering the years 1995-2014.

In the following, China, Germany, and USA, each the largest vehicle producer in the regions Asia, EU27 and NAFTA, are focused on (see section 4.1.1). The automotive industries of the named countries are analyzed based on input-output analysis (Miller and Blair 2009) regarding their international input structure in 2014, the most recent available year. In coherence with European Classification of Economic Activities (NACE, *Nomenclature generale des Activites economiques dans les Communautes europeennes*), the WIOD reports the industry "Manufacture of motor vehicles, trailers and semi-trailers" which covers the manufacturing of vehicles, supplies and parts and is understood as the automotive industry (eurostat 2008). Figure 11 displays the shares, the largest intermediate trading partners of the three national industries hold. The left side of the figures shows how much the different countries contribute directly to the final value of the production. The right side shows how much the countries contribute along the total value chain in order for e.g. China's automotive industry to produce one unit or products worth one dollar.

China's automotive industry is strongly marked by the large domestic share in both direct and total intermediate inputs. In direct supplier relations, less than 5% of inputs are imported. Indirectly, a larger part is sourced from abroad which indicates that the domestic direct inputs in turn contain upstream international parts. China mainly partners with countries from the Asian region. Japan, Korea and Taiwan are among the largest partners. Besides them, Germany and USA are important suppliers. The RoW region shows a large increase in shares, comparing the international structure of direct and total inputs. RoW includes many Asian countries whose economies are too small in order to be reported individually, African countries and South-American countries apart from Brazil. These countries probably supply upstream products as small parts or even raw materials to the Chinese automotive industry.

Figure 11: Regional origin of intermediates into the motor vehicle manufacturing industries

Share of direct and total intermediates delivered to the motor vehicle manufacturing industries of China, Germany and USA, by regional origins, largest supplying nations, 2014

Source: Own calculations based on WIOD database (Timmer et al. 2015)

Among the three countries, Germany has the lowest share of domestic intermediates. However, Germany is a small country in comparison to China and USA and directly sourced intermediates mostly origin from other European countries. Along the total supply chain, the roles of China and RoW increase. China and Italy are the largest single nation partner. The German domestic share increases slightly, when looking at total value chain, suggesting that Germany is also active in producing intermediate parts.

The USA has, regarding the location of leading trading partners, the most international value chain. The largest partners of direct inputs are the direct neighbors Mexico and Canada, followed by China, Japan, Germany and RoW. Taking into account the preceding steps along the automotive value chain, China gains in importance, being by far the largest single nation partner with almost 5% alone. Both, the group of the six largest partners as well as their combined share, stay the same when considering the total intermediates.

The comparison shows the varying structures of the leading automotive manufacturing industries. A high domestic share, especially in politically centralized China, may give the opportunity to implement changes quicker throughout the industry and react more focused on upcoming challenges due to close and established domestic relations. Larger international shares might come along less control but also larger flexibility.

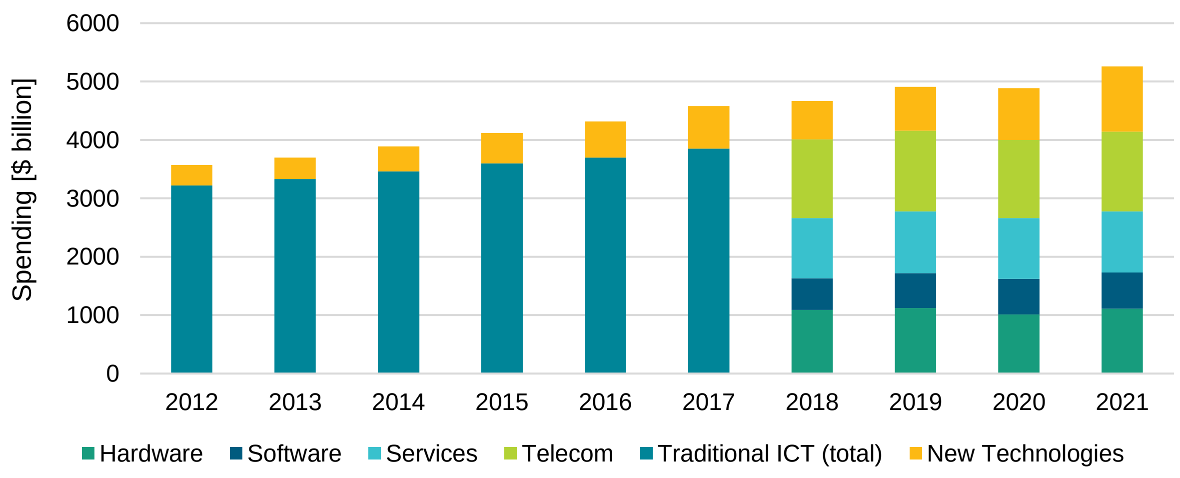
4.2 The ICT sectoral system

4.2.1 Key characteristics

The ICT industry provides a large and growing variety of products and services. The products and services are increasingly embedded in products provided by other manufacturing sectors, which makes a sharp definition of the ICT industry hard. The OECD defines ICT industries as follows: "The production (goods and services) of a candidate industry must primarily be intended to fulfil or enable the function of information processing and communication by electronic means, including transmission and display." (OECD 2011, p. 59). That covers consumer electronics, household appliances, IT-Services, hard- and software as well as telecommunications.

Measured in US $ sales, the ICT industry was considered the second largest industry in 2019 (GlobalData 2019). Figure 12 shows the development of worldwide ICT spending from 2012 - 2021, which is characterized by an (almost) steady growth. Compared to other industries, the demand for ICT products and services experienced only little decline during the beginning of the COVID-19 pandemic in 2020. In 2021, the ICT industry grew strongly, even compared to 2019 levels. Factors as home office and travel restrictions boosted digital work and thus the need for ICT products and services. The growth in ICT splits up in both, increased spending on traditional and new ICT. The growth rates of new technology spending exceed those of traditional ICT spending.

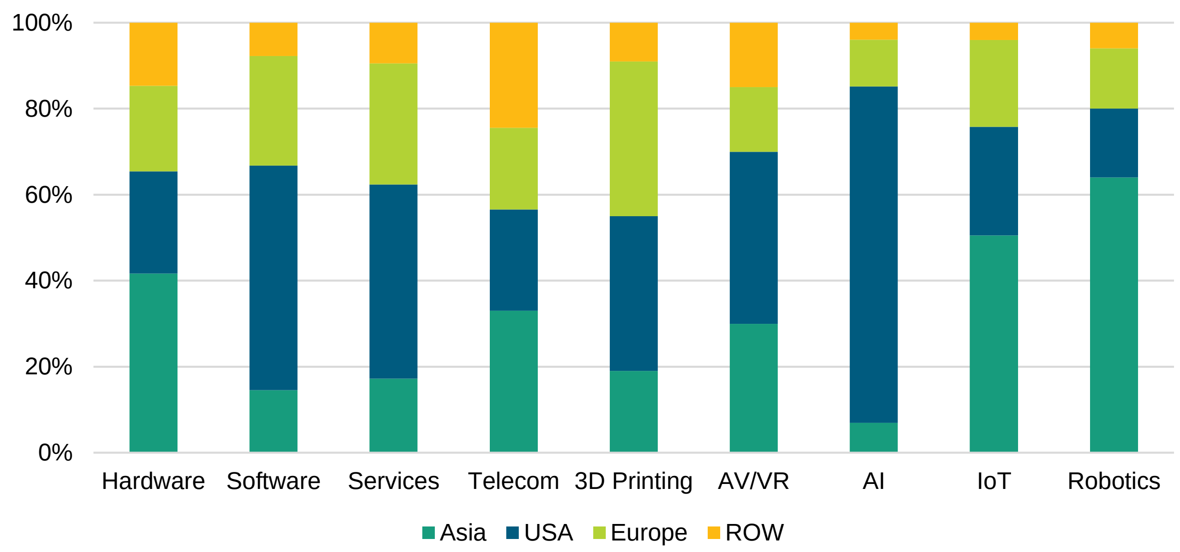
Figure 12: Worldwide ICT Spending



Source: Own representation based on IDC Corporate (2022)

Overall, with 36% share, the USA have the largest revenue from ICT, followed by the EU with around 15% and China with almost 12% (bitkom 2022). The shares vary in parts significantly between different traditional and new technological fields and services as can be seen in the display of regional shares in different ICT markets in 2017 in Figure 13. Among the traditional ICT fields, Asia plays the largest role in providing ICT hardware, thus in hosting and operating production sites (IDC Corporate 2022). The USA dominate the fields of ICT software and services. In both fields, Europe ranks second. Telecommunication is the only traditional ICT fields, in which the RoW accounts for mentionable shares. This would be due to the domestic character of telecommunication services that are, despite the overall trend of globalization, usually carried out locally. Among new technologies, the USA and Asia combined account for more than 50% of market volume in all fields. The USA is especially relevant in the field of AI, while Asia hosts the major share of the IoT and robotics global market. Europe mostly plays a role in 3D printing.

Figure 13: Regional Share of Traditional / New Technology Markets 2017



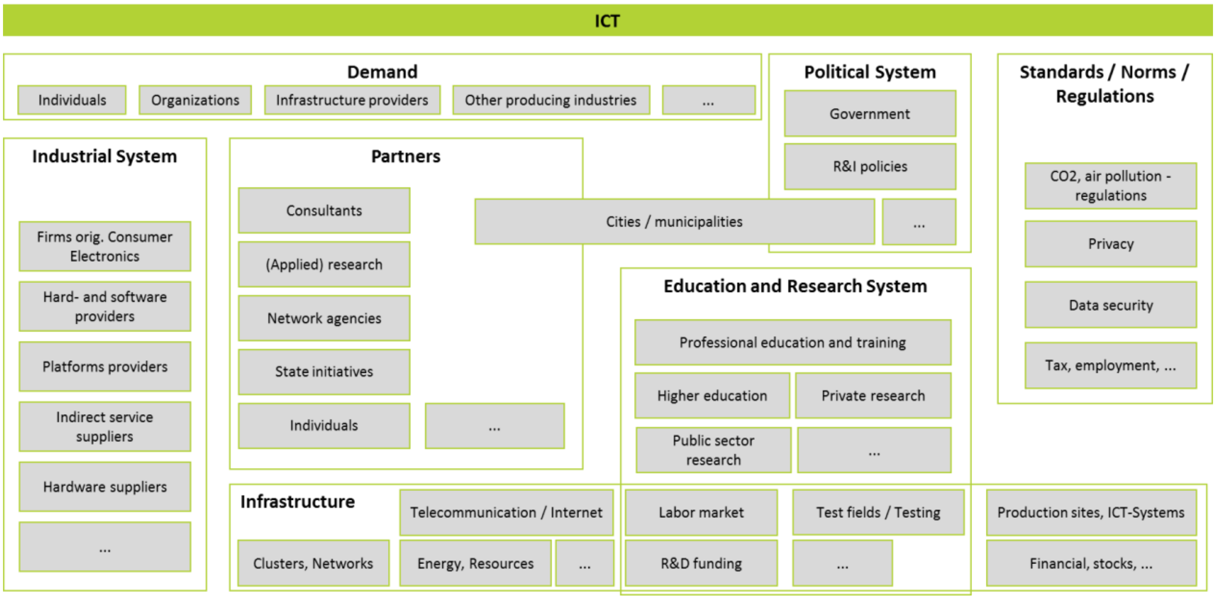
Source: Own representation based on IDC Corporate (2022)

The ICT industry is considered to be a subsystem of the ICT sectoral system. This follows the perspective on the automotive industry to be a subsystem of the automotive sector. In contrast to the automotive industry, which is more hardware-oriented, the ICT industry is to a large extent characterized by both, hardware and software providers. Figure 14 displays the ICT sectoral system. Following the overview in the automotive section (4.1.1), the green and thinly framed boxes indicate the various subsystems of the sector, the smaller gray colored boxes within them display elements or components of the subsystems.

The number of subsystems, as well as general components are similar to the display of the automotive sector. The industrial system consists of hardware and software designing and manufacturing firms and their part and raw material suppliers. Compared to the automotive sector, the majority of suppliers originates from the ICT industry itself. The accompanying production and supply chain services as plant engineering or logistics are required for all manufacturing industries, thus also for the ICT industry.

On the demand side, the ICT industry supplies individuals, organizations, infrastructure provider and industries. Due to the digitization of products and processes in the economy and society, the ICT industry is now heavily interconnected with actually all global industries.

Figure 14: Components of the ICT sectoral system



Source: Own representation following the display of Kuhlmann and Arnold (2001)

Partnerships exits between the industrial system and other organizations as well as individuals. Especially in the field of software products, the ICT industry has lower entry barriers compared to the automotive industry. The interconnection with individuals, e.g. in the form of hackathons that are organized by companies, plays a more important role compared to the automotive sector. Interfaces with cities or municipalities exist in form of allocation processes for plants and offices and joint projects. In addition there are large interrelations between infrastructure providers and cities or municipalities in installing and maintaining the regional ICT infrastructure.

Regulation in the ICT industry focuses mainly on topics as privacy and data security as well as standards for products. Especially in big tech, regulation becomes more and more important (Jacobides 2021) and regulatory frameworks will probably evolve alongside further innovation and market dynamics. Besides rather technological aspects, the almost monopolistic status of some large ICT firms, especially platform providers increasingly comes to the attention of law makers and the regulatory body (e.g. Federal Trade Commission 12/9/2020).

In the ICT sector, the education and research system basically fulfills a similar role as in the automotive sector: basic research and the training and education of the workforce are carried out in ICT fields. For instance, in the case of the Silicon Valley, local universities as Stanford are considered to play a crucial role in both the rise and success of the local ecosystem (Piqué et al. 2020).

Basic infrastructure for the ICT sector is needed, as it is for other sectors. The provision of the telecommunication and internet infrastructure, including its own, is a key field of the ICT industry. Firms that engage in software development and provision do not need large production sites and machinery, whereas the hardware providers do. While especially the software-related field of ICT is younger than the automotive industry, established networks and especially regional clusters have already evolved, that host many of the well-known ICT leaders. The most prominent example is probably the Silicon Valley, where, among others, Alphabet / Google, Meta, Apple or Intel are located (Tarver 2022). It is not only the geographical proximity of the large firms that makes the cluster that successful, but also the access to financial resources e.g. via venture capital firms or startup incubators and accelerators, which are based in the region.

Within in the scope of the thesis, the focus within the ICT sector lies on the elements and especially actors that engage in the field of autonomous vehicles and mobility platforms that target autonomous driving. That includes firms and institutions that directly conduct research on the technology of autonomous driving as well as those that engage in supplying components.

4.2.2 Products, services and strategies

The ICT industry provides a wide range of products and services. With proceeding digitization in many fields, it becomes increasingly challenging to unambiguously allocate a firm with all its different businesses to being ICT or not: Software firms that were clearly ICT, provide hardware e.g. in the field of consumer electronics (e.g. Google), electronics firms provide software solutions, both to come with their own products but also independently (e.g. Intel) (Acker et al. 2016).

The ICT industry has in some kind been reinventing itself, its structures and principles in the past years. The supply of traditional IT-infrastructure is not as lucrative anymore and new applications as e.g. software-as-a-service, especially in the B2B field, gains in importance. Stability in the company landscape seems to exist among the top leaders, while there is much dynamic in the middle field (Acker et al. 2016). On the one hand this can be driven by the high innovation velocity that may leave players behind quickly, and on the other hand by the increasing amount of merger and acquisition (M&A) activities and consolidations. In order to grasp the high level of diversity among firm types, business models and strategies in the ICT industry, some examples of firms that are later revisited in their engagement in the field of autonomous driving, are display in the following.

Amazon is most known for its Amazon Marketplace, one of the largest online e-commerce platforms. Marketplace is the most profitable branch, however many other technology fields were entered (BStrategy Insights 2021). Amazon provides entertainment with Prime Video and Amazon Music, payment services under the name Amazon Pay, and different internet services via the division Amazon WebServices (Storage, Cloud Solutions, Database, IoT, Machine Learning ...). Most of the offered technologies and business models are considered replicable by other firms, but Amazon still has its unique market position that is hardly challenged by competitors. Amazon Marketplace operates based on its own warehouse infrastructure and sells products under its name. Another asset is the provision of a well-known platform that has its own value. Besides selling products themselves, charging other sellers a fee in order to use the Amazon platform is one of the main revenue streams. The platform and trust that Amazon has built via its online retail shop also allows the company to enter new fields quickly. In the digital sphere, the access to markets and customers plays a large role and the offered new product itself must not be the most important determinant (Staab 2019).The basic strategy and aim of Amazon seems to be the satisfaction of the customers and an individualized shopping experience. Paying on top in order to provide a good customer experience is considered the better option compared to being right e.g. in disputes on liability for product conditions between Amazon and customers.

Alibaba Group is a large internet and tech company (Alibaba Group 2022). Similar to Amazon, its roots lie in the provision of an online wholesale marketplace. Alibaba.com is the largest online retail company of China, focusing on B2B transactions, AliExpress.com focuses on B2C for small firms and Taobao is a C2C-platform. In contrast to Amazon, it does not own their own warehouses but functions only as a cost-free marketplace (Roy 2021). The strategy is to help firms grow and provide them with market access. Therefore, the aim might be rather firm than customer targeted. Revenue is generated e.g. by selling sellers the option to be ranked higher. Next to the market place, Alibaba, similar to Amazon, provides many other services, for example in the field of financial transactions, cloud computing, logistics or film production.

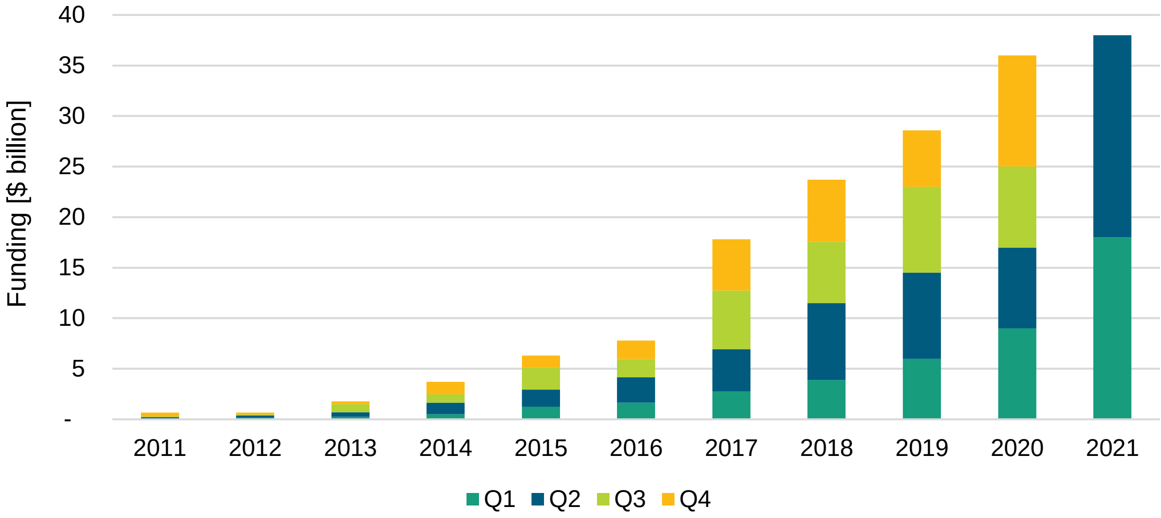
Apple is one of the most known fabricants of computers, smartphones and other consumer devices as well as software solutions, such as their own operating system (Apple 2023). The provided software solutions are mostly related to the applicability with Apple products. While Apple has successfully integrated their own software with hardware and has built a popular digital ecosystem for customers and businesses with well inter-connected devices and solutions, the combination of Apple soft- and hardware is in focus. New business fields as e.g. AppleTV or online Cloud solutions are developed, that can be used with other devices as e.g. Windows computers, however, buying and using Apple hardware is mostly the bridge into the Apple-world. In comparison to Amazon or Alibaba, the company is not as diverse in their service solutions. On the other hand, Apple, as other companies from the ICT hardware or electronics industry, distinguishes itself from other manufacturing firms as automakers by their manufacturing concept. Apple does not own its own production sites, where Apple devices are produced, but works with contract manufacturers that produce the devices for them.

Google, now subsidiary of Alphabet, covers many services and applications as different search machines, navigation, the video platform YouTube, operating system Android that is used on the devices of many Hardware companies, communication applications. Furthermore, it provides many business services as cloud infrastructure for firms to develop different applications (Google 2022). On the hardware side, Google sells their own line of smartphones, laptops and other devices. Revenue from the different applications is mainly generated via advertisement (Johnston 2022). Next to Google, other Alphabet firms cover a large variety of business and innovation fields: GV is a Venture Capital firm, Calico is in biotechnology research, Waymo is the autonomous driving unit. With its large financial resources, Alphabet targets many evolving business fields. The subsidiaries partly have a development (e.g. Waymo) or pilot (e.g. Google Fiber) project character. They are devised in order to cope with new fields and not to generate money right away.

Intel, as another example, is popular for its semiconductors and processors. The firm initially focused on the electronics market but in the past years increasingly developed software knowhow, e.g. in the field of IT-security, artificial intelligence or autonomous driving, also through the acquisition of specialized firms (Mcgregor 2022; Lunden 2022). In comparison to other firms in the semiconductor business, as e.g. Qualcomm, Intel acts as an integrated device manufacturer, meaning that Intel covers all development and production steps of semiconductors itself. Since semiconductor technology becomes more complex, some firms started to focus on one of three central steps: So called "fabless" concentrate on the design of chips without owning production sites (e.g. Qualcomm), "foundries" are specialized manufacturers and "OSAT" companies are responsible for outsourced semiconductor assembly and testing (Kleinhans and Baisakova 2020).

The introduced companies differ when it comes to their offered services, products and business models. The selection gives a first impression of the heterogeneity of ICT players that engage in innovative fields. The firms have the steady extension and dynamic development of their product or service range and the technologies themselves in common. Being a software or digital service provider allows to update products in any desired time period which entail different innovation dynamics, compared to pure hardware providers. However, none of the introduced companies act as a pure hardware provider and thus, all of them cope with short digital innovation cycles and the updating principle. Furthermore, the firms do not only innovate within their initial business models and offers, but move forward into new fields.

Figure 15: Artificial intelligence (AI) startup funding worldwide from 2011 to 2021 (in billion $), by quarter



Source: Own representation based on Statista (2022)

Many of the fields, such as artificial intelligence or autonomous driving, are on the forefront of current technological developments and require large investments, the will to experiment but also to take the risk. ICT firms themselves invest large amounts into their own R&D division. Furthermore, the ICT sector is known for the many startups and large investments by capital firms. Looking only at artificial intelligence startups (Figure 15), funding was expected to exceed 35 billion $ in 2021, which equals almost 1% of global ICT spending or market volume (see Figure 12).

4.2.3 Production networks and value chains

Along with the many products and services that the ICT industry provides, the production networks and the manifestation of actor types within the ICT industry differ. The lead firms in ICT can be clustered into product-oriented, service-oriented or a combination of both. Product-oriented firms provide consumer-electronics, ICT infrastructure components and other ICT hardware products and parts. Service-oriented firms e.g. engage in software development and distribution or telecommunications, provide platforms or offer consulting services. In the following, the principles of the ICT hardware production network are shortly introduced. While a lot of literature and public knowledge exists on the functioning of automotive production networks, there are hardly any generic ICT production networks characterizations. Table 3 displays the same logic of actor types for the ICT production network, as introduced for the automotive production network in section 4.1.3. The aim is to show differences between the two sectors, rather than providing the universal ICT production network characterization.

Table 3: Actor types in the ICT (hardware) production network

Type	ICT examples
Lead firms	- Product-oriented ○ Consumer-electronics ○ Infrastructure ○ Other ICT hardware - Service-oriented ○ Software providers ○ Telecommunication ○ Platform providers ○ Information services ○ Consulting services - or a combination of both
Strategic Partners	ICT sector is heavily dependent on contract manufacturing: - EMS (Electronics Manufacturing Services) - ODM (Original Design Manufacturer) - …
Specialized suppliers (industry-specific)	Product components - Semiconductors - Batteries - …
Specialized suppliers (multi-industrial)	Many technologies or services that are used in ICT products, however also existent (or originated) in other industries - Electronic parts - Specialized logistics - …
Generic suppliers	- Simple parts - Raw material suppliers - …
Key customers	- Individuals - Companies ○ Procurement, equipment for staff ○ Supply of components to other manufacturing industries ○ Production equipment

Source: Own representation following Yeung and Coe (2015)

Lead firms in ICT hardware are also called OEM, however, in comparison to the established automotive term, they do not necessarily manufacture or assemble their products on their own. The OEM gives the product its brand. As describes in the company examples in the preceding section, hardware companies work closely together with contract manufacturers. The business models and form of the partnerships vary, regarding the division of competencies. Electronic manufacturing services (EMS) manufacture products according to the design, specified by the OEM. However, the EMS might also offer additional services in supporting e.g. the design or required supply-chains. Original design manufacturers (ODM) design the entire products themselves and are thus able to sell the manufactured products to different OEMs who brand them. The named examples as Apple or Qualcomm work with EMS.

Defining the industry-specific, multi-industrial and generic suppliers in the ICT hardware production network is not fully unambiguous. In the case of Apple, Apple is the lead firm that sells an IPhone and a strategic partner would be a contract manufacturer as Foxconn. In order to manufacture the IPhone, different components are needed from a variety of suppliers or they are produced in-house. These components would for example be semiconductors or batteries. Semiconductors for the IPhone would be supplied by specialized suppliers who in turn are supplied by suppliers with components and parts. The semiconductor supplier might in turn have an EMS as a strategic partner and other specialized suppliers besides the generic parts suppliers.

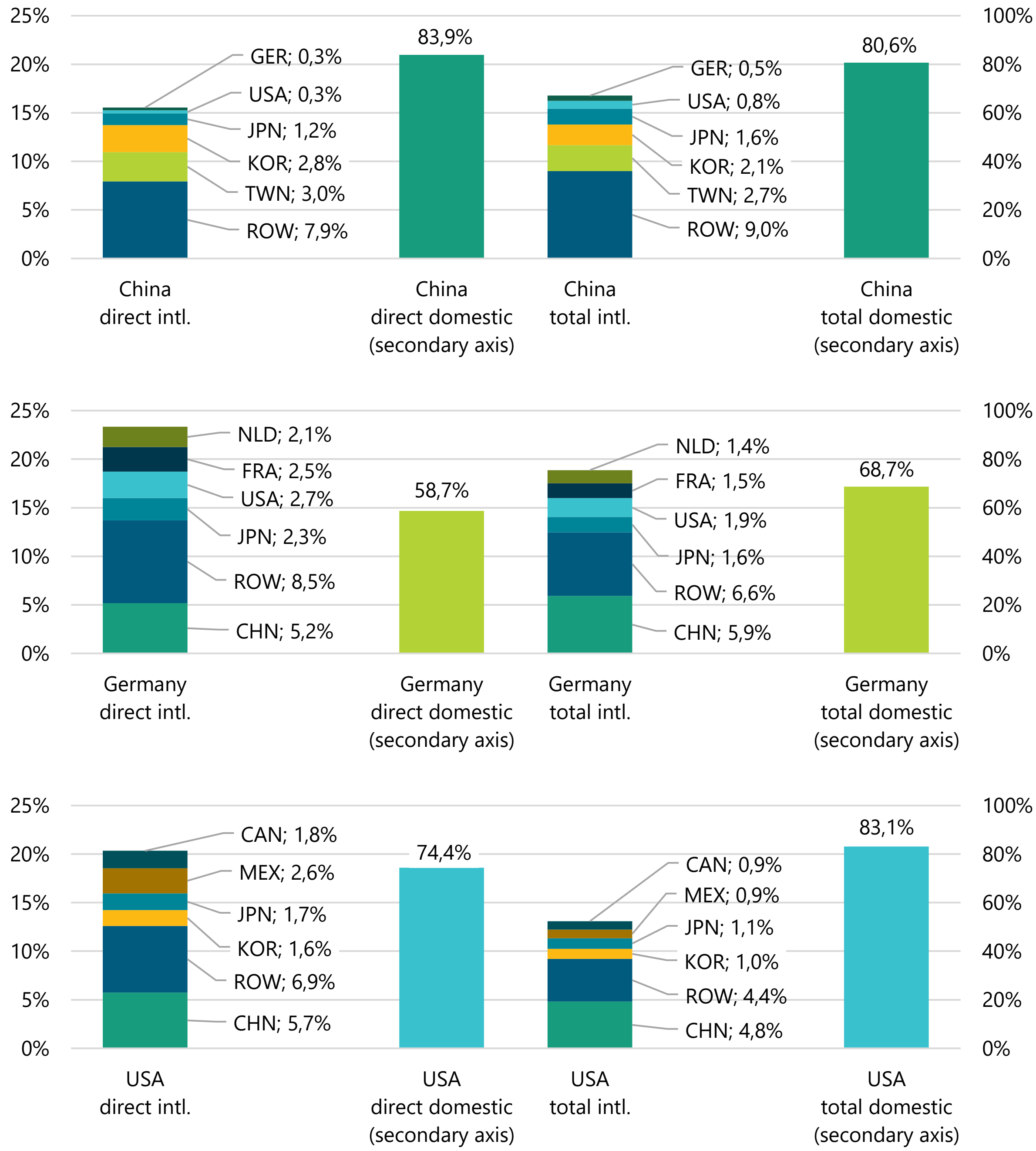
The central difference between the automotive and the ICT industry is probably the fragmentation of the production network between the design and the production of a product. Automotive OEMs have established their own production sites worldwide and are thus bound to their choices. ICT OEMs are, depending on the contractual specifies, more flexible when contracting EMS. While the value-added of automotive OEMs has always consisted in parts of the manufacturing of central systems and the assembly of vehicles, ICT OEMs strategy and business model relies on the product design.

The outsourcing of production often comes along the offshoring of production to other countries. A look at the economic entanglements of the ICT hardware industries on basis of the WIOD shows differences in the international structure between individual national ICT hardware industries and between ICT and automotive manufacturing principles. Figure 16 displays the leading partners of the ICT hardware industries China, Germany and USA and is similar to the representation of the automotive industries in Figure 11. The calculations are based on input-output analysis and use WIOD (Miller and Blair 2009; Timmer et al. 2015). The NACE industry “Manufacture of computer, electronic and optical products” is considered as the ICT hardware industry.

All three countries show smaller domestic shares in direct inputs compared to the automotive industry. Considering total inputs, this is only the case for China, Germany shows a similar domestic share in inputs to its ICT hardware and automotive industries. The USA has the largest domestic share in inputs along its total value chain among the three countries in focus, which also exceeds its domestic share in automotive production. The regional origin of inputs into the three national industries is clearly characterized by Asian partners regarding both, direct and total inputs. In addition to that, the region RoW plays a much larger role in ICT hardware production networks.

Figure 16: Regional origin of intermediates into the computer, electronic and optical product manufacturing industries

Share of direct and total intermediates delivered to the computer, electronic and optical product manufacturing industries of China, Germany and USA, by regional origins, largest supplying nations, 2014



Source: Own calculations based on WIOD database (Timmer et al. 2015)

The German ICT hardware industry is less intertwined with other European countries compared to the German automotive industry. RoW, China, USA and Japan combined make up almost 20% of direct inputs. Looking at the total inputs, German ICT hardware industry, in turn, is more dependent on domestic inputs.

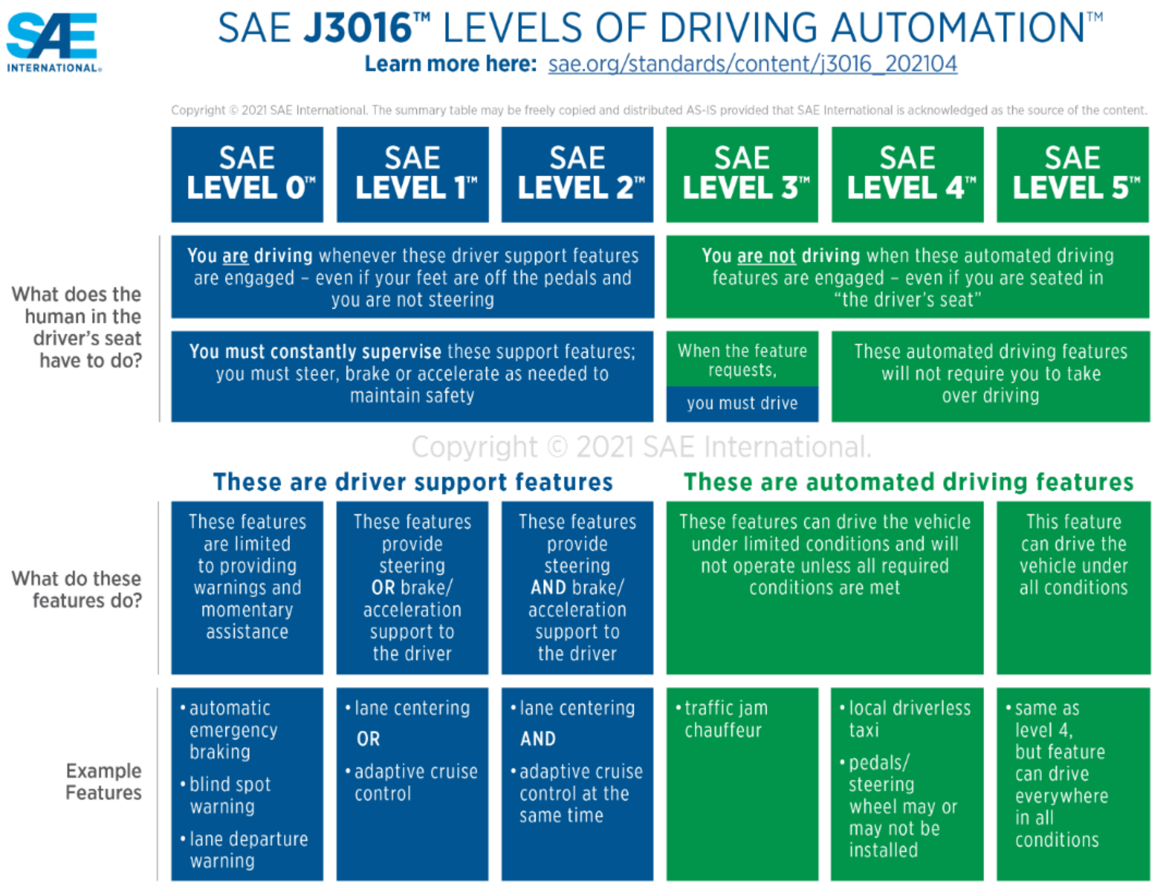
The US American ICT hardware industry is directly supplied by nearly the same set of countries and regions as the US American automotive industry. The exception is Germany, which does not appear among the important supplier and is replaced by South-Korea. However, the shares vary significantly. China and RoW play a much larger role in direct inputs, and similar roles in total international inputs. Other countries as the direct neighbors Canada and Mexico seem not to be as important in both, direct and total inputs.

The global networks of the software-oriented ICT industry are harder to interpret, since there are no physical products traded across country borders. Numbers on the NACE industry "Computer programming, consultancy and related activities; information service activities", which could be used as a proxy, show large domestic shares of all three countries. Service industries in general are usually characterized by domestic structures. Figure A 1 in the Annex includes the similar display of international shares in the respective national industries. High domestic shares may suggest a large degree of national entanglement or, more generally, less outsourcing in software industries and firms.

5 The functional innovation system of autonomous driving[8]

Autonomous vehicles are self-driving vehicles that do not require a human driver to carry out the driving tasks. Currently available cars already contain a set of assisted or partly automated driving functions. The differing ability of the vehicle to take over tasks during the ride can be classified along different stages. The common classification system includes 6 stages, where Level 0 describes the stage of no automation at all and Level 5 the fully autonomous driving in all environments (SAE 2021a). Figure 17 gives an overview of the automation levels and its specifics.

Figure 17: Levels of driving automation according to SAE international



Source: SAE (2021a)

Assistance functions on the first level include technologies such as blind spot assistants, which support the driver (SAE Level 1). These technologies are currently available in the majority of new vehicles. Other systems that are widely purchasable in new cars can already be counted among the functions of partially automated driving, which is classified in the second level (SAE Level 2). Examples are emergency braking or lane departure warning systems. The introduction of SAE Level 3 functionalities in new vehicles is currently ongoing (Daimler AG 2021). The stage is called conditionally automated driving and specifies the ability of the vehicle to drive autonomously in a defined setting, where the driver can always take over within a given time frame. Level 4 automated driving

[8] Parts of the chapter have been published in Grimm and Walz 2024.

is called highly automated. The central difference to the preceding level of automation is that the driver is not expected to interfere at any point. In case of an emergency the vehicle will maneuver itself into a status of a controlled emergency stop. The operation, however, is still limited to a defined setting, which presents the gap that still exists towards fully autonomous driving in Level 5. The last stage describes autonomous driving functions that allow for autonomous transportation from one place to another, passing through different settings as city traffic, overland streets and highways.

The implementation of autonomous vehicles requires the combination of a large number of technologies, including various hardware and software components. The relevant technologies cover for instance sensor technologies (e.g. Light Detection and Ranging (LiDAR), radar, camera technology), hardware for GPS positioning, CPU units as well as various software systems that bundle translate the observed information into automated driving maneuvers. Table 4 provides an overview of the relevant technologies for the implementation of autonomous vehicles. The upper part of the table lists the required on- and off-board hardware. The lower part presents the software fields. The right-hand column gives a description of the role, each technological component plays in the provision of autonomous driving functions. The increasing relevance of software components goes beyond the traditional technological knowhow of the automotive industry and entails the engagement of ICT players into autonomous vehicle development.

The development of autonomous driving does not only include the advancements in autonomous vehicle technology, but also the evolution of concepts and business models for the future usage of autonomous vehicles. That covers on the on hand side, the development of accompanying service solutions and the formation of a new automotive aftermarket. Autonomous vehicles can be designed without a steering wheel which allows for altered vehicle concepts and interior designs. Furthermore, new patterns of time spending during the drive may give rise to an extended set of in-vehicle entertainment and infotainment services. On the other hand, the use of a shared autonomous vehicle fleet may become more attractive and may alter the present dominance of the privately possessed car. Fitting mobility service concepts that build on autonomous vehicles have to be developed and implemented. In the course of the thesis, the term autonomous vehicle is used for the rather technological perspective on the autonomous vehicle itself and its functions, while the term autonomous driving is meant to include the vehicles as well as the implementation related surroundings.

The functional innovation system analysis focuses on the countries Germany, USA, and China. The analysis of the sectoral systems in sections 4.1 and 4.2 shows that these three countries are both, large markets for and suppliers of automotive and ICT products and services. In the case of Germany, the activities are influenced by the membership in the European Union and the geographic location in Europe (e.g. regulatory frameworks of the EU, outsourcing within the EU, trade within the EU, cultural proximity ...). Therefore, the German actives are partly discussed while referring to European activities, too.

Table 4: Relevant technologies for the implementation of autonomous vehicles

Autonomous Driving	Hardware	On-board hardware	Camera Systems	Collects optical images to be interpreted by advanced AI & analytics
			Radar Systems	Determines speed and distance of object using electro-magnetic waves
			Ultrasonic Sensor Sys-tems	Short distance object recognition (e.g. parking)
			Odometry Sensor Sys-tems	Measure wheel speed to predict vehicle travel and com-plement localization
			System on a Chip (SOC)	High performance energy- efficient computer hardware
			V2X Communication Systems	Communication with vehicles & infrastructure over short range
			Actuators	Translation of electronic signals into mechanical actions
			GPS	Localization of vehicle using satellite triangulation
			LiDAR Systems	High resolution sensor using light beams to estimate dis-tance from obstacles
		Off-board hardware	Data Center	Storage and processing of vehicle data
			Autonomous vehicle cloud operation	Learning, adopting and up- dating HD maps & algo-rithms
	Software	High Definition On-Board Maps		Precise localization information about roads, infrastruc-ture and environment
		Localization & Mapping		Data fusion for vehicle localization and environment analysis
		Perception & Object Analysis Al-gorithms		Detection and classification of objects and obstacles
		Prediction		Foresight of movements and actions by vehicles, pedes-trians and other moving objects
		Decision-Making		Planning of vehicle route, maneuvers, acceleration, steer-ing and braking
		Vehicle Operating System		Operating system running algorithms in real time
		Supervision Platform		Analytics to monitor the autonomous vehicle system op-eration, detecting & correcting faults

Source: Translated from Grimm and Pfaff (2022)

5.1 Entrepreneurial activities

Fully autonomous vehicles are not yet sold or used commercially outside pilot-like projects. Therefore, entrepreneurial activities cannot yet be described via indicators on actors that sell or use the technology (Hekkert et al. 2007; Vasseur et al. 2013). Instead, all activities of actors around the R&D process related to autonomous driving are considered to be entrepreneurial activities. Even though autonomous driving has the ability to disrupt the automotive industry, technological innovation can, at least in some cases, be considered an incremental process. The levels of driving automation include assisted and highly autonomous driving next to fully autonomous driving. Thus, in some cases, the sale of vehicles that allow for assisted driving might be included in the analysis. The focus in the analysis of the first function lies on differences and similarities (technological focus, business models …) between primarily industrial actors that are attributed to their sectoral origins and on differences and similarities of the entrepreneurial landscape between regions (Germany/EU, USA, China)

Three leading questions should be answered by the analysis of entrepreneurial activities:

1. Who is engaging in the field of autonomous driving?
2. Are there regional differences between the entrepreneurial landscapes?
3. Do actors from different sectoral origins pursue the same technologies / business models around autonomous driving?

A broad set of different actors is engaging in the field of autonomous driving. The actors originate from the established automotive industries, but, to an increasing amount, form other sectors such as ICT or electronics. Regarding the analysis of entrepreneurial activity, the focus lies on industrial actors. The analysis of the entrepreneurial activities around autonomous driving builds on three types of data sources. Company data is extracted from Crunchbase database (Crunchbase 2022) in order to report key indicators as industrial backgrounds of companies, the regional spread as well as foundation years. The analysis of the data focuses on the generation of an overview of the industrial landscape in the field of autonomous driving and remains on a rather aggregate level. In addition to that, based on patent data, the most active individual industrial actors are identified. Lastly, information from companies' websites complements the analysis of the most active companies regarding their strategies and technological focus.

5.1.1 Firms active in autonomous driving

A broad search in Crunchbase database for all companies whose industrial classification[9] or description includes the search word "autonomous driving" and / or "autonomous vehicles" yielded 1,690 companies that, intensively or peripherally, engage in the field[10]. Each company is assigned to at least one, mostly numerous, industries in which the company is active. Figure 18 shows the industrial classifications that are named at least 50 times among all companies.

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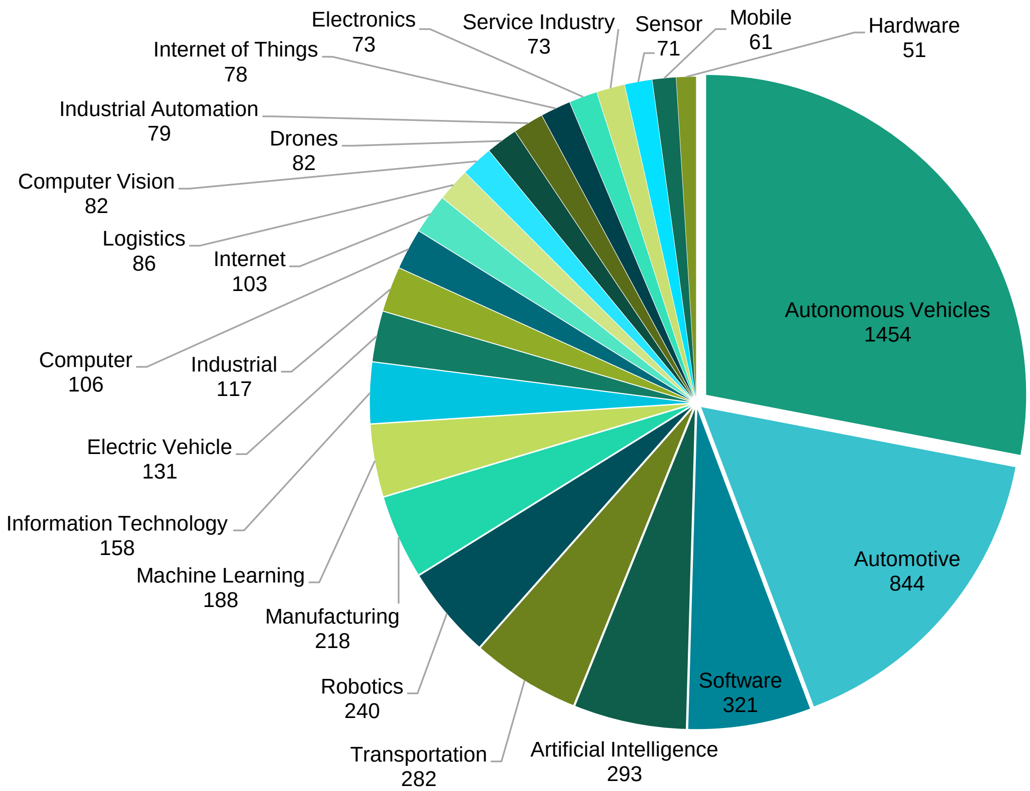
[9] Each company, listed in Crunchbase, is assigned to one or a number of industries. The classification is an exclusive classification and does not follow international industrial classification systems.

[10] The search was conducted on 01/17/2022, some mismatches may occur e.g. false positive hits in the field of aerospace technologies

Figure 18: Industrial classifications of companies active in autonomous driving (multiple entries per company possible)

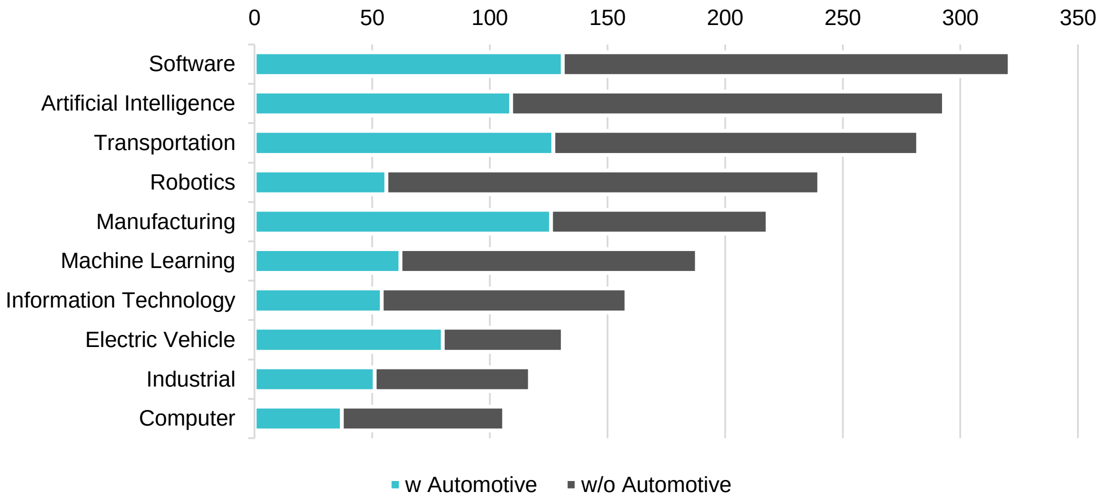


Source: Own representation based on Crunchbase (2022)

Next to "Autonomous Vehicles", which is named for nearly all of the companies, the industry descriptions named most often are "Automotive", "Software", "Artificial Intelligence", "Transportation" and "Robotics". The majority of the shown categories can be assigned to a broad understanding of ICT industries. Only a minority of companies engages in the field of autonomous vehicles according to their description, but is not assigned to the industry description "Autonomous Vehicles".

The strong representation of companies from non-automotive industries can also be shown via the analysis of the joint mention of exemplary industry descriptions with the industry description "Automotive". Figure 19 shows the Top 10 industries excluding "Autonomous Vehicles" and "Automotive" and displays how many of the firms within the industry are also attributed to "Automotive" blue bar). The gray bar illustrates how many companies are not attributed to "Automotive". In a majority of cases, the allocation to the industries "Manufacturing" as well as "Electric Vehicle" comes along with the allocation to "Automotive". Companies, assigned to the other industries such as "Software", "Artificial Intelligence" are assigned to "Automotive" in less than half of the cases. Even though "Automotive" represents the largest single industrial classification type in the field of autonomous vehicles, the majority of active companies focusing on ICT approaches to autonomous driving are not assigned to the automotive industry.

Figure 19: Mention of the Top 10 industrial categories in combination with „Autonomous driving"



Source: Own representation based on Crunchbase (2022)

While ICT related firms are present among existing firms in the autonomous driving field according to the Crunchbase search, they are not as prominently represented, when looking at patent applications. Due to the long process between the filing of a patent until the actual publishing, patent data can only be displayed with some time delay. Table 5 displays the list of firms that have in sum filed the most patents between 2005 and 2017 in the field of automated and autonomous driving. Details on the applied search strategy as well as the patenting activities of companies and countries are revisited in chapter 5.2 in the context of knowledge development. The table includes information on the location of headquarters, the sectoral background of firms, firm type, and foundation year.

Large and established automotive firms, both OEMs and suppliers lead the list of the Top 30 patenting companies between 2005 and 2017. Established firms partly profit from "older" patents that were filed in the beginning of the considered time period. The list indicates the increasing relevance of new actors from other sectors, while established players as e.g. Bosch still lead in the field. Patents mainly contain technological advancements that are hardware related and may contain some software application. Autonomous driving is referred to as a technological innovation, but it also requires a lot of software-related innovation. Software itself is not patentable in transnational patents, which are used in the analysis. This means that especially ICT firms that focus solely on software solutions are likely not to appear in patent based rankings.

Table 5: Firms patenting in the field of assisted and autonomous driving

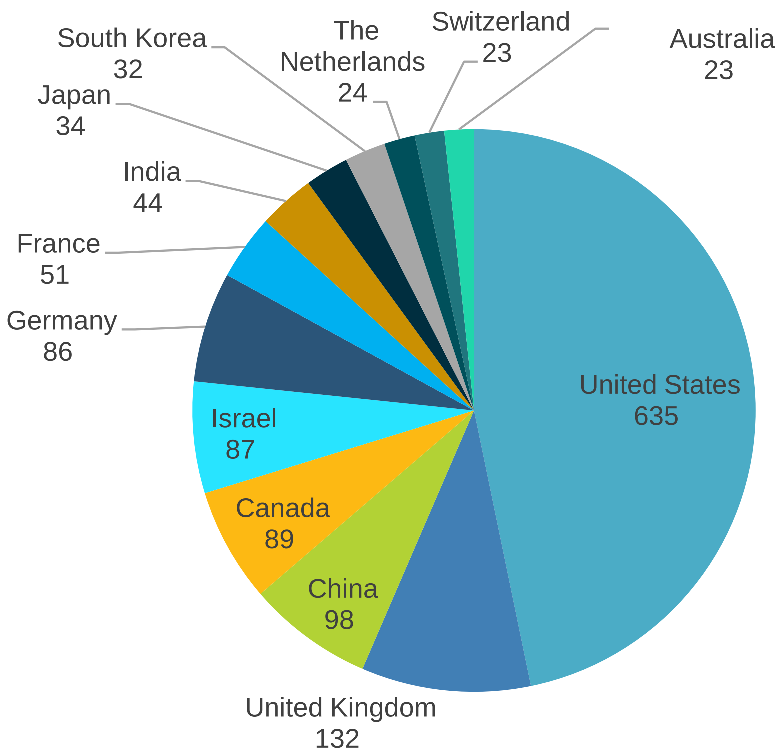
Rank 2017	Firm	Headquarter (country)	Sector / Industry	Type	Founding year	Total patents 2005 - 2017
1	Bosch	Germany	Conglomerate	Supplier	1886	840
2	Volkswagen group	Germany	Automotive	OEM	1937	676
3	Toyota	Japan	Automotive	OEM	1937	532
4	Continental	Germany	Automotive	Supplier	1871	497
5	Valeo	France	Automotive	Supplier	1923	461
6	Audi	Germany	Automotive	OEM	1909	326
7	Samsung	South-Korea	Electronics, telecommunication		1938	307
8	Denso	Japan	Automotive	Supplier	1949	283
9	Honda	Japan	Automotive	OEM	1948	273
10	Nissan	Japan	Automotive	OEM	1933	269
11	BMW	Germany	Automotive	OEM	1916	228
12	VW	Germany	Automotive	OEM	1937	227
13	Hitachi	Japan	Electronics, engineering		1910	212
14	Aptiv (former Delphi)	Ireland	Automotive	Supplier	2017 (1998)	193
15	Volvo	Sweden	Automotive	OEM	1927	192
16	LG	South-Korea	Electronics, appliances		1958	185
17	Aisin	Japan	Automotive	Supplier	1949	177
18	ZF	Germany	Automotive	Supplier	1915	170
19	Mitsubishi	Japan	Conglomerate		1870	163
20	Daimler	Germany	Automotive	OEM	1926	133
21	Panasonic	Japan	Electronics, appliances		1918	130
22	Renault	France	Automotive	OEM	1898	124
23	Stellantis	Netherlands	Automotive	OEM	2021 (PSA 1976)	117
24	Jtekt	Japan	Automotive	Supplier	1935	108
25	Waymo (incl. Google)	USA	Software		2009	95
26	Autoliv	Sweden	Automotive	Supplier	1953	95
27	Siemens	Germany	Conglomerate		1847	94
28	Ford	USA	Automotive	OEM	1903	90
29	NSK	Japan	Automotive	Supplier	1916	83
30	Scania	Sweden	Automotive	OEM	1891	81

Source: Own representation based on PATSTAT, already published in Sievers and Grimm (2022)

5.1.2 Regional origin of firms

Almost half of the relevant companies that are listed in Crunchbase, are located in the USA (drawing from their headquarters' locations), as can be seen in Figure 20. The figure shows the region and number of located companies, while only countries are displayed which host more than 20 companies. The USA is followed by the United Kingdom, China, Canada and Israel. Germany ranks sixth. In the USA, a clear regional concentration can be observed. With 245 of the identified 635 companies, California hosts the majority of industrial actors, followed by the state of New York, which hosts 41 companies. In Germany, most companies are located in Bavaria (19), Berlin (16), Baden-Württemberg (15) and North Rhine-Westphalia. In China, Beijing (36), Shanghai (19) and Guangdong (15) are the most relevant locations to companies active in the field of autonomous vehicles.

Figure 20: Location of headquarters of companies active in autonomous driving



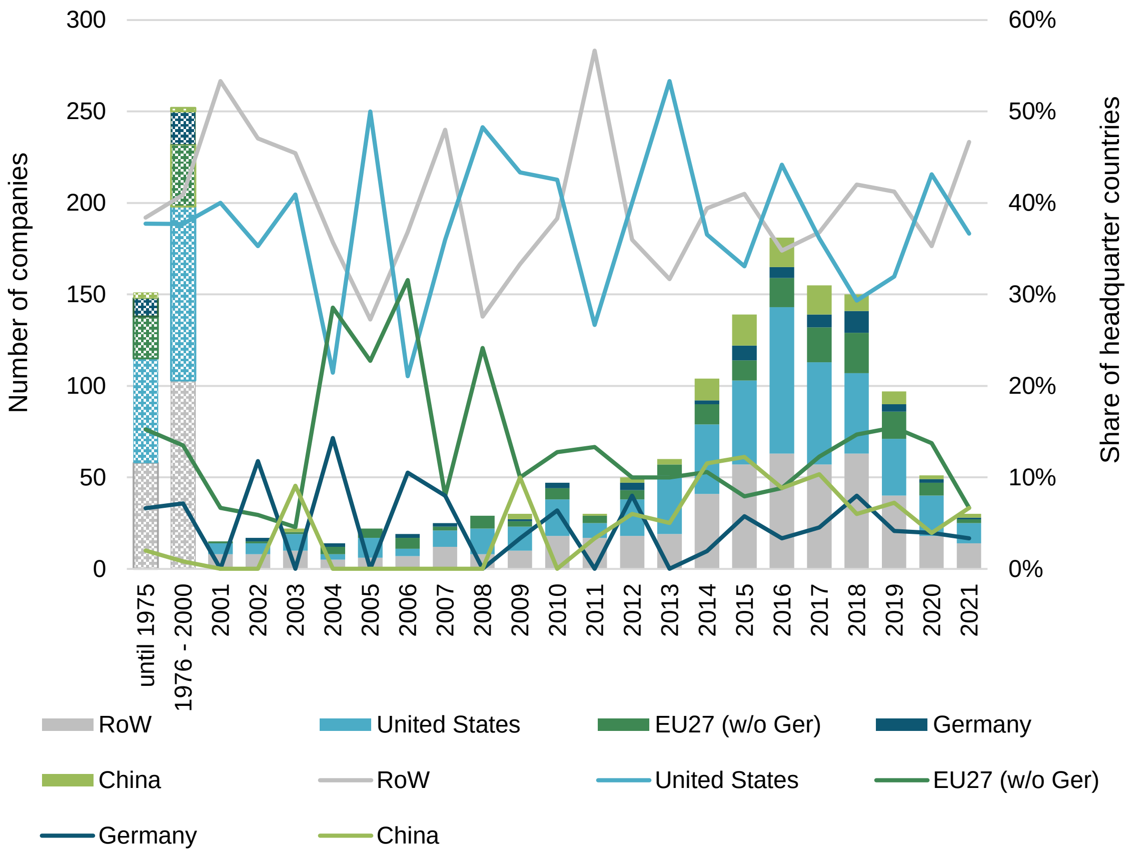
Source: Own representation based on Crunchbase (2022)

Almost 1 300 of the 1 690 identified companies that are now active in the field of autonomous vehicles were founded after 2000, which corresponds to 75%. Figure 21 shows the development of aggregate foundations until 1975, between 1976 and 2000, and for each year between 2001 and 2021. The bars, referring to the primary axis, represent the number of companies founded in that year / time period. They distinguish between foundations with headquarters in the USA, Germany, EU27 without Germany, China and RoW (rest of the world). The line graphs, referring to the secondary axis, represent the share of foundations in one country or country group compared to all relevant foundations.

The data shows a high number of foundations of new companies between the years 2014 and 2019 with a peak of 181 foundations in 2016. Foundations started to rise around 2010 (with a drop in 2011), started to decline 2017 and fell back to 2010 levels in 2021. Throughout the years, the group of USA, EU27 and China account for more than 50% of foundations (exceptions: 2001, 2011). The USA accounts for the most foundations conducted out in one country or country group per year.

The share of foundations in the USA fluctuate around 40% of all relevant foundations. Exceptions occur in 2004 and 2006, when EU27 records more foundations, however, absolute numbers were small and the indicated shares not as conclusive. While no clear trend is observable regarding country shares, China tends to increase its activity, even though Chinese foundations remain on a lower level compared to foundations registered in the EU27 during the past five years. While US foundations have been on a high level throughout the observed period, an increasingly strong position of US companies in the field of autonomous vehicles in the recent years is not shown by the data.

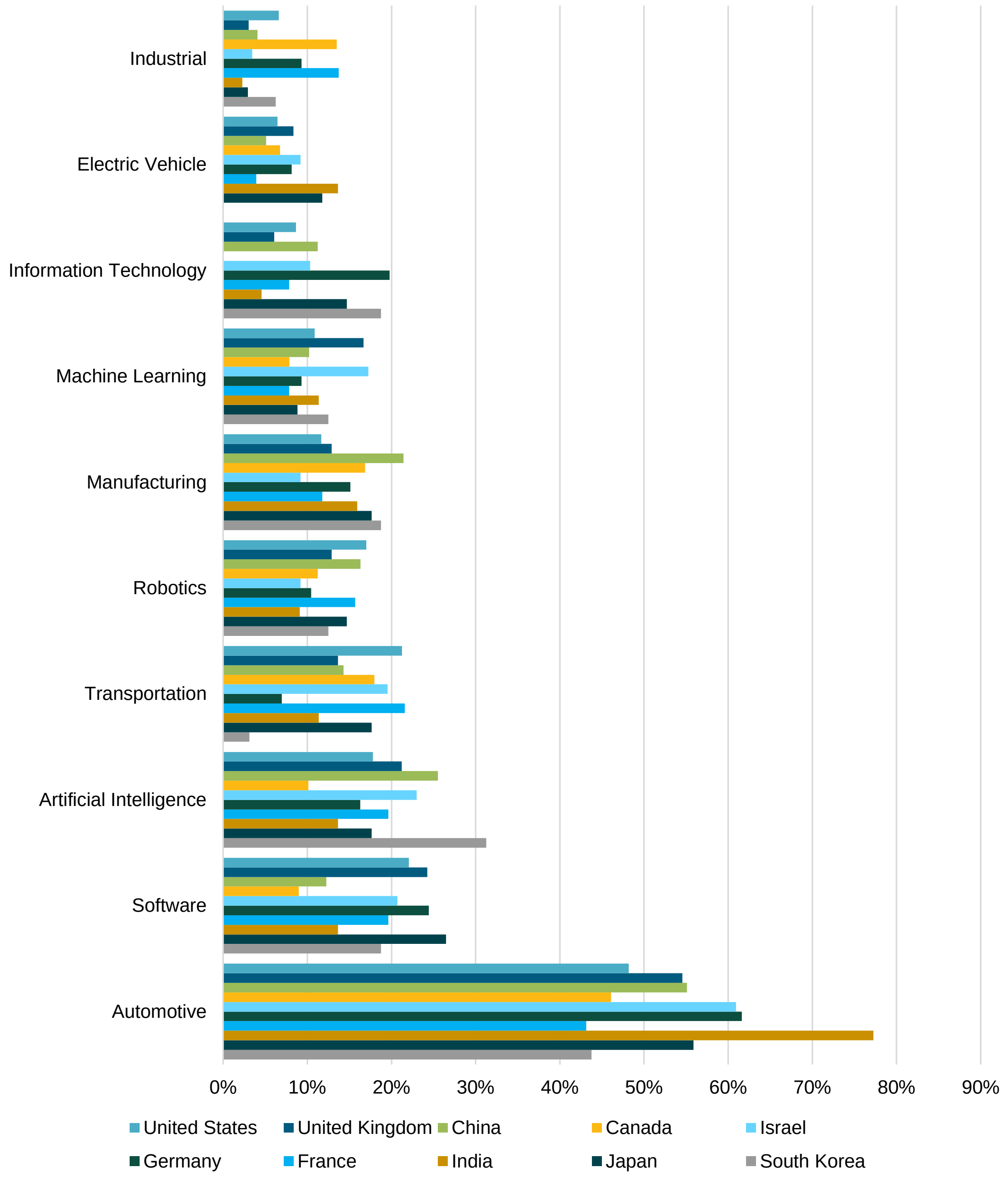
Figure 21: Founding years and headquarter locations of companies active in autonomous driving



Source: Own representation based on Crunchbase (2022), variant published in Grimm and Walz (2024)

The activity of companies may vary between countries regarding their industrial or sectoral backgrounds. In order to identify possible regional hotspots and to gain an impression of the industrial structure on the global scale, Figure 22 shows how many companies per country are assigned to selected industries. One company can be assigned to several industries, thus percentage points do not add up to 100 percent per country. The figure displays the shares of the Top 10 industrial classifications, as measured by number of mention, per Top 10 countries, as measured by the number of active companies.

Figure 22: Share of companies per Top 10 industries and Top 10 countries (multiple industry entries per company possible)



Source: Own representation based on Crunchbase (2022)

The analyzed data shows no clear trend or hotspot, the importance of the mentioned industries is mostly distributed among all op 10 countries. However, some countries do show exceptionally small or large shares in single industries. Being the most mentioned industrial classification, "Automotive" is assigned to around 50 percent of the relevant companies for the Top 10 countries. Germany shows a larger share of companies that belong to "Automotive" compared to the USA and China, although the gap remains small. India shows an over average relevance of the "Automotive" industrial classification that comes along a large share of companies assigned to "Electric Vehicle" classification. Next to India and Japan, all other countries show less than 10 percent shares of companies assigned to "Electric Vehicles". Taking the simultaneous development in the fields of the electrification of the power train and the digitization of vehicles and traffic the low shares might show the distinct activities of companies in the two fields: companies that engage in the field of autonomous driving sparsely focus on the “Electric Vehicle” as well.

The rather generic industrial classifications of “Software” as well as “Information Technology” are mostly assigned to companies from Germany, Japan and South Korea. Canada shows small shares, so does China in the “Software” field. The USA and the UK show over average shares for the “Software” classification but under average shares for “Information Technology”. Within in the more specific fields “Machine Learning”, “Robotics” as well as “Artificial Intelligence” country focuses vary. Israel as well as the U.K. show large shares in “Machine Learning”, the USA, China and France in “Robotics” and South Korea, China and Israel in “Artificial Intelligence”.

German companies are rarely assigned to the “Transportation” industry, which could be related to the strong automotive manufacturing background with a more product-oriented perspective. The USA shows large shares of companies that belong to the “Transportation” industry. Consistent with the established trend in outsourcing manufacturing activities to China, Chinese companies active in the development of autonomous vehicles are over average assigned to the “Manufacturing” industry.

With regard to the regional origin of firms, the analysis of firm foundations shows a different picture compared to the analysis of the Top 30 patenting firms that was displayed in Table 5 in the previous section. This was the case, looking at the sectoral origins, too. The country hosting the most foundations has by far been the USA, followed by the UK and China. The countries, where the most successful patenting firms are based, are Germany and Japan, who rank sixth and ninth, respectively, regarding foundations.

5.1.3 Technological focus of firms

The analysis in the preceding two sections shows the variety of firms, which are engaging in the field of autonomous driving, and the different sectoral backgrounds they originate from. The firms focus on different technological components, their integration or services. The central question to be answered is: Do actors from different sectoral origins pursue the same technologies or business models around autonomous driving? Or, put differently, can one observe typical engagement types of automotive or ICT firms in the development of autonomous driving that differ from each other? Since an extensive analysis of all active firms would be beyond the scope of the thesis, the focus was put on a comprehensive selection of important firms with different sectoral backgrounds. The question was approached by an in-depth, case-study like analysis of selected firms in February, 2022, regarding

1. the technologies in focus,
2. the formulated slogan the firm has for autonomous driving, and
3. the engagement in autonomous driving services.

The set of firms was conducted by starting from the list of the top patenting firms, presented in Table 5. The German OEMs (and their brands, explicitly Audi and Scania) were selected. Furthermore, Toyota and BYD as well as Ford and Tesla were added to the set, in order to represent the Asian and US region by one established and one younger OEM. All other non-OEM firms from the top 30 list were included. While collecting the information on the first selection of firms, other active firms that were named in related newspaper articles or press releases on e.g. cooperations or acquisitions were added to the set. A total of 40 firms from the automotive (22) and ICT sector (11), young firms that solely engage in the field of autonomous driving (5) as well as mobility service providers (2) were analyzed. The latter two categories could represent the new, emerging mobility sector, and are thus classified separately. They are considered to be closer to the ICT sector, since the majority of their product or service is about processing information, may it be from sensors in vehicles to let them drive autonomously or on platforms to match and provide rides.

Table A 1 displays the collected information and used sources in detail. Partly, difficulties arose when trying to distinguish between the distinct technologies one firm develops themselves and components that are bought in from suppliers. That was especially the case for OEMs, which integrate all components into their vehicles. Due to that lack of seamless overviews of technologies made available by the firms, some inaccuracies might be included. However, at least one field of activities was identifiable for all firms.

Drawing from the lists of technologies in focus, five fields of engagement were identified: full autonomous vehicle systems, autonomous vehicle components (including both, hard- and software), digital environment, information and communication solutions, and accompanying solutions such as simulation platforms or consultancy. Depending on the technological focus of each individual firm, it was assigned to either one or several fields. E.g. Denso, a Japanese automotive supplier provides environment detection systems (sensors, radar, lidar, cameras) and vision support systems as well as information security systems and cockpit information systems. Furthermore it develops quantum computing for a "Mobility IoT". Thus, the firm was assigned to the field autonomous vehicle components, digital environment and information and communication solutions.

The slogans of the firms regarding autonomous driving were extracted from the company websites. They are used in order to gain an understanding for the underlying strategy and business approach. Firms either formulate a slogan that is vehicle-oriented, that addresses the mobility system as a whole or that focuses on softer key aspects such as security or trust. Some firms did not have a specific vision slogan formulated for autonomous driving or provide a rather broadly formulated slogan at the time of the analysis. Each firm that provides a vision on autonomous driving was assigned to one of the above named four specific topics or the category "other aspects".

The engagement in mobility services with autonomous vehicles was identified mainly via press releases or newspaper articles on pilot projects as well as information on company websites. The activities are listed for each firm. Two types of mobility service orientations were identified: first, firms that provide on-road autonomous services via their own platform and secondly, firms that provide the accompanying technologies or other solutions. Ford and DiDi, for example, run robotaxi services together, where Ford provides the vehicles and DiDi parts of the automation technologies as well as the platform. Since customers book the trips via DiDi, it is classified the on-road service provider. Furthermore, DiDi also provides enabling technologies in the vehicles and thus is part of the second orientation, too. Ford only provides accompanying technologies in form of vehicles.

To give an overview of the activities of the selected firms, Table 6 summarizes the assignment of firms (technological focus, vision, mobility services) with regard to their sectoral background. It is pointed out that the set of firms does not provide a fully representative sample of all firms engaging in the field of autonomous driving. In addition to that, in the highly dynamic entrepreneurial landscape firms may change their activities and focuses within short time periods. The overview thus represents a snapshot from February, 2022. Still, certain tendencies are observable.

Firms from the automotive industry show more activity in developing autonomous vehicle systems and providing the technological components for autonomous vehicles. Especially OEMs focus on the integration of the different components in their vehicles in order to provide autonomous driving, which recently also includes the development of own operating systems for most of the analyzed OEMs. Focuses in the in-house development of specific technological components by the OEMs were not identified. In contrast, firms from the ICT industry mainly appear in the role of component, digital environment as well as information and communication solution developers. It indicates a complementary separation of activities or roles in the autonomous value chain along sectoral boarders, corresponding to the core fields of their usual activities.

Table 6: Overview of autonomous driving activities of firm selection

Company types	*total*	Technologies					Slogans						Mobility Services		
		Fully autonomous vehicle systems	Components	Digital environment	Information / Communication solutions	Accompanying solutions	Vehicle-oriented	Mobility system	Safety	Trust	Other aspects	None	On-road services	Accompanying solutions	Both
Automotive	*22*	12	11	2	1	0	7	4	1	1	1	8	2	11	2
ICT	*11*	1	7	4	4	3	1	3	0	1	1	5	4	3	2
Autonomous vehicles	*5*	4	1	3	0	0	2	0	2	0	0	1	0	2	2
Mobility services	*2*	1	0	1	1	2	0	1	0	0	0	1	2	1	1

Source: See Appendix Table A 1 for detailed information on sources

Examples such as SONY, who introduced their own Vision-S autonomous vehicle on the Consumer Electronics Show (CES) in Las Vegas in January 2022, are hard to classify in this context (Sony 2022b). It remains unclear whether SONY plans on producing their own vehicles on a large scale or whether it serves as a prototype for testing their solutions. The entrance of ICT players in the autonomous vehicle production is continuously discussed (other example: the Apple car) but not yet implemented. Other firms such as Foxconn, a contract manufacturer for Apple, introduced electric vehicle prototypes and announced the goal to become a vehicle manufacturer (Foxconn 2022). The firm describes an open electric vehicle platform that can be configured according to wishes of the customers, including the compatibility with external self-driving systems. Other press releases of own vehicle lines of ICT firms mostly refer to cooperations with established OEM such as the DiDi and GAC Group who partner to "accelerate the development and mass production of fully self-driving EV's" (DiDi 5/17/2021). The production of battery-electric vehicles can be considered less complex compared to vehicles with internal combustion engines, which eases the entry of new players and allows for further shifts in established automotive production systems in the future.

Four out of five analyzed firms that solely engage in the field of autonomous vehicles focus on the development of the entire self-driving system. Interestingly, all four firms are strongly backed by established firms from both, the automotive as well as the ICT industry. Argo AI profits from large investments by and partnership with Ford and VW (Argo AI 2020), Mobileye was inquired by Intel in 2017 (Mobileye 2022a), Waymo continues the Google driverless car project as an Alphabet firm (Waymo 2022a) and Cruise is GM's autonomous driving spinoff (Tanenblatt 2022). Mobileye and Waymo also engage in mapping.

In the field of mobility service providers, Uber and DiDi were selected for analysis towards engagement in autonomous driving. Uber strongly focuses on its role as a mobility service platform provider, after selling its own autonomous vehicle division to Aurora (Metz and Conger 2020), an autonomous vehicle startup founded by former high position employees of Google's self-driving car project, Tesla's Autopilot division and Uber's autonomous vehicle program (Ohnsman 2021). Uber keeps shares in Aurora and pilots autonomous food deliveries with Aptiv and Hyundais Joint Venture Motional (Agustin 2021). DiDi offers a large set of mobility services and works on many ends in the field of autonomous driving. Next to the development of self-driving systems, DiDi also provides cloud technology, AI labs for testing purposes and aims at building smart transportation systems, not limited to autonomous cars (DiDi 2022a, 2022b).

Firms that were identified as digital environment providers often include other aspects next to the mapping of autonomous vehicles in their approaches. They aim at providing a Mobility IoT (Denso 2022b), building digital twins of cities (Siemens Mobility 2022b; Denso 2022a) and offer technologies and solutions for intelligent transport systems (Intel 2022b).

Only half the firms with an automotive or ICT background publish a distinct slogan regarding autonomous driving. The majority of automotive players puts the autonomous vehicle in the center. Aspects as safety or trust are prominently communicated by component suppliers.

The majority of firms, among all firm types, does actively engage in the field of mobility services. While automotive firms mostly provide the vehicle hardware (OEM) or components (suppliers) for the on-road (pilot) services, players from the ICT industry rather host the platforms themselves. All of the analyzed actors engage in autonomous mobility services in cooperations among several firms only. These cooperations are further discussed in section 5.2.4. The large German automotive suppliers Continental, Schaeffler and ZF all introduced or announced autonomous vehicle concepts, which are oriented towards shared shuttle transportation rather than private autonomous cars. Currently, the projects still remain in the development or conception process. The information gathered on the firms' activities, which was presented here, will be revisited in different contexts during the following sections.

5.1.4 Implications

The analysis of entrepreneurial activities, using data on the foundations of firms and on the patenting activities, reveals different patterns of engagement along both, sectoral and national borders. While still the automotive orientation is present for half of the active firms, the majority of ICT firms that engages in autonomous driving, are not associated with an overall automotive orientation. ICT firms from fields such as "Software", "Artificial Intelligence", or "Robotics" make up a large number of participating firms and new foundations. The USA, the UK and China rank top when it comes to founding activity and headquarter locations. In contrast, among the most active firms in patenting on autonomous driving, there are mainly established automotive firms, including OEMs and suppliers. Only a few ICT firms are ranked among the top patenting firms from 2005 to 2017. Furthermore, Germany and Japan are ahead counting headquarter locations of the top patenting firms. The top patenting firms over the whole considered period are established players. Only three were founded after 2000, whereas, only Waymo is a "real" young firm. Aptiv was founded in 2017, but resulted from a restructuring of Delphi, Stellantis was founded in 2021, but is merger of a group of automotive OEMs that have themselves been founded back in time.

The two indicators show that on the one hand, the total of firms that engage in autonomous driving is characterized by both, automotive and ICT oriented firms, which are, to a majority, founded after 2000 and are mainly located in USA, UK and China. On the other hand, the top patenting firms are by a majority established automotive firms and are mainly located in Germany and Japan. For both indicators different time periods were considered (Crunchbase: until 2021, patents: 2005 - 2017). Patent data always contains a certain time lag, due to the processing of the patents from application to release. When considering the current edge of the patenting activity, the presence of ICT firms increases (see section 5.2.2), while it is not enough to make it up to the top 30 patenting firms over the whole period. The dominance of automotive firms in patenting thus may be challenged on the basis of updated data for the recent past and further development.

The engagement of different firm types in a variety of thematic fields of autonomous driving sheds some light on the differing technological focus of firms, while there was no distinction observable regarding the technological focus of countries. Regarding their technological orientation, the automotive firms in the set of considered actors mostly engage in developing fully autonomous vehicle systems and technological components. Also, the automotive firms' slogans highlight their vehicle-orientation. ICT firms seem to concentrate on technological components, the digital environment and information and communication solutions. The focus of firms that only focus on automotive driving cannot be attributed to a subset of technologies. Interestingly, the few that were studied, are all in partnerships with large automotive and ICT players, which suggests complementary competencies between the participating firms in the partnerships. Firms that were founded solely with regard to the area of mobility services do not focus on vehicle technology much, but rather the surrounding and infrastructure. Regarding the activity in mobility services, much dynamic is expected and all firms engage in some way. The automotive firms mainly focus on supplying the hardware, ICT firms rather focus on the platforms. While there are still some overlaps observable in the technological and service fields, there are many fields in which the impression of complementary engagement among automotive and ICT firms emerges.

On the global level, many established firms as well as new firms engage in the field of autonomous vehicles and autonomous driving. Especially the number of foundations shows the high expectations that both, entrepreneurs but also the capital markets, have in the technology from the economic perspective. Thus, generally speaking, the function of entrepreneurial activities in the innovation system of autonomous driving seems fulfilled on the global level. Differences arise when looking at the regional spread of entrepreneurial activities. There are some countries with high activity in different forms, but also many that do not show a lot of activity. While it is probably more likely, that firms from the active countries as USA, Germany, China, Japan or UK will be leaders in the future autonomous driving market, it remains unclear, where the value generation takes place in the future. Global production networks spread the generation of value added across the different production stages and thus across participating countries. Furthermore, an increasing servitization of mobility shifts markets from being product-related to being service-related. That may entail differing patterns of market functioning and regional spreads (see chapter 5.4 on market formation for further detail).

Thinking about the future entrepreneurial landscape, it also comes down to the question of who is more successful in developing the components of a functioning autonomous driving system: established firms with large and grown technological and also production knowhow and capacities or a large number of younger firms that are software-focused and maybe more resourceful in trying out new ways of thinking. When is goes beyond "pure existence" and it is about the profitability of firms and their share in future markets, the power distribution and thus the realization of margins in future value chains will play a role beyond the technological and service-concept related competence in providing autonomous driving.

5.2 Knowledge development and diffusion

While the idea of autonomous vehicles and mobility has existed for decades, more recent technological achievements, especially in the fields of computing and artificial intelligence, have enabled the actual implementation of autonomous driving functions in (prototype) road vehicles. A bibliometric search in the Scopus database and the already mentioned patent registrations are used as classical indicators for the observation of knowledge development over the course of time and allow for a comparative analysis of the activities of different countries, and, in the case of patents, for the sectoral engagement (Hekkert et al. 2007). While publications are often related to rather basic research and the activity in universities, patenting in the field of autonomous driving is pursued mostly by companies. For both, the academia and industry, the posed research questions are on the one hand, how have R&D activities evolved in the course of time, and, on the other hand, can one observe differences in the dynamics between countries and between the two sectors in focus, the automotive and the ICT sector.

The technology of autonomous driving not only needs knowledge development, but especially the mutual exchange and combination of automotive and ICT knowledge and competencies. Furthermore, the patterns of diffusion of knowledge between the two sectors and different modes of partnerships are studied along selected examples.

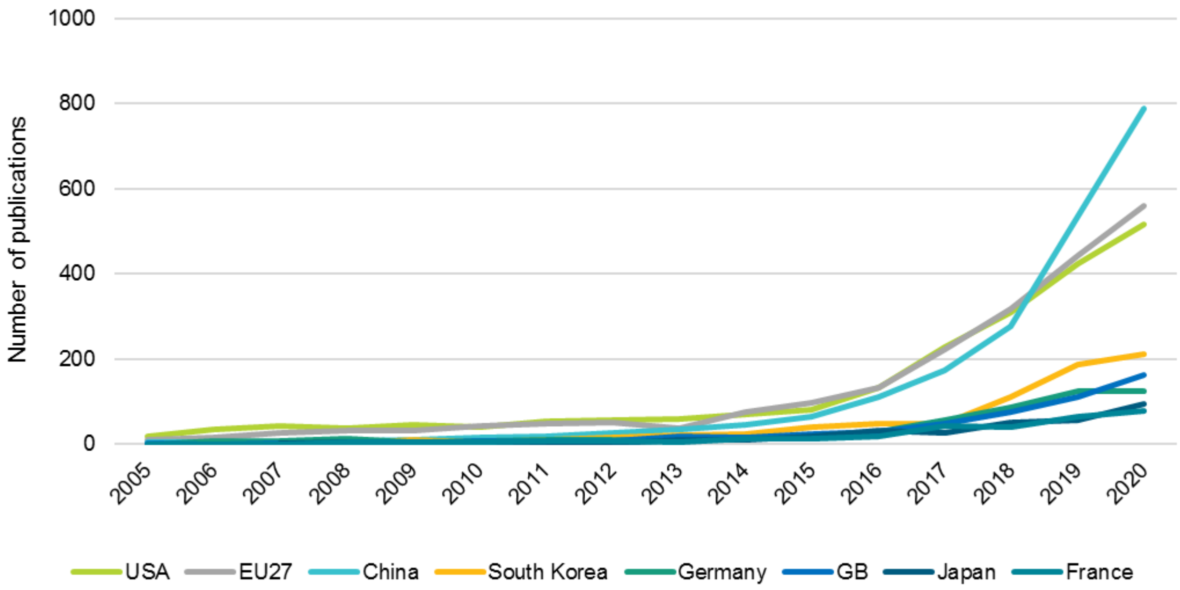
5.2.1 Knowledge development in academia

The industry or entrepreneurs picking up the development of a technology is in many cases preceded by achievements in basic research. Universities and other research institutions play a crucial role in this type of basic knowledge development. Regional networks and clusters around universities profit from their activities.

The activity of universities in the field of autonomous driving is analyzed by looking at scientific publications in Scopus. While the patent analysis, mentioned in section 5.2.2, did not show much activity of universities, it is mainly universities that publish scientific papers. A basic search strategy was applied that included the search terms “autonomous driving”, “self-driving car”, “driverless automobile”, “vehicle-to-vehicle” and permutations of the terms. Results that focused on underwater, water, or railway transportation were excluded. While some publications on transferable knowledge might have been neglected, the primary goal was to only include publications that clearly relate to autonomous driving. The strategy was chosen to be parallel to the principles that the patent search strategy was built on.

Figure 23 displays the number of publications that match the search criteria from 2005 to 2020. The USA and the total of the EU27 were the first to show notable activities in scientific publications on autonomous driving. Numbers of publications accelerated from about 2015 onwards. China started to catch up after 2010, finally passed the USA and EU27 in 2019 in terms of total publications and ranked first in 2020 with around 50% more publications than the USA or EU27 that have evolved similar to each other. Publications by actors from the established automotive nations such as Germany, Japan or South Korea increased in number only after 2016 or 2017 with some delay to the leading three countries or regions.

Figure 23: Publications in the field of autonomous driving by country, 2005-2020



Source : Own representation based on Elsevier Scopus, variant published in Grimm and Walz (2024)

In the early years, the thematic focus of publications was on the technological components and related aspects, required for a functioning autonomous vehicle. In the past years, publications on more systemic topics such as the social impacts and integration of autonomous driving have increased, being the thematic cluster with the most publications in 2019 (Mora et al. 2020).

The majority of publications in the field of autonomous driving is conducted by university scientists. Public awareness for the universities' activities, however, is rather raised by project work or popular autonomous vehicle prototypes. One of the most popular international events has been the DARPA Grand Challenge that was first organized in 2004 and funded by the US Defense Department (World Intellectual Property Organization 2019). The task was to let a self-built or rather self-upgraded vehicle autonomously drive from a starting to an end point. No team finished the task in 2004, the second challenge in 2005 was won by the Stanford University team and the 2007 challenge by the team of Carnegie Mellon University, Pittsburgh. Stanford University finished second. The fact that the two winning teams' universities are not among the US Top 5 publishing institutions shows that less publications must not necessarily mean less activity or less success. However, the majority of universities that appear in press are also on the top publishing list such as Tsinghua University in Beijing, China, Oxford University in England, Massachusetts Institute of Technology in Boston or Seoul National University in Korea (Salter 2021).

In the field of autonomous driving, universities do not only to conduct basic research and design prototypes, but apparently bring forth entrepreneurs. That was especially the case for the members of the two winning teams of the DARPA Grand Challenge. More than a handful of them worked with Waymo and later on acted as co-founders of well-known mobility start-ups as Zoox, Argo AI or Aurora, which suggests a dense network, at least in the USA.

5.2.2 Patent applications by the industry[11]

In contrast to publications, patents are considered to map the development status of a technology closer to implementation. In order to study the development of patent applications and to identify national as well as sectoral differences in patenting activities, a search strategy was developed. The technological areas that were investigated cover components

- for recording the vehicle environment, data processing and analysis, and decision-making mechanisms,
- vehicle handling, e.g. control of automated driving maneuvers,
- communication technologies for data transmission, networking and co-operation between vehicles, and
- intelligent traffic systems and infrastructures.

The analysis includes patents that provide concepts and solutions for completely driverless driving, as well as those that include technologies for assisted and (partially) automated driving. Vehicle digitization in the sense of entertainment applications and the digitization of vehicle production are not explicitly considered.

In the field of automated driving, technologies and approaches from the classic automotive industry are merging with information and communication technologies, which makes it difficult to draw a clear line between the relevant patent classes and patents. In the current state of the classification systems "International Patent Classification" (IPC) and "Cooperative Patent Classification" (CPC), specific subclasses with a concrete reference existed in some cases, which could be selected and directly assigned for the analysis (status beginning of 2021). At the same time, patent classes that deal with the many required basic technologies must or can be included. An example is data transmission or image processing, which are also used in other applications. Here, the question arises to what extent the technologies have been developed specifically for the application of automated driving and to what extent the patent activities are meaningful for evaluating the innovation capability of a country / a company for the automotive / mobility sector. A look at existing evaluations and analyses of patent activities in the field of automated driving reveals differences in the patent figures determined and thus the strong dependence of the results on the search strategies selected in each case (European Patent Office 2018; Meng et al. 2019; Ji et al. 2020). The conducted analysis here follows the principle that patents can originate from a broad spectrum of technologies, but must contain a clear reference to the use case of automated driving.

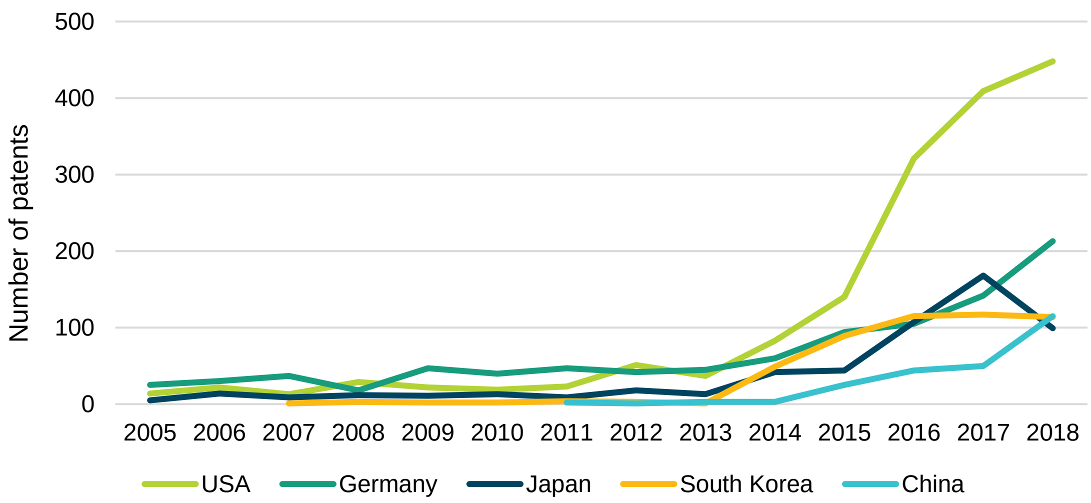
In the first variant of the search strategy, patents are counted whose titles or abstracts contain the words car/vehicle/driving in combination with autonomous/V2X/connected (search strategy 1: autonomous/connected). Here, only those patents are counted that contain a clear reference to the overall concept of autonomous or driverless driving as well as technologies for vehicle communication. The second variant represents an extension and, in addition to the results of the first variant,

[11] The search strategy was developed within the study Sievers and Grimm 2022: “Innovationstätigkeit des Automobilsektors”, funded by Expertenkommission Forschung und Innovation (EFI), an independent consulting institution for the German government. The description of the search strategy and results have in part already been published in Sievers and Grimm 2022 in German language. Similar wordings appear. Anna Grimm was responsible for the development of the patent search strategy on autonomous vehicle technologies and the related analysis.

also contains the patents in which the words such as car/vehicle/driving occur in combination with surrounding/environment/assist* (search strategy 2: search strategy 1 + assist*/surrounding). In the second search strategy, technologies for assisted driving, such as environment recognition, are added. Some of them are already included in currently approved vehicles or can be described as predecessor or individual technologies, i.e. they may also be relevant for autonomous vehicles in the future. Transnational patents, registered at the European Union intellectual property office (EUIPO), were searched via PATSTAT.

Figure 24 displays the results for the first variant of the search strategy, thus the registered patents that cope with the full concept of autonomous driving or autonomous vehicles between 2005 and 2018[12]. Figure 25 shows the results for the second variant, which also includes technologies for assisted driving.

Figure 24: Number of patent applications by countries – Autonomous driving (search strategy 1)



Source: Own representation based on Sievers and Grimm (2022)

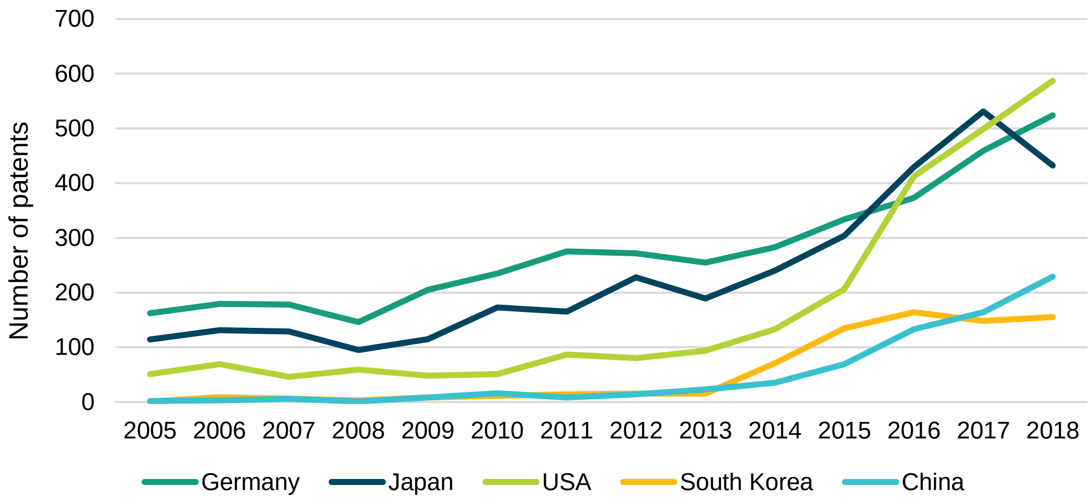
A strong increase in patenting activities is visible from 2013 onwards. The steep rise is more obvious in the results of the first variant, where it follows eight years of only moderate patenting numbers (Figure 24). In contrast, numbers of patents regarding assisted and autonomous driving (second variant) were on a much higher level between 2005 and 2012 (Figure 25). The figures show the chronology of technological development focus and the shift from the "partial" solution of assisted driving functions, which are sold in cars for quite some time now, to the full concept of autonomous driving, which has only appeared in the recent past. However, the partial technologies still play a large role in the overall development of autonomous driving components. For instance, in 2017, only about 150 of 450 German patents focus on the full autonomous driving concept, while the remaining cope with the components already needed for assisted driving.

In assisted and autonomous driving, Germany, Japan, and the USA show high activity for the whole time period, while China's participation has increased only lately. When focusing on patents on autonomous driving technologies only, Germany and Japan fall behind the USA who register the majority within the field of autonomous driving. The German and Japanese performance can be

[12] Patent registrations for 2018 were still preliminary at the time of analysis in spring 2021.

related to their roles as large automotive industries, where applicable assisted driving functions have for long been in focus of the established automotive firms.

Figure 25: Number of patent applications by countries – Assisted and autonomous driving (search strategy 2)



Source: Own representation based on Sievers and Grimm (2022), variant published in Grimm and Walz (2024)

Figure 26 and Figure 27 show the results for the leading companies. On the left of each graph, the timeline of patent registrations from 2005 to 2018[13] is displayed. On the right, the total of patents registered by the most active firms between 2005 and 2018 and 2015 and 2018 is showed. The development of companies' activities over the course of time show the same pattern as the national perspective. When focusing on the full concept of autonomous driving, activities increased significantly after 2013, while patents applications with regard to assisted and autonomous driving have appeared earlier.

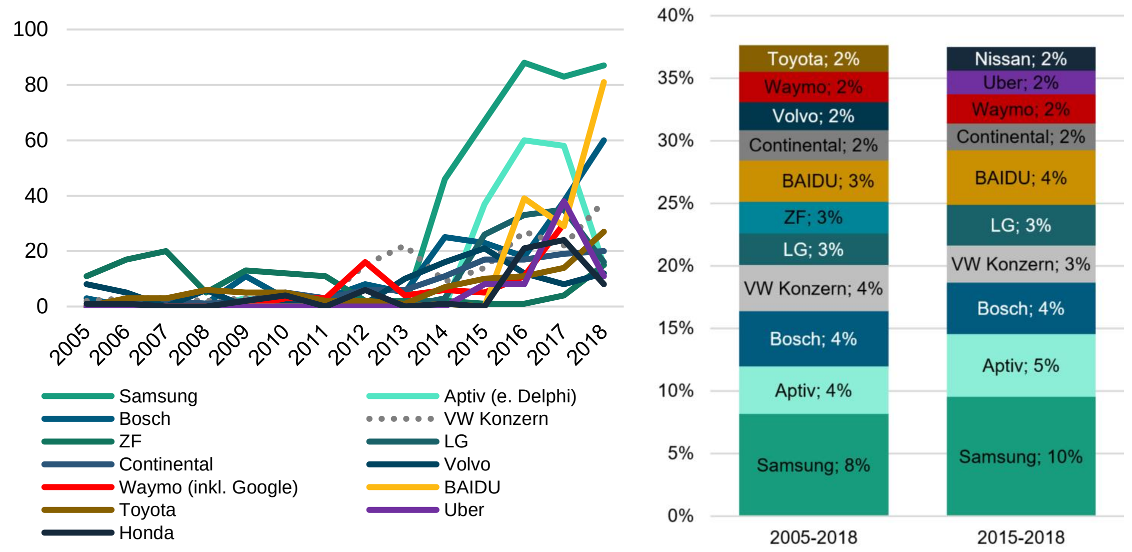
The set of active firms changes when comparing the two search strategy variants. Companies that cover the assisted and autonomous driving technologies are mostly from an automotive background. The most active companies that focus on the full system of autonomous driving have different backgrounds. While Aptiv, Bosch, Volkswagen, ZF, Continental, Volvo and Toyota are established automotive firms, Samsung, LG, BAIDU, Waymo and Uber can be counted to the broader ICT sector.

Dynamics also become visible when comparing the results for the two time periods 2005 - 2018 and 2015 - 2018 for both search strategy variants. Almost all automotive firms lost in shares of total registered patents in the field of autonomous driving, while firms such as Samsung, BAIDU or Uber increased their shares.

As briefly addressed in the analysis of entrepreneurial activities, differences in the dynamics of knowledge development thus also arise from a sectoral perspective (Sievers and Grimm 2022). Automotive firms started to engage in the field of autonomous driving earlier, and especially in assisted driving, which could be understood as a precursor of autonomous driving. However, ICT firms are catching up, focusing on the whole concept of autonomous driving instead of the assisting technologies.

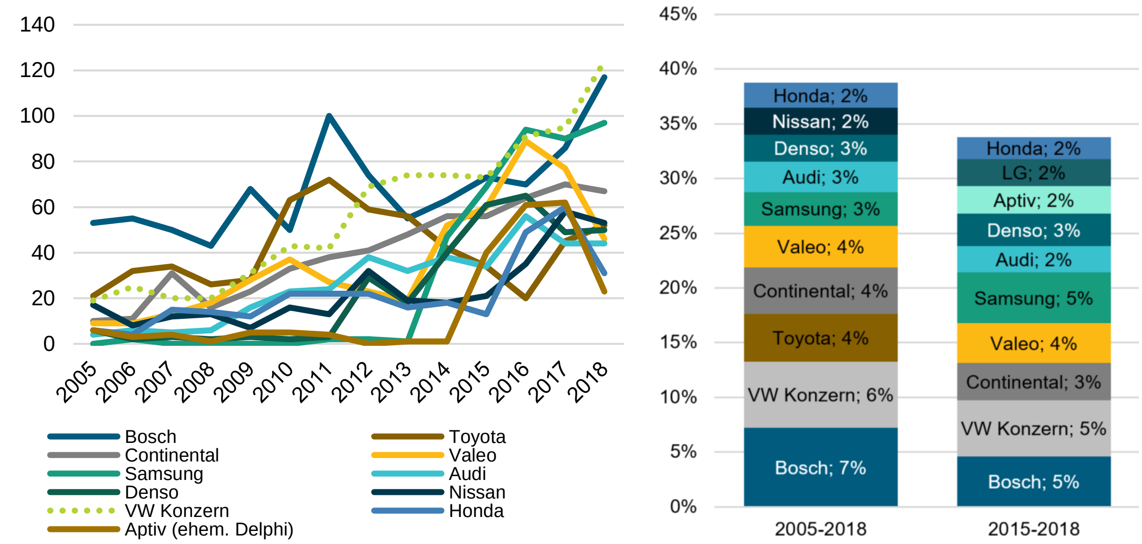
[13] Patent registrations for 2018 were still preliminary at the time of analysis in spring 2021.

Figure 26: Number of patent applications by firms – Autonomous driving (search strategy 1)



Source: Own representation based on Sievers and Grimm (2022)

Figure 27: Number of patent applications by firms – Assisted and autonomous driving (search strategy 2)



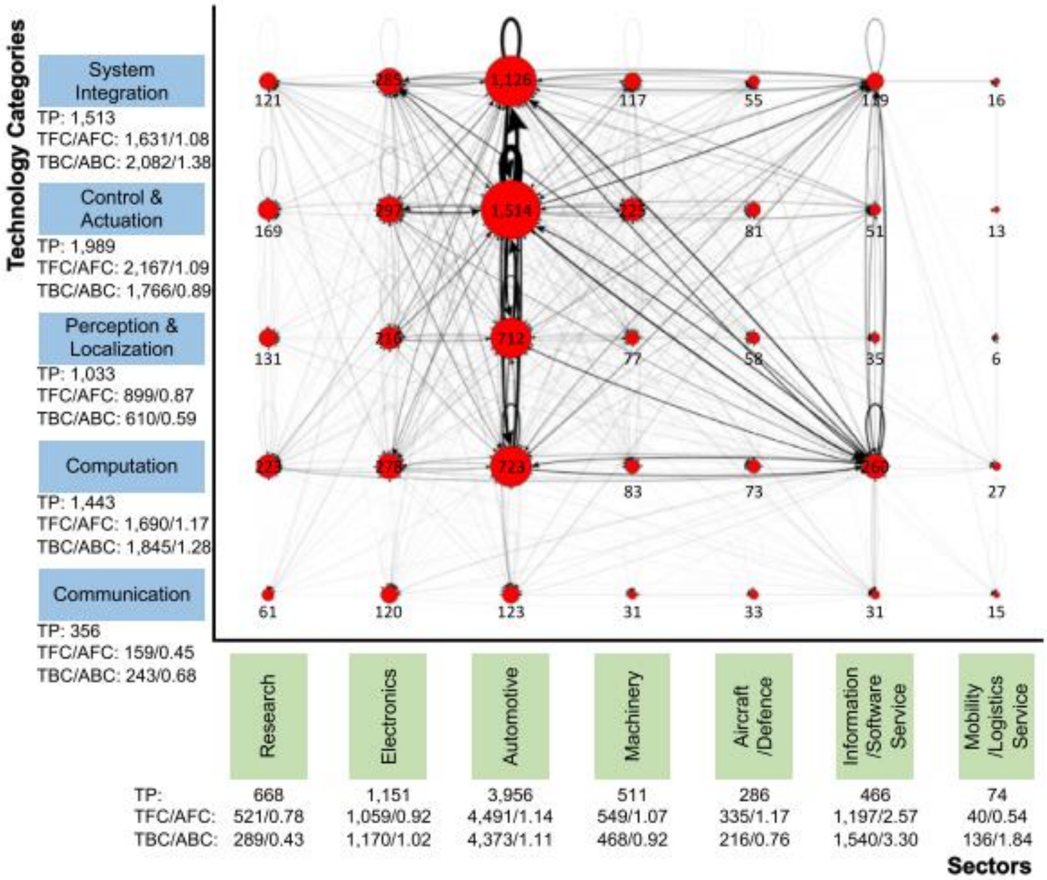
Source: Own representation based on Sievers and Grimm (2022)

It is pointed out that the distinction in full concept of autonomous driving and assisted driving or components to autonomous driving does not mean that one is possible without the other. While patents on the full concept of autonomous driving might be technologies that allow for the integration of singular technologies, these singular technologies, for instance sensors for the detection of the environment, are needed anyway in order to make fully autonomous driving possible.

5.2.3 Knowledge diffusion through industry, academia and governments

Next to patent registrations, patent citations give an indication on knowledge diffusion on the aggregate level. Meng et al. (2019) study the "distribution of patents and citations across sectors and technology categories in the autonomous vehicle TIS [between] 1997 – 2016". The authors show particularly high numbers of patent citations between the automotive sector and the electronics as well as the ICT sector (see Figure 28). While knowledge diffusion between the automotive and electronics sectors seems to have occurred from the beginning of the studied period, linkages with the ICT sector started to evolve from 2007 on. The automotive and ICT sectors also show different focuses and evolutionary paths regarding the technological fields in which they were patenting. While the automotive sector eventually started to patent in ICT core fields such as computation, the ICT sector mainly patented in its own core fields.

Figure 28: Distribution of patents and citations across sectors and technology categories in the autonomous vehicle TIS (1997-2016)



Notes: TP – total patents. An explanation of other abbreviations can be found in the note under Figure 1. Figure 10 is based on the same abbreviations, which will not be repeated. For the sake of simplicity, the number of citations, i.e., size of arcs, are not specified in the figure but are provided in Appendix C (Table C3).

Source: Meng et al. (2019)

The relevance of knowledge diffusion in networks is also on the agenda of governmental organizations. For instance in China, the Strategy for Innovation and Development of Intelligent Vehicles was introduced in 2020 (Schaub and Zhao 2020). The involvement of more than ten central governmental departments in the development of the strategy indicates cooperation on the political level. Furthermore, the strategy includes the intention to form an international industry cooperation platform. The NHTSA in the USA formed the Automated Vehicle Transparency and Engagement for Safe Testing (AV TEST) Initiative that focuses on improving safety, testing and public engagement and is supported by several states as well as companies (National Highway Traffic Safety Administration (NHTSA) 6/15/2020). In Germany, the National Platform Future of Mobility (NPM) was introduced by the government coalition in 2018. Besides other aspects, one working group focuses on the digitization for the mobility sector, including autonomous driving, which is steered by representatives from industry, organizations and (regional) governments (National Platform Future of Mobility 2022). While there are differences in how the initiatives are configured, the basis for exchange between actors from different origins is established in the major countries. All countries understand the technology of autonomous driving as a key competency for future economic success of the domestic automotive or mobility industry. Thus, there is high political interest in providing good framework conditions and support.

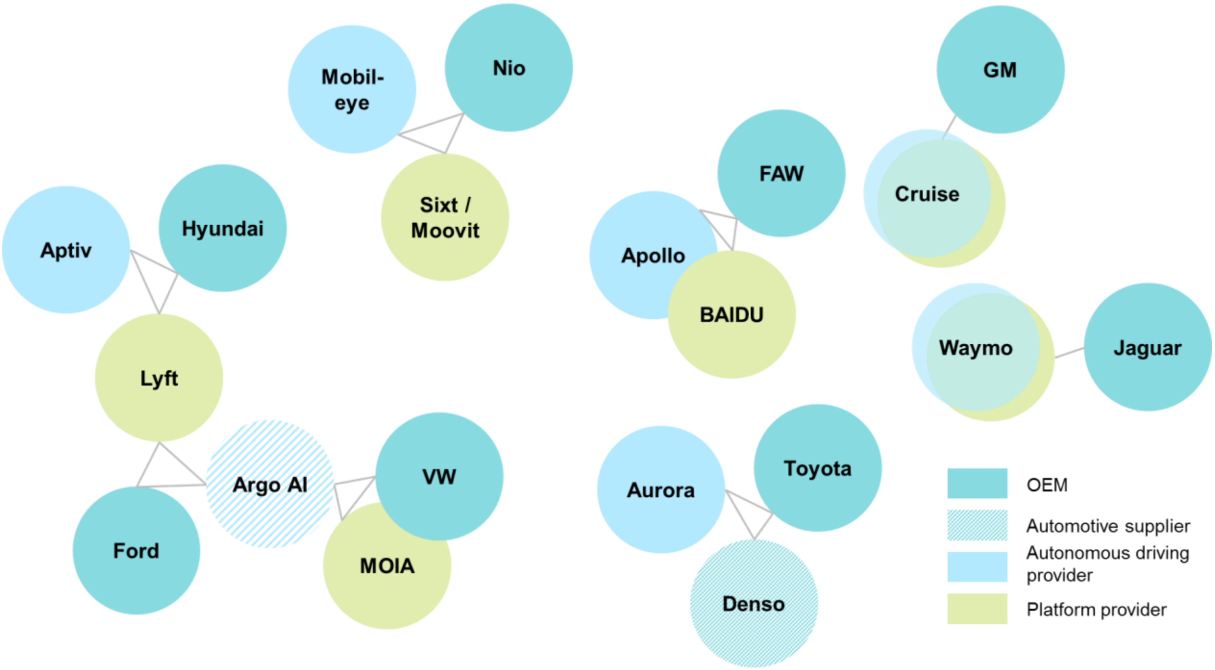
5.2.4 Partnerships in industry

The complexity of the technological system of autonomous driving, paired with the large investment requirements, especially for automotive firms that simultaneously have to adapt to the production of electric powertrains and implement digital and connected production principles, makes it hard for individual firms to build up the required knowledge by themselves. Cooperation among firms gains in relevance. Between 2010 and 2019 only, Hofstätter et al. (2020) estimate an increase from 10 to 380 partnerships in autonomous vehicle technologies, connectivity, electrification, and shared mobility.

In the field of technological development of autonomous driving functions, for instance, the OEM VW partners with Apollo on advancements in autonomous driving in China (Volkswagen 11/2/2018), with Microsoft on their cloud-based platform (Microsoft 2/10/2021), and with Bosch on the development of automated driving functions (Bosch 1/25/2022). The OEM Mercedes-Benz cooperates with Nvidia on computing capacity (Mercedes-Benz Group 2020), with Here on digital maps (HERE 2022), and with Luminar on lidar sensors (Mercedes-Benz Group 2022). After the announcement of partnerships, which are usually accompanied by press releases, it is partly hard to track the status and activities. For example, a partnership between Mercedes-Benz and Bosch, announced in 2018, was terminated in 2020 (Korosec 2020). While this is far from a full coverage of all partnerships, the few examples show the high dynamic in the field as well as the heterogeneity of partnerships that span globally and over sectoral borders.

Partnerships are also prominent in the testing of autonomous mobility services. Figure 29 displays some examples of recently announced cooperations for robotaxi projects. The teams show partly similar patterns in their configuration: autonomous driving technology providers equip the vehicles of OEMs and they partner up with platform providers to bring the services to the street. Strong linkages between the partnering firms exist, too. VW partners with its daughter company MOIA, BAIDU with its autonomous driving subsidiary Apollo. The partnerships again suggest a division of competencies along sectoral borders.

Figure 29: Examples of announced cooperation for robotaxi services



Source: Own representation based on companies' websites, published in Grimm and Walz (2024)

Besides partnerships in defined development or pilot projects, investments and M&A appear as other prominent strategies in order to gain competencies and to widen the own portfolio. In some cases, combinations of the different strategies arise, for instance Ford and VW partner with Argo AI in providing robotaxi services, as displayed in Figure 29, and both have also invested large sums in Argo AI. Furthermore, VW merged its in-house autonomous intelligent driving unit with Argo AI, which now are the headquarters of Argo AI Europe (Volkswagen 7/12/2019). The two automotive OEMs hold similar shares and will both cooperate with Argo AI independently, each developing their individual vehicles, in which Argo AI's technology is implemented. The press release names the US and European market as first target markets for the involved companies. Other examples of M&A activity from the ICT sector are Intel's acquisitions of Mobileye, the Israeli autonomous driving company and Moovit, an Israeli mobility platform (Intel 5/4/2020), or Amazon's acquisition of robotaxi developer Zoox (Taulli 2020). Acquisitions in the field of autonomous driving seem to serve as an important tool to acquire knowledge in the complex and diverse field of autonomous driving (Alvarez León and Aoyama 2022). Both, automotive and ICT firms acquire other companies that in turn have expertise in the field of autonomous driving technologies or in providing platforms for mobility services, and thus future robotaxi services.

5.2.5 Implications

Knowledge development in the field of autonomous driving has accelerated after 2010, as can be shown when studying publications in a bibliometric analysis and patents. While the majority of publications was conducted in universities and research institutions, the majority of patents has been registered by the industry. Researchers in the USA and China are found to be very active in publishing on the matter of autonomous driving. Germany and Japan have for long been the largest patent applicants in the field of autonomous driving, when including technologies that are also used for assisted driving in the second patent search strategy. The USA, however, have caught up, which is mainly driven by the enormous activity of US firms in the technologies focusing on vehicle communication and the full autonomous driving concept. From the firm perspective, it is mainly large automotive firms that rank high when looking at the broader definition of assisted and autonomous driving, however the firms lose in the share compared to all patents in the field. When looking at patents which target solutions to the full concept of autonomous driving only, it is both, automotive and ICT firms that are active in patenting. In the most recent past, ICT firms tend to slightly increase shares in total patenting activity in the field, while the shares of automotive firms slightly decrease.

The realization of autonomous driving requires the integration of components and solutions from both knowledge fields, automotive and ICT. As it has been shown in the previous section on entrepreneurial activity, actors from the automotive and ICT fields partly focus on complementary technologies and solutions. However, at some point the competencies and innovation have to be brought together. This requires a functioning diffusion of knowledge between, on the aggregate level, the two sectors including their different institutions. In the interdisciplinary field of autonomous driving, knowledge diffusion is considered a mode of knowledge development. Patent citations and the successful introduction of test vehicles (see section 5.4) show that the diffusion takes place. The results on patent citations suggest a technological focus of sectors: the automotive sector patents technologies in its own core field, but also in ICT fields, the ICT sector rather stays within its own core competencies. This goes in line with the findings in section 5.1.3, that the technological focus of automotive firms is on the autonomous vehicle and its components and that ICT firms concentrate on technological components, too, but also the digital environment and information and communication solutions. Taken together, these indications imply that automotive firms rather work on the integration of new components into the vehicle, the construction of the vehicle still being their core competency. While it is not clear what will finally be developed in-house and what will be bought in, the extension of their key automotive product with a variety of ICT components is targeted by the automotive firms. On the other hand, from the findings on the technological focus of ICT firms and the patent citations, ICT firms seem not to enter the classic automotive competencies but rather try to develop their core competencies with regard to an application in the automotive field. This underlines the complementary focuses in some fields among the automotive and ICT sector. Overlaps seem to exist rather with regard to who will develop certain software components: automotive firms as an extension of their existing products or ICT firms as their established products that are modified to the automotive application field.

Knowledge diffusion does not only happen implicitly with regard to the different sectoral knowledge fields, but is also very explicitly targeted in partnerships, investments and M&A activities of large firms. The various activities include firms from both, automotive and ICT backgrounds, who partner up in different constellations. In M&A it is mainly large ICT or automotive firms that acquire either mobility service platform providers or firms with technological expertise in autonomous driving components and systems. While the analysis of the entrepreneurial activities showed a lot of foundations, which can be regarded as a mode of creating variation in the number of firms and perspectives, especially M&A activities entail a consolidation in the entrepreneurial landscape.

5.3 Guidance of the search

The focus in the development of autonomous driving right now is much on the technological feasibility and the interplay between the many hardware and software components. By using data on disengagement in testing drives, provided by California state (California DMV 2022), technological bottlenecks are identified that give insight on the remaining technological challenges.

Despite the technological focus, much discussion is also ongoing on the application of vehicles. The development of regulatory frameworks in Germany, USA and China is analyzed (Hekkert et al. 2007), where much focus was on the circumstances, under which autonomous or automated vehicles are allowed to be operated on streets in real life conditions. The safety for passengers is a key issue and one can observe a high dynamic in the adaptation of regulatory frameworks on autonomous vehicles in recent years.

When autonomous vehicles are at some point entering markets in larger quantities and technology is advancing further, new questions and targets of regulation may come up. As it is for big tech companies with their digital services right now, the regulation of the digital sphere might accelerate. And autonomous driving, which is to some extent the accumulation in the combination of new tech, will be touched by that. Regulation may influence business models and technology development (Yun et al. 2016). Especially in the case of big tech, regulation is considered to play an important role in the focuses of firms and the way products, services and markets develop (Jacobides 2021). Right now, regulation of autonomous driving might be compared to guard rails, however, in the future, regulation is considered to increasingly guide how autonomous vehicles are applied. Regulation is also crucial to market formation, which is discussed in chapter 5.4. Since the technology of autonomous driving is targeted by the regulatory frameworks, independent of who provides the technologies or services, no sectoral comparison is pursued. It is rather the national differences in regulation and the dynamics that are in focus in section 5.3.2.

5.3.1 Technological bottlenecks

In order to implement autonomous vehicles in everyday traffic, basically two challenges have to be solved. First, the technology has to work safely and second, society has to agree on and define the form and rules of the usage of autonomous vehicles.

In California, all vehicle manufacturers or operators that test their vehicles in the "Autonomous Vehicle Tester (AVT) Program and AVT Driverless Program are required to submit annual reports to share how often their vehicles disengaged from autonomous mode during tests (whether because of technology failure or situations requiring the test driver/operator to take manual control of the vehicle to operate safely)" (California DMV 2022). The reported data is available online to the public. The most recent 2021 dataset is used in the context of the thesis (California DMV 2022).

The data includes information on the name of the manufacturer, the date of the disengagement incident, the permit as well as vehicle identification number (VIN), whether the vehicle is capable of operating without a driver and whether the driver is present. The incident itself has to be described by the reporting organization in their own words. Furthermore, it has to be indicated where the incident occurred (Interstate, Freeway, Highway, Rural Road, Street, or Parking Facility) and who initiated the disengagement (AV System, Test Driver, Remote Operator, or Passenger).

After the elimination of undefinable entries, 2 676 reported disengagements of 26 manufacturers or operators and a total of 282 different testing vehicles remained. In all testing vehicles, a driver was present in the moment of the disengagement. For three vehicles, operators indicated that the vehicle was capable of operating without a driver. In 2 228 cases the driver initiated the disengagement, in 446 cases the autonomous vehicle system did so, an operator disengaged only twice. Incidents happened on the street 2 173 times, on the freeway 158 times, on the highway 191 times and once in a parking facility.

As mentioned above, the description of the incidents regarding the reasons why the disengagement was initiated is requested in free text fields. The individual wording and differing level of detail, provided by the reporting organizations, results in some interpretation challenges due to partly ambiguous expressions, rough and short descriptions as well as variants in the expression of the same topic. From the provided specifications a list of short descriptions of reasons for disengagement was developed. 85% of all disengagement reports were matched with the suggested disengagement types. Table 7 provides an overview of the reasons for disengagement, clustered into 25 categories. The right column states how often the reason was named among the considered incidents.

Table 7: Reasons for disengagement in autonomous vehicle testing 2021 in California

Reason for Disengagement	Occurrence
Map discrepancy	> 200
Software failure / discrepancy	> 200
Inappropriate velocity	> 200
Inappropriate object / obstacle detection	150 - 200
Trajectory adjustment needed	150 - 200
Traffic light incorrectly / insufficiently detected	150 - 200
Inappropriate braking	100 - 150
Inappropriate lane change maneuver	100 - 150
Planning discrepancy / inaccuracy	100 - 150
Incorrect prediction	50 - 100
Inappropriate maneuver	50 - 100
Autonomous system initiates emergency stop	50 - 100
Unable to generate valid trajectory	50 - 100
Undesirable motion plan	50 - 100
Inappropriate object / obstacle detection	50 - 100
Incorrect perception	50 - 100
Reckless behavior of other road users	50 - 100
Inappropriate distance keeping	50 - 100
Hardware health issue	0 - 50
Issue with data recorder	0 - 50
Positioning error	0 - 50
Data fusion error	0 - 50
Inappropriate braking	0 - 50
Hardware diagnostic caused software kick-out	0 - 50
Localization error	0 - 50

Source: Own analysis based on data from California DMV (2022)

Testing activities by several actors have shown that autonomous driving is already possible, at least in a certain share of the cases. The absolute ability of autonomous vehicles to handle every possible situation correctly, however, has not yet been guaranteed. Table 7 shows that map discrepancies are the most occurring reason for disengagement in 2021. Software failures or shutdowns, for instance due to a discrepancy in the computed information as well as inappropriate velocity chosen by the vehicle are also common problems. The latter is interesting to the extent that the inappropriate velocity, especially in cases of a too high velocity, was in many cases considered inappropriate by the driver due to overall conditions, while it was actually within the speed limits. A comparable problem, to the extent that the autonomous vehicle also operated rule-consistently, arose when other road users behaved recklessly. Other reasons are, e.g., incorrect detections of traffic lights or inappropriate obstacle detections. Hardware health issues were reported rarely.

5.3.2 Regulatory frameworks

Autonomous driving does not only provide challenges on the technological end but also on the administrative and regulatory side. The concept of autonomous vehicles has to be integrated into existing traffic and vehicle admissions regulation and new rules have to be set. A functioning regulatory framework that allows for the admission of increasingly automated vehicles as well as the testing of autonomous vehicles is considered a key success factor in the development process of autonomous driving. Furthermore, domestic existence of well-organized and implemented regulations is viewed crucial for the activities of domestic industry and research facilities, and thus stand in relation to support innovation and the economy.

Right now, even though the general term "regulation on autonomous driving or vehicles" is used, it is Level 4 and not yet Level 5 autonomy (based on the SEA definition: SAE 2021b) that is usually regulated and brought to the street in Germany, China or the USA. Level 4 vehicles can operate autonomously in a defined area while Level 5 vehicles would not be limited to defined areas.

5.3.2.1 Regulation in the USA

The USA do not have a common regulation on autonomous vehicles implemented on the national level, besides the definition of standards and rules on the design and manufacture of the vehicles (Dentons 2022). It is up to the states to formulate their own laws regarding testing and deployment of autonomous vehicles. The result is considered a "patchwork of state-centric laws" (Dentons 2021), that covers up to the unique allowance for robotaxi services without a safety driver in California. The authors of the „Global Guide to Autonomous Vehicles 2021" (Dentons 2021) have identified three strategies that most state-level approaches can be grouped by. Among the strategies, the coverage varies significantly. Firstly, the "Laissez-faire, hands-off regulatory approach" that is followed, for instance by Arizona. Secondly, the "Welcoming testing environment" that is provided, for instance in Colorado, and lastly, the "Hands-on approach" that can be seen, for example in California. The latter has the strictest rules in place, or put differently, "has instituted a robust regulatory system" (Tanenblatt 2021). While the laissez-faire approach in Arizona has attracted operators to launch test driving projects in the state, California has nonetheless kept its role as an important testing location. The example of Cruise, who received the permit of operating vehicles without a driver in California (Bellan 2022b), suggests, that as an operator, being in line with strict rules may also have the effect of generating trust of the consumers. Testing activities show that automakers and service providers are more likely to choose states with defined rules for their projects (Dentons 2022).

5.3.2.2 Regulation in China

In 2020, China passed "The Regulations on the Administration of Road Testing of Autonomous Vehicles (for Trial Implementation)" (Dentons 2021), which has been updated in 2021 (Hongpei 2022). A number of different authorities have oversight of autonomous driving laws, such as the Ministry of Transport, the Ministry of Public Security or the Ministry of Industry and Information Technology (Dentons 2021). The regulation contains a list of conditions a vehicle has to fulfil. One of it is that one can switch between automatic and manual driving functions, which is also connected to the prerequisite that a test driver must sit in the vehicle. Furthermore, a third-party testing institute shall verify the self-driving function of the vehicle. Regulatory efforts to accelerate autonomous driving development are also embedded in the Chinese strategy concerning intelligent vehicles, which targets frameworks as well as the technology of intelligent vehicles and infrastructure to be ready by 2025 and the "standard intelligent vehicle system [to] be fully completed" by 2035 (Dentons 2021). On the national level, "qualified companies" are now allowed to test self-driving vehicles (Dentons 2022). Besides the regulation on the national level, local governments partly granted special permissions or even formulated individual regulations, including the permission of robotaxi testing with passengers e.g. in the city of Shanghai. Furthermore, special permits have been granted to Baidu in order to charge for the rides and even operate without a safety driver in Beijing and now Chongqing and Wuhan (Bellan 2022b). Considering the regulatory variation among regions and the heavily differing road conditions even within cities, the implementation of services can be considered rather punctual. Adding to that, incentives were introduced by different regional or city administrations in order to attract firms and investment in the field. This entails a focus of activities and robotaxi services in the economic centers as Shanghai, Shenzhen or Guangzhou (Dentons 2022).

5.3.2.3 Regulation in Germany

Germany, which did not have comprehensive regulation on autonomous driving in place until the second half of 2021, seemed to lag behind China and the USA (Dentons 2021). With the law on autonomous driving entering into force in July 2021 as well as the complementary regulation being in the process of passing in spring 2022 (Bundesministerium für Digitales und Verkehr (BMDV) 7/27/2021, 2/23/2022), Germany settled on the allowance for Level 4 autonomous driving in public traffic (Dentons 2022). The regulation was passed on the national level and is described as a temporary solution until appropriate international regulation, especially on the European level, is adopted. Furthermore, Germany participated actively in the setting of standards on the UN level. The law and targeted supplement shall allow for autonomous vehicles to participate in public traffic without a driver, regulates the technological or maintenance requirements as well as the operators' duties and specifics of the admission process (Bundesministerium für Digitales und Verkehr (BMDV) 7/27/2021, 2/23/2022). In addition, data security measures such as encryption requirements are addressed (Malterer 2022). Being part of the European Union, Germany on the one side complies with the European standards, but, on the other side, moves ahead in fields, where there is not yet a superordinate regulation in place. The German regulation on autonomous vehicles might be considered more uniform in comparison to the USA or China. When considering Europe as the next larger unit, German activities might be comparable to state activities in the USA. Commercial robotaxi services with a security driver may also be conducted under case-by-case permits when meeting both, regulation regarding autonomous vehicles as well as standard passenger transport laws (Blechner 2021).

5.3.3 Implications

From the technological perspective, no single defective hardware or software component is identifiable from the disengagement report and components basically function in most cases. The problem still to be solve, is probably to achieve the reliability of the components, functions and their interplay. The disengagement reports only cover California and test drives that were registered there. Therefore, additional technological bottlenecks, that may occur when switching between different regions and types of infrastructure, are not covered. The adaptation to a favorable human driving behavior, that not necessarily fulfills the rules (e.g. driving slower than allowed due to a unclear situation far ahead, or driving slower in street curves), might be another issue. The ignorance of rules in favorable situations could be a field that is not entirely solvable just by further technological advancements.

Partly different stages or characteristics of the regulatory frameworks are observable in the USA, China, and Germany. However, autonomous driving is possible under different circumstances and progress can be observed for all of the considered countries. Currently, much of the regulation is focused on allowing for and specifying market entry by formulating rules for real world usage. While regulation covers the operation of Level 4 vehicles for that purpose, only Level 3 automation just began to be regulated for individual use in vehicles for private customers (United Nations (UN) 3/4/2021). That means there are two forefronts that regulatory bodies are working on. On the one hand, the regulation for private vehicles with highly automated driving functions for sale such as the Mercedes-Benz S-Class that is now allowed to be used under different circumstances with Level 3 automation in Germany. On the other hand, the autonomous (actually Level 4) vehicles that are used in robotaxi services. The latter still need specific permissions for the regions that they are operating in. They can still be characterized as large scaled and widely spread pilot projects, as the sale and private use of these vehicles is not yet allowed.

From the organizational perspective, further adaptations are needed in three fields. First, legal frameworks will still need time to be fully adjusted to current as well as future technological developments. For instance, the targeting of Level 5 autonomous vehicles, e.g. passenger shuttles, requires the overturn of very basic laws in the future, such as the existence of a steering wheel as an admission requirement for cars. Just recently, the USA have updated their standards on the matter (National Highway Traffic Safety Administration (NHTSA) 3/10/2022), following a petition by autonomous vehicle operator Cruise and GM (Tanenblatt 2022). Second, several framework topics, such as insurance or cyber security, have to be worked out. These are also strongly connected to legal frameworks as well as to questions of ethics and liability in the case of, e.g., unavoidable collisions or accidents in general, especially with respect to insurance. Third, it remains unclear what role autonomous vehicles will play in future intelligent and connected mobility systems and how these systems may look like. While especially technological specifications still need to evolve, societal requirements on these mobility systems and autonomous vehicles and especially their compliance have to be discussed, defined and monitored. Topics span around inclusion or environmental effects.

The actual status of regulation may not heavily influence the development process of autonomous driving technologies but rather itself is developed in exchange with the technological advancements. However, when it will come to the widespread diffusion of autonomous driving, the role of regulation in guiding the application is large and expected to grow. Dynamics, especially in the digital field, where actual regulation is probably not as advanced as regarding hardware technologies, will increase. Aspects of the influence of regulation on the current and rather short term market introduction will be revisited in the following chapter.

5.4 Market formation

For the successful implementation of a technology and its diffusion, the formation of markets is fundamental. With regard to autonomous vehicles, the pursued technology may have large effects on the functioning of mobility systems, which in turn may heavily affect related field such as associated value chains.

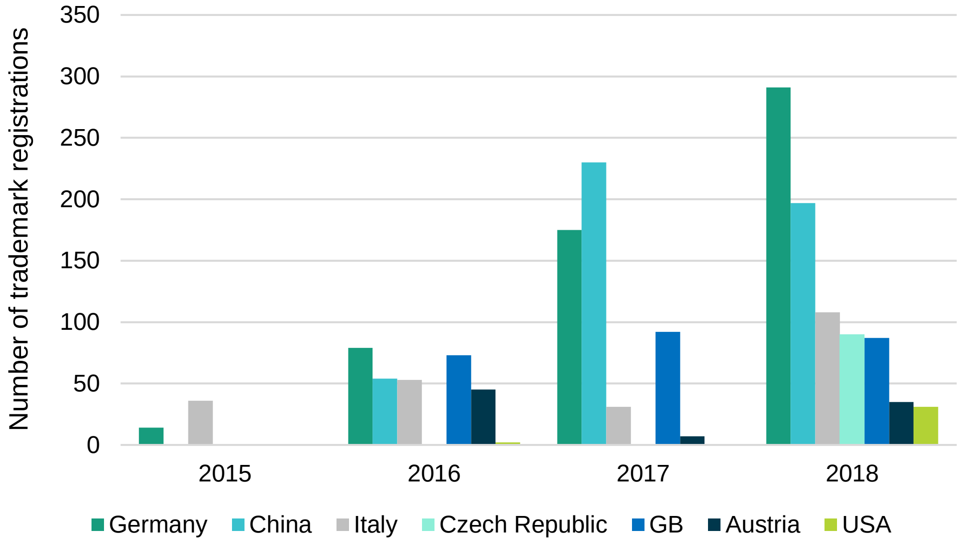
The analysis of market formation can be divided into aspects that relate to the short term introduction of a technology and aspects that are important to, or define, the potential long term development of markets. In the following sections, a short summary is given on the current status of trademark registrations and testing or pilot activities in order to cover the short term market introduction. Afterwards, incipient business model strategies and the implications from servitization and platform economics are discussed. Furthermore, prospective modeling studies are reviewed to give an overview of potential future market sizes.

5.4.1 Status of market formation

Referring to the five levels of autonomous driving, development can (at least to some extent) be considered a kind of incremental process in which increasingly more features and abilities are included in the vehicle. When looking at the formation of the market of autonomous driving there are thus two "streams" of market introduction or formation that are both relevant to understanding the diffusion of autonomous vehicles in the mobility market. On the one hand, the automation of certain functionalities of vehicles, especially assisted driving functions, has already been included in sold vehicles for years. Right now, several vehicles are able to operate on SAE Level 2, and the first car with Level 3 functions is expected to be available in the summer of 2022 in Germany (Mercedes-Benz Group 2021). On the other hand, as described above, firms have been testing autonomous vehicles in real life conditions for a few years. Recent adjustments of regulations now allow operators to commercially offer robotaxi services to the public. Examples are Cruise in San Francisco (Tanenblatt 2021) and Baidu in Beijing (Cheng 2021).

In order to complement the above examples with more aggregate information, data on trademark applications, provided by the European Union Intellectual Property Office (EUIPO), was used to analyze activities in the field of autonomous vehicles in the European market (deGrazia et al. 2019). Based on the approach and database of Neuhäusler et al. (2021), trademark registrations by country, associated to the category "driverless car", were counted. Figure 30 displays the number of registrations for the most active nations between 2015 and 2018, where trademark registrations cover technologies as well as services. The data show an increase in registrations, already until 2018, with Germany leading in the number of registration among European countries. While in 2015 and 2016, China played a subordinate role, Chinese registrations increased a lot in 2017 and 2018, which can be interpreted as an effort to gain market shares in Europe. The USA, in contrast, do not show as much activity in Europe.

Figure 30: Trademark registrations in the category "driverless car" at EUIPO 2015 – 2018 by country



Source: Own representation based on EUIPO, Neuhäusler et al. (2021)

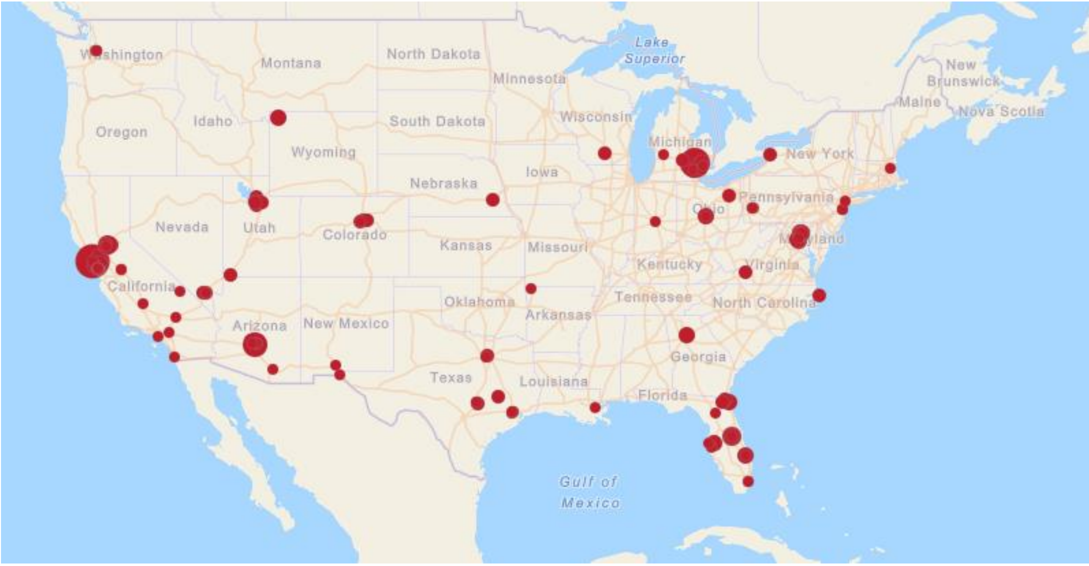
While the analysis of EUIPO data is restricted to developments in the Europe, some implications can be drawn. First of all, in concordance with the results from section 5.1.2, the data shows increasing activity in the field of autonomous driving or, here, driverless cars. That means expectations regarding the market entry manifest. Secondly, it seems more likely that regional markets, at least in the early phase of market formation, are targeted by players from the region. While China nevertheless prepares market entry in Europe, the sum of registrations of European countries exceeds Chinese registrations. Drawing from the presented data, the European market seems not to be on the priority list of the USA.

5.4.2 Testing and pilot projects

Testing in real world conditions and public traffic is a fundamental building block in the development of autonomous vehicles. The lack of corresponding regulatory frameworks on the deployment of autonomous vehicles has for long been one key barrier to testing, which is increasingly overcome by governments (see section 5.3.2). While especially the region of San Francisco, USA, used to be the main hotspot of autonomous test driving, testing locations now have spread, not only across the USA (NHTSA 2022), but also on a global scale (e.g. Shanghai and Beijing in China, Tel Aviv in Israel, Hamburg in Germany). The dynamics and extent of implementation vary between states and countries. However, the importance of bringing testing activities to domestic roads seems to be acknowledged.

Data on driven miles of testing vehicles in California shows large differences in the amount of covered miles between operating companies. Waymo (Alphabet) with 2.3 million miles driven in 2021 and Cruise (General Motors) with almost 0.9 million miles are, by a large margin, the most active operators on Californian streets (Bellan 2022a). Other operators are for instance Pony.AI, Zoox or Mercedes-Benz. While one can observe increasing activity in testing by actors with different sectoral backgrounds, one can hardly draw conclusions from driven mileages to the maturity of technological advancements or a company's success, as e.g. Waymo stated (Lienert 2020). Without similar data from other regions, an in-depth national comparison is also not possible.

Figure 31: Testing Locations in the USA[14]



Source: NHTSA 2022

The amount of covered miles in California, combined with the number of testing locations in the USA, that are displayed in Figure 31, suggest, however, that enough testing environment is available and that the opportunities are also used. That is at least the case for the USA. The regulatory frameworks, displayed in section 5.3.2, allow for testing in both, Germany and China. It is reported that Baidu alone has a testing fleet of 500 test vehicles, that combined have covered more than 20 million kilometers of road tests in more than 30 cities across China. Baidu has also been collecting on-road kilometers in California under a license for manned demonstration (Dentons 2022).

The term testing is associated with the rather technological testing of the functions of a vehicle. Usually an engineer is on board in order to report the functioning and potential challenges. Pilot projects are considered to be projects, where autonomous vehicles are used in a way that resembles potential future usage. That includes two streams of projects.

First, pilot projects have been conducted in providing autonomous shuttle services. There are examples from all three countries that are in focus of the thesis, and probably many more, also from other countries. Autonomous shuttles usually operate at slow velocity and give space to 6 -10 people. For instance, the German railway company Deutsche Bahn introduced the first autonomous shuttle bus in Bavaria in 2017 (ioki 2022). The bus serves as part of the public transport in the small town of Bad Birnbach, where it connects the town center with the railway station. The booking platform is provided by ioki, a Deutsche Bahn subsidiary, while the vehicle is developed and manufactured by EasyMile, a firm that offers autonomous mobility solutions for intralogistics, e.g. on airports or in factories (ioki 2022; EasyMile 2022). In China, QCraft, an autonomous driving startup, runs public bus services in Suzhou, Shenzen and Wuhan. The startup develops autonomous driving technology that is implementable in autonomous shuttles, buses and cars (Li 2021; QCraft 2022). Another example is Chinese tech firm Baidu's shuttle service in Guangzhou, which runs on a bus line covering more than eight kilometers (Silver 2021; Mobility Innovators 2022). For the USA, a case study by Haque and Brakewood (2020) provides an extensive overview of autonomous shuttle

[14] The NHTSA states: "This tool does not represent all testing activity throughout the United States – only what our initial set of participants have provided."

services. Shuttle services have been carried out using EasyMile shuttles in almost half of the displayed cases. The services have been deployed mainly in public spheres that are not completely open to public traffic such as office parks, campuses or stadiums.

The discussed shuttle bus projects are in most cases initiated by the "public" sphere, which refers to railway or public transport companies, city administrations or universities. The vehicle hardware suppliers are just in a few cases automotive OEMs. In addition to that, only in the Baidu case it is an ICT firm that provides the services and access to the mobility platform. The focus of the thesis is, as mentioned in the beginning, on autonomous cars rather than autonomous shuttles and buses. The examples show that this stream of projects and technologies seems to be another innovation system with a different group of engaging actors. Large automotive and ICT industrial players that were so far discussed do not actively engage in the field.

Pilot projects in the form of autonomous robotaxi services have just recently become more and more available to the public. Especially the allowance for providers to offer robotaxi services commercially, when having the corresponding permit, boosted announcements of firms and partnerships to go live in different cities around the world. In the past five years, services have been carried out for instance by Waymo in San Francisco, Baidu in Beijing or Guanghzou, Cruise in San Francisco, Pony.ai in Guangzhou and California and DiDi in Shanghai (Liao 2022; Tiedemann 2021). Furthermore, as displayed in Figure 29 in context of the role of partnerships in knowledge creation, robotaxi partnerships were announced for other regions, too. For Munich, Germany, Mobileye together with Nio, Sixt and Moovit has announced robotaxi services, beginning in 2022 (Korosec 2021). MOIA, Argo AI and VW released a roadmap, that contains driverless autonomous ridepooling services in Hamburg from the year 2025 (MOIA 2022b). While robotaxi services are already on the road in both, the USA and China, in Germany so far only announcements have been made. The running robotaxi services are in many cases reported on by naming the tech companies behind the projects, meaning it is the Waymo, Baidu, DiDi service. Waymo, Cruise, Pony.ai provide autonomous driving technologies, Baidu, and Didi serve as platform providers for accessing the service. So far, it has hardly been any OEM that was reported on offering robotaxi services. They were rather included in the partnerships, where they supplied the vehicle hardware.

Where and when testing and the implementation of pilot projects in the field of autonomous driving have been taking place has been dependent on the national regulatory frameworks. USA, China and Germany now all allow for commercial robotaxi services and, in certain cases, even the implementation of driverless robotaxis. In Germany, announcements have been made to introduce (driverless) robotaxi services soon (Korosec 2021). So far, services, that are already running, only offer autonomous shuttle transportation on defined routes in Germany. In China and the USA, robotaxi services are carried out for a few years now, recently including the first driverless services, too. In addition to that, autonomous shuttle services are also implemented in the two countries.

5.4.3 Business models

The previous sections 5.4.1 and 5.4.2 have discussed current observations on the first introductions of autonomous vehicles. The following sections cover the more general aspects of potential business models and platform economics in the mobility industry that may shape actors' strategies and market dynamic in the long run.

The future deployment of autonomous vehicles for road-bound passenger transport can be broadly distinguished in privately owned autonomous vehicles and shared autonomous vehicles, where rides are booked via a mobility service platform. Looking at current activities, one can observe the rather technology focused test vehicle fleets as well as autonomous robotaxi service pilots, thus the combination of technology and service operations. Besides that perspective on autonomous vehicles, regardless their type of final deployment, another focus is on the rather incremental process of advancing assisted driving functions that can be already used in the present generation cars, which will eventually evolve into fully autonomous driving functions.

Revisiting the selection of active companies in the field of autonomous driving, already discussed in the section of "Entrepreneurial activities" 5.1, the companies' slogans may give some insights into the roles, the different active players see for themselves. The majority of analyzed automotive companies, both OEMs as well as suppliers, either has not formulated a distinct slogan focusing on the vision on autonomous mobility or has a vehicle-oriented slogan, where the technology of the autonomous vehicle is in focus. Less than a fifth of these companies mentions the concept of mobility systems as a whole. Other firms focus on other aspects, such as safety or trust. The majority of considered active ICT companies also has no distinct slogan on autonomous driving. Out of six ICT companies with a slogan, three focus on mobility systems. Their activities are accompanied, as already mentioned, by automotive firms delivering hardware or components to autonomous mobility services, while ICT firms offer the on-road services themselves in relatively more cases. The definition of roles in future mobility systems has not yet been concluded and it is still under question whether it is a "sectoral" or rather an individual strategy decision.

The sale of private autonomous vehicles by OEMs to private or corporate customers would in its core still represent the same business model, just with an enhanced product. That business model would also work when OEMs sell their autonomous vehicles to mobility service providers. However, the larger the customer, usually the larger the negotiating power. When OEMs lose the direct contact to final customers to the mobility service providers, their margins may drop. In the past, several automotive firms have increased their activities in offering (non-autonomous) mobility services. However, their core revenue pool and operations are still based on the selling of vehicles. With autonomous vehicles entering the market, it is expected that mobility services and the shared usage of vehicles may experience a boost (Narayanan et al. 2020). The current activities of OEMs suggest, that they will keep on focusing on the sale of autonomous vehicles, while it remains unclear whether and to what extent they enter mobility services themselves. OEMs work along the incremental development path, which means that they include new and updated functionalities regarding assisted and increasingly automated driving in their new car models. These activities are still in line with the classic automotive innovation cycles, where a new generation of cars has new functionalities. In parallel, OEMs also work on advancements towards fully autonomous driving, which are, however, not yet accessible to purchase by private customers.

Players from the ICT field have in the past not taken the role of lead firms in the automotive or mobility industry. For ICT firms, it is not their core product that changes. It is rather their way of thinking and business model of platform services that is now applied to another field of consumption: mobility. In the case of ICT firms that develop autonomous driving technologies, it is the development of a new product that has not yet existed. Among ICT firms, there are actors that engage as parts suppliers for assisted driving technologies. These are the only ones participating the incremental development process. Other ICT firms only focus on fully autonomous driving systems, with which they equip vehicles, and the last group acts as platform providers or as aggregators of different mobility platforms. These two engage in robotaxi services, often in partnerships. The sale of vehicles in their full concept seems not to be in focus for any of the groups.

5.4.4 Market dynamics and platform economics in the mobility industry

A shift from privately owned vehicles towards the shared usage of autonomous vehicles via platforms comes along a fundamental change in the principles of the automotive industry. The application of autonomous vehicles for ride sourcing may foster monopolistic structures among providing firms (Goletz and Bahamonde-Birke 2021). The future mobility service market, based on autonomous vehicles, is expected to be shaped by a natural monopoly, since marginal costs will always undercut average costs. In non-autonomous mobility services, the driver often represents the largest cost factor (Bösch et al. 2018). With the introduction of autonomous vehicles, this factor no longer plays a role. The initial investment in an autonomous vehicles might be higher, however, the initial investment substitutes the costs of a driver which would otherwise accrue per kilometer driven.

The rise of platforms in the mobility market presents the chance for newcomers from the ICT sector to enter the automotive market. The platform economy is known for its monopolistic structure, where often one or very few firms end up supplying all the market ("winner takes it all") (Alvarez León and Aoyama 2022). Currently, the ride-sourcing industry, using non-autonomous vehicles with drivers, is not profitable (Goletz and Bahamonde-Birke 2021). Firms might bet on securing market shares now to be prepared when the technology of autonomous vehicles is ready. In this process, some firms are heavily backed by financial investors that allow them to operate further on loss level. Vehicle manufacturers do not access that kind of financial structure. They rather secure their current market shares via the technological path and by still focusing on privately owned vehicles.

Principles of the new mobility market might also differ from established automotive markets regarding their regional variation. With autonomous vehicles and autonomous vehicle services, scholars expect the differentiation of markets to increase even more compared to current nationally adapted products in the automotive field. The specific characteristics, not only of countries and regions but on the heterogeneous level of individual cities, may be crucial to understanding the development of the markets (Goletz and Bahamonde-Birke 2021). While the services of an established and prominent platform brand can, at least theoretically, easily and quickly be introduced to new regional markets, the international introduction also has their limits. Uber, for instance, targeted many countries after being successful in the USA. In European countries, Uber repeatedly had trouble in complying with national passenger transportation laws, which resulted in a punctual availability of their service rather than nationwide presence. In China, Uber was taken over by the Chinese equivalent DiDi (Crabtree 2018).

Overall, "success in the high-tech industry no longer goes automatically to those with first-mover advantage, or even to those with a superior platform; it goes to companies with the most distinctive value proposition, and the ability to deliver on it." (Acker et al. 2016). With regard to autonomous driving, the technological development of a functioning system is considered crucial to the success of the company. Whether the first firm to provide an autonomous car to the public will also be the one securing largest market shares, remains very unclear. However, while many aspects of future market dynamics remain still unclear, it is obvious that further developments will be very dynamic. Future revenues and the industrial structure, including entrepreneurial landscapes and value chains, are heavily dependent on the split of shares between privately owned autonomous vehicles and shared autonomous vehicles and the unique selling points that customers will care about.

5.4.5 Long term market potential

As discussed above, the interplay between established automotive OEMs and ICT firms will be, to a large extent, determined by the long term market potential of privately owned and shared autonomous vehicles. The mode of deployment of autonomous vehicles will not only be driven by the offerings of the industry, but is dependent on the preferences of customers. A comparison of the results of various international studies from 2016 to 2020 shows that people tend to make a minority of their trips in shared autonomous vehicles in the future (Narayanan et al. 2020). 13 out of 15 analyzed studies conclude that for various dates up to 2040, the share of predicted trips in shared autonomous vehicles is below 50% which leaves the majority of trips to privately owned vehicles.

Individual studies even conclude that if shared autonomous mobility was offered completely free of charge, it would not be 100% of respondents who use the corresponding services (Haboucha et al. 2017). A survey by Menon et al. (2019) finds that more than 53% of respondents consider it (very) unlikely that they would forgo a private vehicle if shared autonomous vehicles were available. Just under 19% rate it as likely, and about 7% rate it as very likely. Grush and Niles (2018) show that even with autonomous driving features, private vehicle ownership continues to dominate.

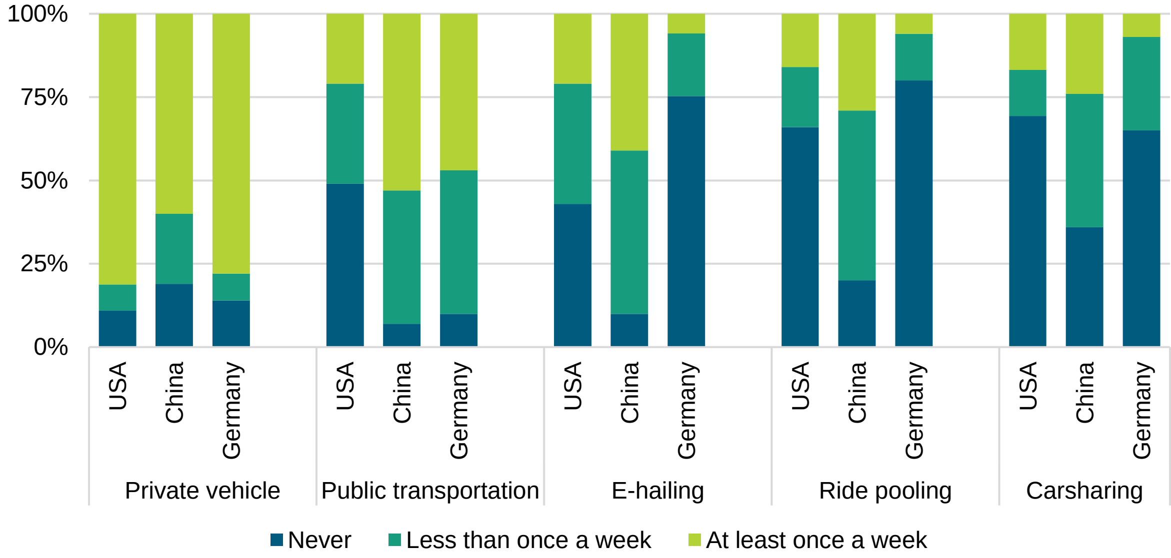
Overall, the extensive literature review of Narayanan et al. (2020) suggests an agreement among scholars that the total kilometers driven will increase when autonomous vehicles are introduced. Mobility tends to become cheaper for end customers when using shared mobility services in comparison to owning a private car. While negative effects are more likely for the automotive market, digital tech groups are more likely to experience positive effects.

As introduced in the previous section, markets may vary significantly between regions. That results from different modes of supply, but also from different consumer preferences. A variety of studies show differences in the mobility behavior and preferences between the USA, China and Germany (Heineke et al. 2021; Xiao and Goulias 2022; Capgemini Research Institute 2019). Figure 32 displays the results of a McKinsey consumer survey among 7 000 respondents worldwide, asking how often they use different kinds of transportation modes (Heineke et al. 2021). The results show large differences in the mobility patterns between respondents from the USA, China, and Germany. While the private vehicle is still the most used means of transport in all countries, China shows frequent use of shared vehicles. Only 10% of Chinese respondents have never used e-hailing compared to 75% in Germany. Also, ridepooling and carsharing are much more popular in China. Almost 50% of US respondents state that they never use public transportation. In contrast, the share of respondents that never use public transportation lies at 7% in China and 10% in Germany.

Within regions, the expected benefits from and thus the potential adoption of autonomous vehicles varies depending on socio-economic backgrounds as Xiao and Goulias (2022) show for California. Several studies find that young and educated males are most likely to use autonomous vehicles and that income plays an important role regarding the intention of autonomous vehicle purchase. When distinguishing between direct and indirect effects, less income seems to have a negative effect on the intention of buying autonomous vehicles, but not so much to the intention of using shared autonomous vehicles. Furthermore, especially younger people who have already used non-autonomous mobility services show higher intention to using shared autonomous vehicles (Xiao and Goulias 2022). The latter indicates that one can, at least partly, draw from current behavior to the future usage of autonomous vehicles.

Figure 32: Modes of transportation used in USA, China, and Germany

Frequency of transportation used, share of respondents in %



Source: Own representation based on Heineke et al. (2021)

In China, the majority of respondents in a survey of around 5 500 consumers indicate positive emotions towards autonomous vehicles (53%) while only 12% show negative emotions (Capgemini Research Institute 2019). In comparison, among Germans, who were surveyed, 38% have positive and 30% have negative emotions, and in the USA only 36% have positive and 33% have negative emotions. When looking at the preferences to substitute journeys in human-driven cars by trips in autonomous cars, the regional variance is not as high. 72% of Chinese consumers state that they will prefer a trip in an autonomous car in ten years. In the USA, 63% and in Germany, 61% show a preference to use autonomous cars in ten years. The differences may arise from a variety of reasons. For instance, the bad traffic situation in Chinese cities may foster the preference of consumers to not drive themselves (Capgemini Research Institute 2019).

Surveys asking about the potential future preferences of consumers towards autonomous vehicles have a hypothetical character, since the technology is not yet available on a large scale. Furthermore, consumer preferences are not always stable and may change in the course of time (Narayanan et al. 2020). Estimations on and eventually the realization of the long term market potential may thus underlie high dynamics in the upcoming years. Drawing from the current mobility behavior and current surveys, the Chinese market for autonomous vehicles, especially shared vehicles, may be expected to grow quicker and larger than the USA and German markets. That is implied by both, the higher usage of shared mobility services right now as well as larger shares of positive emotions and preferences towards autonomous vehicles. Besides the overall regional differences in the development paths of autonomous vehicle markets, the influence of socio-economic or sociodemographic factors will shape the spread of autonomous vehicles.

5.4.6 Implications

The current and thus early stage market formation spans over testing activities with autonomous vehicles and pilot-projects on autonomous mobility services. Offered robotaxi services mostly take place in the home-markets of the respective firms. China and USA are very active in this matter. Especially China has fostered the quick roll-out of Chinese robotaxi services in Chinese cities in the recent past. This progress is mostly centered in the strong economic regions, indicating the coherence between the fragmented regulation and the fragmented application of robotaxi services in China (section 5.3). Large differences in Chinese infrastructure might play an important role when targeting a future roll-out of autonomous vehicles. The vibrant activities in introducing autonomous vehicles to the public, combined with the open mindedness of Chinese individuals towards the new technology, currently suggest a quicker market development on the large scale in China compared to the USA or Germany. The testing of autonomous vehicles, excluding public usage, is available and takes places in all the considered regions and is used by both, automotive and ICT firms.

The operation of autonomous shuttles seems to have only little relevance to the automotive and ICT industry. Autonomous shuttles or small buses are found to be mostly integrated into public transportation offers and test projects. Also, the hardware supplying firms are in many cases no traditional vehicle manufacturers. The regional focus in the application of autonomous shuttles seems to be mostly rural areas, off-public roads such as university campuses and only partly cities, while the introduction of robotaxis almost exclusively takes place in cities. Public transportation, in its more traditional understanding, has not been in the center of attention of both, automotive and ICT players (apart from the manufacturing of buses by automotive OEMs) so far. If that stays the same, no large shifts in value chains are expected from the field. However, through the technology of autonomous vehicles, the lines between public and individual transport services become increasingly blurry and so might the allocation of revenues among the industrial landscape that offers transportation. The potential future dynamics in the usage and application of autonomous driving are to a large extent driven by public acceptance and potentially the intervention of the governments in order to secure environmental and societal benefits. Some of these aspects and the interrelations to market formation are revisited in chapter 5.6, which covers the creation of legitimacy.

With regard to the future roles and revenues in the mobility market, two issues are crucial. One is the shape of future public or shared mobility services and the market breakdown between the providers involved. The other is the fundamental shift from product to service markets. Especially the automotive industry that has for long focused on the automotive product market would have to adapt and find its new role. Service markets in different fields, which have been operated via digital platforms, tend to develop monopolistic characteristics. A similar development is possible for the mobility service market, too.

In current observations, it is mostly ICT placers that offer robotaxi services, while automotive OEMs partly participate as vehicle hardware suppliers. On the other hand, it is automotive OEMs that offer vehicles that include assisted driving functions, now up to automation level 3. While the large scale introduction of mobility as a service would in theory entail major shifts in market principles, studies on market dynamics show that the private ownership of vehicles is expected to still play a major role. In this segment, the established business model of automotive companies could prevail. It has to be noted that the discussion is still hypothetical, so are the answers of survey respondents. The preferences of consumers might change, when the services are offered on a larger scale (Narayanan et al. 2020).

5.5 Resource mobilization

For the development of autonomous driving, as for other technological development processes, the access to financial as well as human resources is crucial. In the thesis, the availability and structure of financial resources dedicated to autonomous driving are analyzed by using exemplary information on actors. With regard to human resources, official statistics on employment and education are studied. The chapter analyzes whether there are differences between the automotive and ICT sector, and between regions when it comes to the mobilization of resources, namely financial and human resources.

5.5.1 Financial resources

The development of autonomous vehicles is cost-intensive and comes at a time when, especially for firms from the automotive sector, other investment needs already pose challenges. The automotive sector is also confronted with challenges in order to adapt to the electrification of the power train as well as to digitize production sites. In the early beginnings of developing autonomous vehicles, government initiatives such as especially the DARPA grand challenges, funded by the US department of defense, fostered research activities, e.g. at universities (World Intellectual Property Organization 2019). Today, governments still fund R&D of academia and industry in the field of autonomous driving. At the same time, expectations towards future profits from autonomous vehicles have already induced large investments by industry and capital markets.

Industrial partnerships, as described in the function of knowledge diffusion, play an increasing role in the development of autonomous driving. One aim is the splitting of the investment burden (Williams 2021). Furthermore, acquisitions and thus the relevance of mobility start-ups and venture capital are growing as well (Holland-Letz et al. 2019). Waymo, the autonomous driving daughter of Alphabet, announced a 3.2 billion dollar funding round, where Alphabet itself was just one of many investors (Feiner 2021). Another example is Cruise, which was acquired by GM in 2016, and received investments by large firms such as GM, Microsoft, or Walmart (Shepardson and Jin 2022). In comparison to the established internal technology R&D investments of large companies, these investments can be considered a new form of funding. German carmaker Volkswagen announced large investments in both its own daughter Cariad and start-up Argo AI (Alamalhodaei 2021), Mercedes-Benz also invested in several start-ups in the field of autonomous driving as well as in own research (Palmer 2022; Handelsblatt 2021). The acquisitions and investments by large firms from both, the automotive and ICT sectors, in their own organizations and in other firms, have already been introduced in section 5.2.4 as a form of knowledge development and knowledge diffusion. The sums spent by the large players suggest the availability of financial resources, even though they are of course not unlimited. The number of foundations of firms in the field of autonomous driving, as displayed in chapter 5.1, are also a sign of trust in the potential of the technology and the willingness and availability of resources to invest.

A list and further information on active firms in autonomous driving, as introduced in section 5.1.1, was retrieved from Crunchbase. The extracted data partly included information on the top five lead investors in a firm. The most active investors, based on the Crunchbase extraction, are displayed in Table 8. The list was conducted by counting in how many firms one investor has invested in. Table 8 shows all investors that invested in at least 10 autonomous driving firms and lists them chronologically, starting with Accel, that invested in the most firms. The table contains information on the investor's name, type and headquarter location by country and region. The colors of the lines serve for a better overview of the investor types.

Table 8: Most active investors in autonomous driving according to Crunchbase search[15]

Investors	Type of investor	Region	Country
Accel	**Venture Capital**	California	United States
Techstars	**Accelerator**	Colorado	United States
Y Combinator	**Accelerator**	California	United States
EASME - EU Executive Agency for SMEs	**Government Agency**	Belgium	Europe
IDG Capital	**Venture Capital**	Beijing	China
Plug and Play Tech Center	**Accelerator**	California	United States
TA Ventures	**Venture Capital**	Kyiv	Ukraine
Samsung	**Electronics**	Suwon	South Korea
Sequoia Capital	**Venture Capital**	California	United States
SoftBank	**Multinational Conglomerate**	Tokyo	Japan
Intel	**Semiconductor**	California	United States
MassChallenge	**Accelerator**	Massachusetts	United States
Qualcomm	**Semiconductor**	California	United States
ERC	**Government Agency**	Belgium	Europe
Hyundai Motor Company	**Automotive**	Seoul	South Korea
Trucks Venture Capital	**Venture Capital**	California	United States

Source: Own representation based on Crunchbase (2022), published in Grimm and Walz (2024)

The majority of the most active investors are accelerators or venture capital firms. Thus they can be clustered into the financial or startup sector. They are followed by some investors that can be assigned to a broad understanding of the ICT sector, namely Samsung, SoftBank, Intel, and Qualcomm. Hyundai is the only automotive investor that is named among the lead investors that invested in more than 10 autonomous driving firms, according to the Crunchbase search. Besides the corporate investors, two European agencies made it to the most active lead investors: EASME, which is the EU Executive Agency for SMEs and ERC, the European Research Council that fund grants. The snapshot of lead investors in autonomous driving corresponds to the analysis of Heineke et al. (2021) at McKinsey, who find that in the field of non-autonomous shared-mobility companies, almost three quarters of investment amount had been disclosed by venture capital, private equity and other public offerings. Tech players have provided around 20% of investments since 2010, leaving only 4% to automotive players.

The overview suggests differences between regions when it comes to the form of capital that is provided in form of investments. While the active lead investors are mostly accelerators or venture capital firms from the USA, the only two non-corporate investors are government agencies from

[15] Based on a set ~1,600 firms active in autonomous driving. See section 5.1.1 for details on the data collection from Crunchbase

Europe. The active role of US investors matches the lead position, the USA takes in hosting by far the largest number of firms that are active in autonomous driving. In contrast to China's role as the third largest home-country to autonomous driving firms (see section 5.1.2), it is not much represented among the active investors. The large investments by private actors show that even though differences in scale exist on the sectoral and national level, the autonomous driving innovation system has access to large funds.

It is, however, hard to compare the financial resources of large firms and startups that collect venture capital. Data on the distinct internal investment in autonomous driving technology is often not available for individual firms (e.g. Reuters 2021). Furthermore, the relation between dollars invested in different forms and the success in developing autonomous driving is unclear. This allows only for rather vague derivations of aspects for future development paths.

The development of autonomous driving is characterized by high dynamics that were rather unknown for the automotive industry: many new players have entered the field and the established principles of financing automotive R&D have changed. Established firms are confronted with quickly growing firms that, in a very short amount of time, have the potential to become competitors due to large investments through the financial markets that often allow them to operate on losses in the development period. These dynamics have fallen into a time of very low interest rates. Increasing interest rates might have the potential to restructure the priorities of investors and thus influence these new principles of financing autonomous driving development.

Financial constraints are, especially with regard to established players, discussed as a reason for the increasing number of partnerships between firms. Partnerships are announced by both, automotive and ICT players, which suggests that actors from both sectors face these constraints. While financial resources may not limit the global development in the autonomous driving innovation system, they can shape the success of individual firms and regions and induce dynamics as the increasing consolidation in the entrepreneurial landscape.

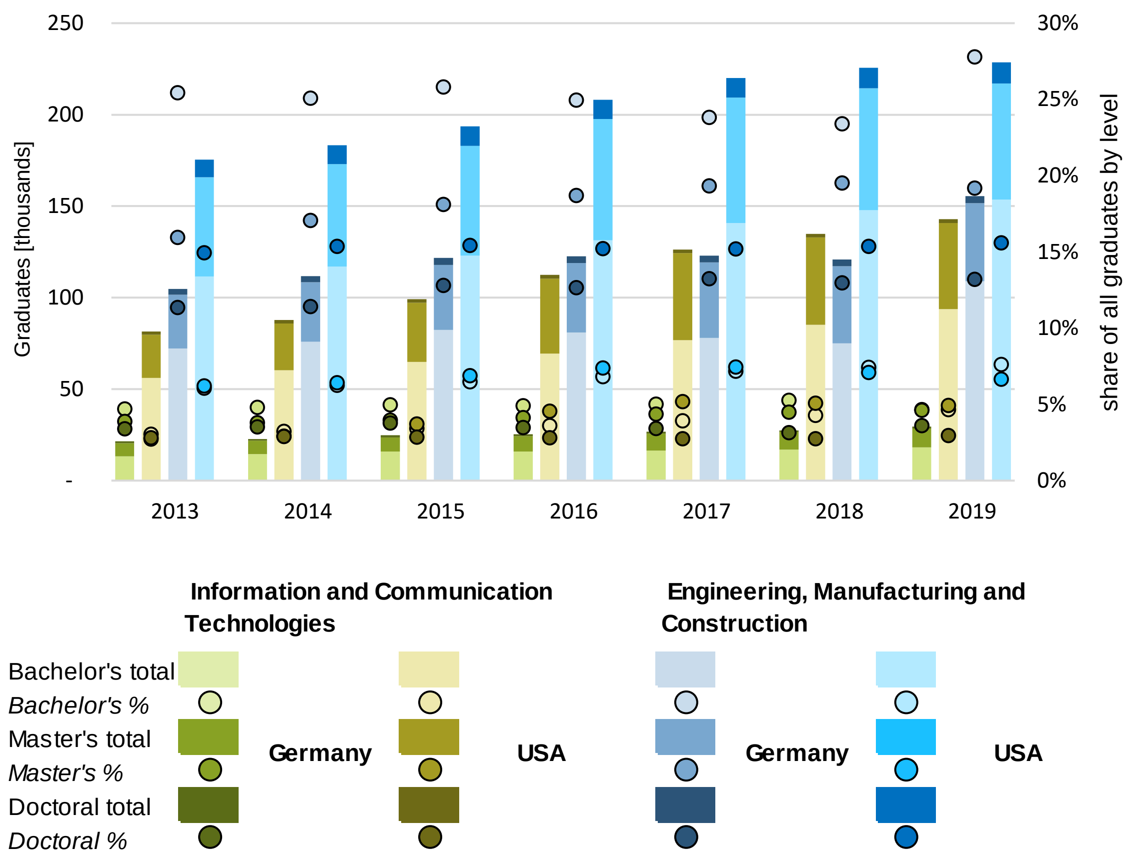
5.5.2 Human resources

In order to develop the complex technology of autonomous vehicles, a large set of competencies and thus the corresponding workforce is needed. For both, firms from the automotive and the ICT sector, new talent has to be attracted, mainly in the fields of engineering, software development and data analytics. Experts are one of the main drivers and thus crucial resource in the development of autonomous vehicles. This can be shown by looking at the display of scientists who participated in the DARPA grand challenges and their spin-offs (World Intellectual Property Organization 2019). As already mentioned in section 5.2.1, scientists from Stanford and Carnegie Mellon University that have worked on autonomous driving at universities later switched to firms such as Waymo or (co-) founded prominent firms such as Zoox, Argo AI, Nuro or Aurora - all US companies. The education of the future workforce and research at universities may thus play an important role for regions to successfully participate in autonomous driving development.

The performance of regions in university education can be measured via graduates, which also allows for the differentiation regarding the studied subjects. While detailed data is available for the USA and Germany, no consistent data for China was found. Figure 33 shows the number of graduates in the fields "Information and Communication Technologies" and "Engineering, Manufacturing and Construction" for Germany and the USA between 2013 and 2019. The stacked columns display the number of graduates in the three different levels "Bachelor", "Master" and "Doctoral" per country and study field. The dots, which refer to the secondary axis, display the share of graduates at each level in the respective subject, relative to all graduates at the respective level per country and year.

In the USA, the number of overall graduates in ICT increased considerably (second stacked, green column). Master's graduates almost doubled between 2013 and 2019. The increase in bachelor's graduates amounts to almost 70%. In Germany, masters' graduates also show the larger gain (+43%) compared to bachelor's graduates (+36%). While the growth in master's degrees in ICT also exceed the growth across disciplines in Germany, resulting in an increase of the share of ICT masters, the share of ICT bachelor's graduates stayed rather steady.

Figure 33: Graduates by field, Germany and USA, 2013 – 2019



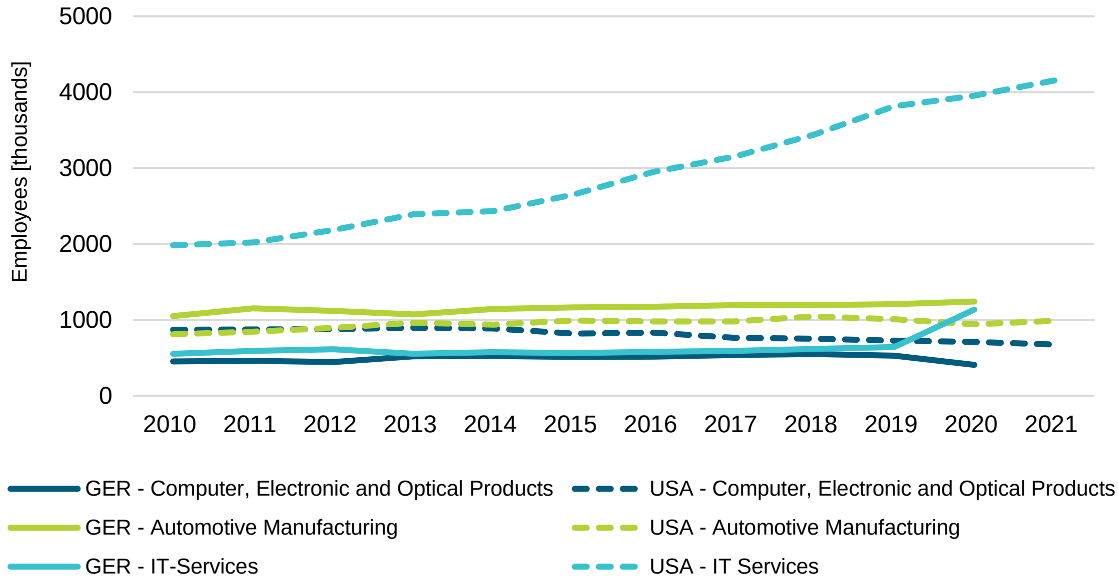
Source: Own representation based on OECD (2022)

Between 2013 and 2019, the number of graduates across all levels in engineering in Germany (bachelor's: by 51%, master's: by 46%, doctoral: by 20%) and the USA (bachelor's: by 38%, master's: by 17%, doctoral: by 19%) increased as well. Hence, the USA improved the share of engineering bachelor's graduates to almost 8%, the share of master's graduates to almost 7%, compared to all bachelor and master graduates, respectively. In comparison, the share of German bachelor's graduates in engineering grew up to 28%, master's graduates to 19%. However, the share of doctoral graduates in engineering is slightly higher in the USA.

Graduates in ICT and engineering must not necessarily end up in the field of autonomous driving, but they form the pool of potential workforce that is accessible to region, assuming that a majority of graduates stays in the USA or Germany after graduation. While the USA, with an absolute larger population and number of graduates brings out more ICT graduates, the shares of ICT graduates compared to all graduates is pretty much the same for Germany and the USA. In contrast, there are proportionally more bachelor and master degree graduates in the field of engineering in Germany, compared to the USA.

The increase in graduates comes along an increase in employment in the corresponding fields. Figure 34 shows the evolution of employment in Germany and the USA in the industries of automotive manufacturing, IT-Services as well as computer, electronics and optical products. The latter are considered product-oriented ICT activities. Consistent data on employment in China was not available. Between 2010 and 2019, employment in the IT-Service industry in the USA grew the most with an increase of around 90% (dotted light blue line), while the German IT-Service industry grew by 16% only[16] (light blue line). In contrast to the manufacturing industries, IT-Services also grew through the pandemic years 2020 and 2021. The workforce in automotive manufacturing grew with 15% and 25% between 2010 and 2019 in Germany and the USA, respectively.

Figure 34: Employment by economic activity, Germany and USA, 2010 - 2020 / 2021

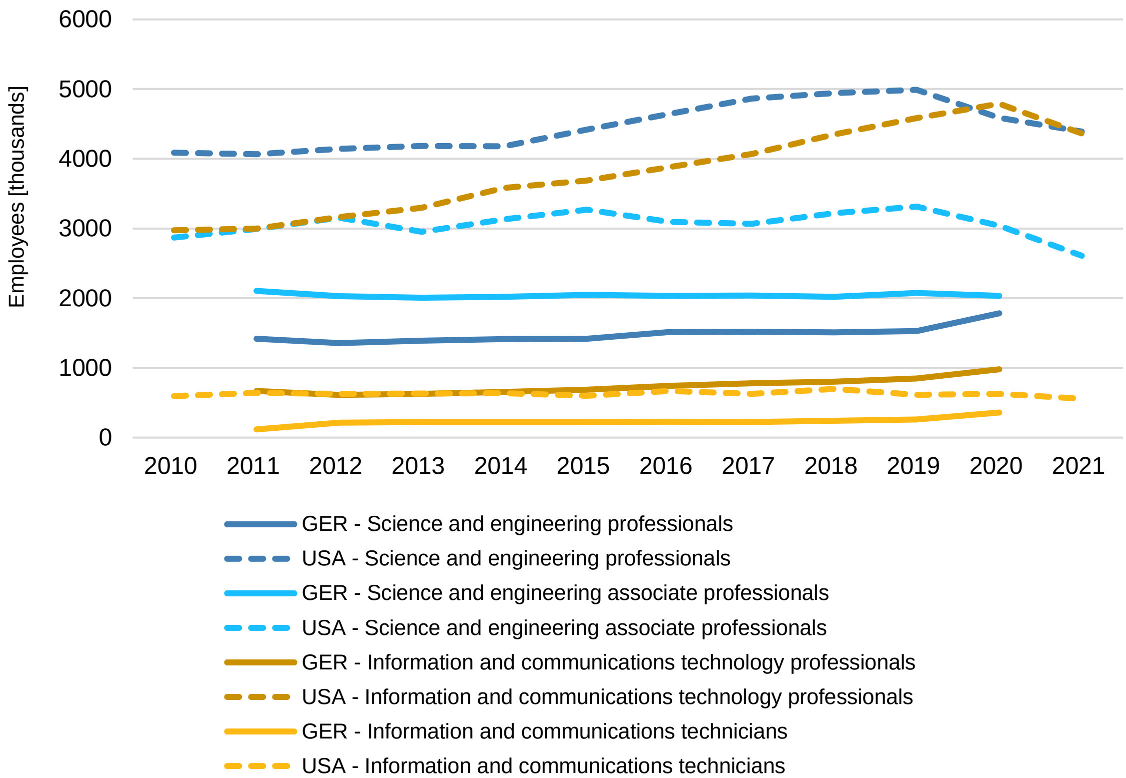


Source: Own representation based on ILOSTAT (2022a)

Figure 35 displays employment in the occupations science and engineering as well as information and communication, independent of the industries they are employed in. The data covers the development in Germany (2011 - 2019) and the USA (2010 - 2020). Occupation as information and communications technology professionals grew the most for Germany and the USA and exceeded growth in the number of information and communications technicians. Growth in the number of science and engineering professionals also exceeded the number of associate professionals in the field. In absolute numbers, professionals in engineering and ICT are the larger workforce compared to associate professionals and technicians in the USA. For Germany, that is the case in ICT, but in engineering, there are more associate professionals than professionals. While the number of professionals in both occupations increased through 2020 in Germany, employment in the USA seems to have reacted more sensitively to the pandemic.

[16] Data on German employment, displayed in Figure 34, shows an abrupt increase between 2019 and 2020 that does not correspond to German accounts. While the provided value in 2020 seems to match, the increase is considered to have started earlier.

Figure 35: Employment by occupation, Germany and USA, 2010 / 2011 - 2020 / 2021



Source: Own representation based on ILOSTAT (2022b)

For both, Germany and the USA, the data shows increases in the number of graduates in engineering and ICT, although the intensity varies in scale. On the other hand, the need for employees, especially in the field of ICT, is growing so rapidly, that the gains to the labor pool do not suffice. All considered countries, Germany, the USA and China report on skill shortages in software fields (Blaum 2022; Huxford 2022; Sloyan 2021; Berteletti et al. 2021). Reports on the deficit in the USA point out that is not only the number of graduates that has to be increased, but also the course contents need to better prepare students for the application in practice. Furthermore, the role of coding boot camps in educating people application-oriented is discussed against the background of the inconsistency in quality of the offered curriculums (Berteletti et al. 2021; Sloyan 2021).

Addressing the shortage of skilled workforce is one of the top priorities for companies in the upcoming years, since both the demand the shortage are expected to grow (Agrawal et al. 2020). At the same time, tech giants, venture capital startups as well as automotive firms tend to be rather attractive because of their brand reputations but also the ability to pay high salaries (Huxford 2022). Thus, for the relevant firms in the field of autonomous driving, the problem might not be as bad as for the many others seeking for ICT experts. However, it is a field that is crucial and under a lot of pressure and needs to be observed. In addition to that, the industry cannot solve that problem by itself, collaboration and exchange is needed with the education and research systems in the regions and also immigration politics.

5.5.3 Implications

The dynamics in the costly development of autonomous driving are driven by both, established players and new firms. While large and established firms mostly allocate parts of their own research budgets to the development of autonomous driving, the rise of new firms is to a large extent financed by venture capital firms or accelerators. The majority of those investors are based in the

USA, which corresponds to the vibrant entrepreneurial activity in the USA and has been displayed in section 5.1. That suggests at least some relation between regional financial resources and regional entrepreneurial activity, despite globalized financial markets.

On the global scale, a lot of financial resources are attributed to the development of autonomous driving. Current individual investment amounts in new companies and established firms, however, do not allow for a direct derivation on the future success of the respective firm. While the overall investments are large, for individual firms, financials may still present barriers. More partnerships to reduce the financial burden for single firms as well as a consolidation among new firms are likely to occur.

In order to develop autonomous driving, skilled employees especially from the engineering and ICT fields are required. While in the USA there has been a substantial increase of professionals and employment in ICT over the past decade, all considered regions face a growing shortage of skilled employees, especially in software engineering. The lack of a skilled workforce, crucial in innovative fields, has the potential to present large challenges to firms. However, the firms active in the field of autonomous driving are likely to profit from their reputation and might not be as affected from the shortages. While financial resources are globally available, despite some regional differences among the USA, China and Germany, the skill shortage seems to be a global problem from which all considered countries are affected.

5.6 Creation of legitimacy

A large number of firms engages in the field of autonomous driving, many of the technological prerequisites are ready, and governments have started pursuing the development of suitable frameworks which allow for the introduction to markets (see chapters 5.3 and 5.4). The industry expects new profit pools and governments favor positive impacts, for instance on traffic efficiency or the improved access to transportation, next to the economic interest in a successful domestic industry. While it seems like the majority of the society is, at least on an abstract level, in favor of the implementation of autonomous driving, the successful future diffusion of autonomous vehicles depends in particular on whether people actually use the technology and when they start with it.

Section 5.6.1 gives an overview of the different positions of actors towards autonomous driving and presents the main arguments in favor and in opposition of autonomous driving. The acceptance of the society as well as environmental concerns are identified to be two key issues that determine the short and long term legitimacy of autonomous vehicles. For prospective users, it is not only the attitude towards the technology itself that plays a role, but also the willingness to participate in newly structured mobility systems that consist of autonomous vehicles and are far more service-oriented. Section 5.6.2 discusses the topic of environmental concerns and potential implications for the diffusion of autonomous vehicles. Studies on the acceptance of autonomous driving are reviewed in section 5.6.3.

5.6.1 Positions towards autonomous driving

A review of current lobbying activities (Hekkert et al. 2007) shows companies and their associations in the participating industries to be in favor of autonomous driving. In Germany, that's for example the "Verband der Automobilindustrie" (association of the automotive industry, VDA), who represents the position of automotive players with regard to a variety of topics, including autonomous driving. Furthermore, in the USA, different constellations of actors have joined forces in order to push the diffusion of autonomous vehicles. One example is the collaboration of Waymo, Lyft, Ford, Uber, Volvo and others in the former "Self-Driving Coalition for Safer Streets", that was just renamed to "Autonomous Vehicle Industry Association (AVIA)". The associations, at the interception between industry and governments, mainly focus their work on the call for consistent regulatory frameworks on the national level, in the case of the USA (Patel 2022), the integration of national frameworks into international regulation, in the case of Germany (Verband der Automobilindustrie 2022b) and the provision of needed general framework conditions such as the expansion of 5G networks (Verband der Automobilindustrie 2022a).

Their main arguments in favour of autonomous driving are the increase in efficiency via connected vehicles and the advantages of a connected mobility system. In that system, effects on the environment are expected to be reduced through better traffic flows which results in less energy consumption by vehicles. Furthermore, increased safety and fewer accidents are a key argument (e.g. Verband der Automobilindustrie 2022c), as well as the overall better travel experience and the possibility to use the time in the vehicle freely. In addition to that, shared autonomous vehicles are discussed to have the potential to substitute private cars which could lead to smaller vehicle stock. This could materialize when people decided on selling their car, or, in the first place, would not buy a car and instead use shared autonomous vehicles. Since one car can then provide rides to several people, a number of cars can be replaced. Lower emissions in production and less land usage through fewer parking cars would be the results. This argument is found rather in the scientific and public debate and in the position of public transport associations (Verband Deutscher Verkehrsunternehmen e. V. 2015) than with the representatives of the automotive industry for whom fewer cars could directly impact revenues.

The overall picture tends to be rather positive. However, there are actors that also claim the negative aspects and raise concerns towards the implementation of autonomous driving. For instance, drivers and labour unions fear job losses among professional drivers in both, passenger and freight transport (Laing 2017). In connected vehicles and connected mobility systems, the threat of hackers taking over vehicles increases and concerns towards data security evolve (Eliot 2021). Also, ethical questions are still unsolved, for instance regarding the decision making of the vehicles' algorithms in the case of crashes, which present moral dilemmas (Martinho et al. 2021). Furthermore, negative effects on the overall energy consumption of the transport sector are discussed, when autonomous vehicles lead to a shift from public to private transport and the overall kilometres travelled increase (Verband Deutscher Verkehrsunternehmen e. V. 2015). With the availability of autonomous vehicles, the concepts of individual transport and public transport are increasingly overlapping. Public transportation companies have to reconsider their established business models (Verband Deutscher Verkehrsunternehmen e. V. 2015). On the one side, they fear a shift from public transportation to private vehicles since autonomous driving provides much more comfort to customers, on the other side they see opportunities in strengthening public transport when providing transport services in flexible autonomous vehicles as one mode of public transport. These considerations depend a lot on consumer choices and thus on the public acceptance of autonomous driving.

When looking at the arguments, presented in the current debate on autonomous driving, it becomes obvious that most of the issues, both positive and negative, do not concern the technology itself, meaning the technological functioning. It is rather about the implementation of the technology and the integration in and the design of the corresponding mobility systems. This suggests, that the majority of actions to realize the positive potentials of autonomous vehicles but also to overcome the raised concerns, will not take place in the research labs of the firms that are active in autonomous vehicle development. It is rather a process of discussion, negotiation, testing and shaping between industry, politics and society. In order to give a short example on such an issue, some thoughts on the impact of environmental concerns on the diffusion of autonomous vehicles and on the design of mobility markets are presented in the following section. Furthermore, the acceptance of autonomous vehicles in society is revisited. Whatever arguments are discussed among industrial players and organization leaders, without customers, the technology of autonomous vehicles will not make it to the streets (Alawadhi et al. 2020).

5.6.2 Sustainability concerns and potential policy intervention

The technology of autonomous vehicles itself is not per se sustainable or unsustainable. It is rather its implementation that can realize both, positive and negative effects on the overall sustainability of the mobility system. The reflection on the sustainability of autonomous vehicles has for long been underrepresented, as can be shown in a bibliometric analysis of scientific articles (Mora et al. 2020), but is increasingly considered in the scientific and public debate. The creation of legitimacy is a dynamic concept. Certain topics, hopes and fears may influence the first introduction of autonomous vehicles, other aspects will shape the implementation in future.

In combination with electric powertrains, autonomous mobility could be locally carbon free. Furthermore, efficiency potentials in traffic flows are considered to be a positive effect of autonomous vehicles (Mora et al. 2020). At the same time, the increase in comfort of road-bound individual transport may induce rebound effects, which could even increase energy and resource demand and thus cause further sustainability issues (Taiebat et al. 2019). First, predictions on the size of the car fleet vary substantially, challenging the widespread assumption that autonomous mobility reduces the overall number of cars due to higher usage rates, and thus the environmental burden of car production. Second, vehicle kilometers traveled are likely to increase, resulting in an increase in total distance traveled and energy demand (Narayanan et al. 2020). In addition to that, the potential cannibalization of the classic forms of public transport, as feared by public transport companies (Verband Deutscher Verkehrsunternehmen e. V. 2015), would also result in increasing emissions. The energy consumption of larger, shares vehicles such as buses usually undercuts the energy consumption of cars due to the higher rate of occupation in larger vehicles. In electricity grids that are not fully supplied by renewables, additional vehicle kilometers would thus still increase emissions. Overall, more energy consumption does always increase the absolute demand for sustainable energy, entailing the need for more renewable energy sources and thus more infrastructure in form of technologies such as solar panels or wind turbines, which in turn tie up resources in their production.

The need for politics to guide the implementation of autonomous vehicles to counter these unfavorable outcomes is stated in the recent literature. Fayyaz et al. (2022) discuss how autonomous vehicles may be deployed environmentally beneficially in the urban space and identify both negative and positive possible impacts. In order for the positive overall impact to prevail, measures such as the fostering of vehicle sharing and shifts in the urban planning principles are suggested. Narayanan et al. (2020) point out that in order to realize the potential of shared autonomous vehicles to noticeably reduce vehicle ownership, "strong policies" need to be set in place. With regard to the transport sector, potential measures will have a different character. So far, policy measures to reduce emissions of vehicles were mainly focused on technological advancements (more efficient combustion engines) and the substitution of old technologies with new solutions (battery electric vehicles). EU emissions fleet targets or the various programs to foster the purchase of battery electric vehicles are examples for these types of measures. When aiming at the protection of not only emission goals but also raw material resources, policy intervention must focus on the implementation and usage patterns. Market intervention, for instance in the form of regulated shares of public transport providing the fleets in combination with their classic services in urban environments, could affect demand and thus the related value chains and business models in the supply of transportation.

5.6.3 Acceptance of autonomous driving

Regarding the introduction of a digitized, autonomous mobility system, the acceptance of the autonomous vehicle technology plays a central role. So does the acceptance of using (shared) mobility services instead of possessing a private car and, of course, the combination of both. Since many predictive modelling studies on the future autonomous mobility market include parameters that are drawn from consumer surveys, some overlap exists between the section here and section 5.4.5, focusing on the long term market potential. This also underlines the interrelation between the acceptance of autonomous driving and market development.

Different aspects impact the acceptance of autonomous driving or vehicles, which are usually studied using surveys and a variety of modelling techniques. The trust of users is found to be an important determinant and positively impacts the potential adoption of autonomous vehicles (e.g. Paddeu et al. 2020; Motamedi et al. 2020; Nastjuk et al. 2020). Furthermore, the perceived usefulness is considered a strong predictor regarding potential usage of autonomous vehicles (Motamedi et al. 2020). The personal "innovativeness", which means the overall openness of a person towards innovative products, has also been identified to have a positive effect on the perceived usefulness of autonomous vehicles (Nastjuk et al. 2020). This relation could be in line with the findings that owners of electric vehicles, also a fairly new technology, are more likely to use autonomous vehicles (Xiao and Goulias 2022).

Many determinants of the acceptance of autonomous vehicles are themselves influenced by other factors. Trust, for example, relies on socio-economic factors such as age or culture, but also experience, beliefs or pre-existing knowledge (Paddeu et al. 2020). The perceived usefulness, as another example, is found to be driven by perceived safety (Motamedi et al. 2020). The perceived safety of autonomous vehicles in turn can also be influenced. Kaltenhäuser et al. (2020) find that for a proportion of respondents in Germany, the confirmation of the safety of the vehicle by an official supervisory body leads to higher openness. Others would want the vehicles to prove themselves for a few years regarding their safety, before using the technology themselves. Some do not consider using the technology at all. Similar results were presented by Xiao and Goulias (2022), who conducted a survey in California on the intentions to adopt autonomous vehicles. They find that 46% of the respondents "would wait as long as possible and try to avoid ever buying a self-driving vehicle (denoted as no adopter)", 45% "would eventually buy a self-driving vehicle, but only after they are in common use (denoted as late adopter)" and only 9% "would be one of the first to buy a self-driving vehicle (either as a replacement or additional household vehicle) (denoted as early adopter)" (Xiao and Goulias 2022, p. 174). The proving of the functionality of autonomous vehicles in real life before using it themselves seems like a key issue. When aiming at the deployment of autonomous vehicles, the attraction of early adopters will be crucial.

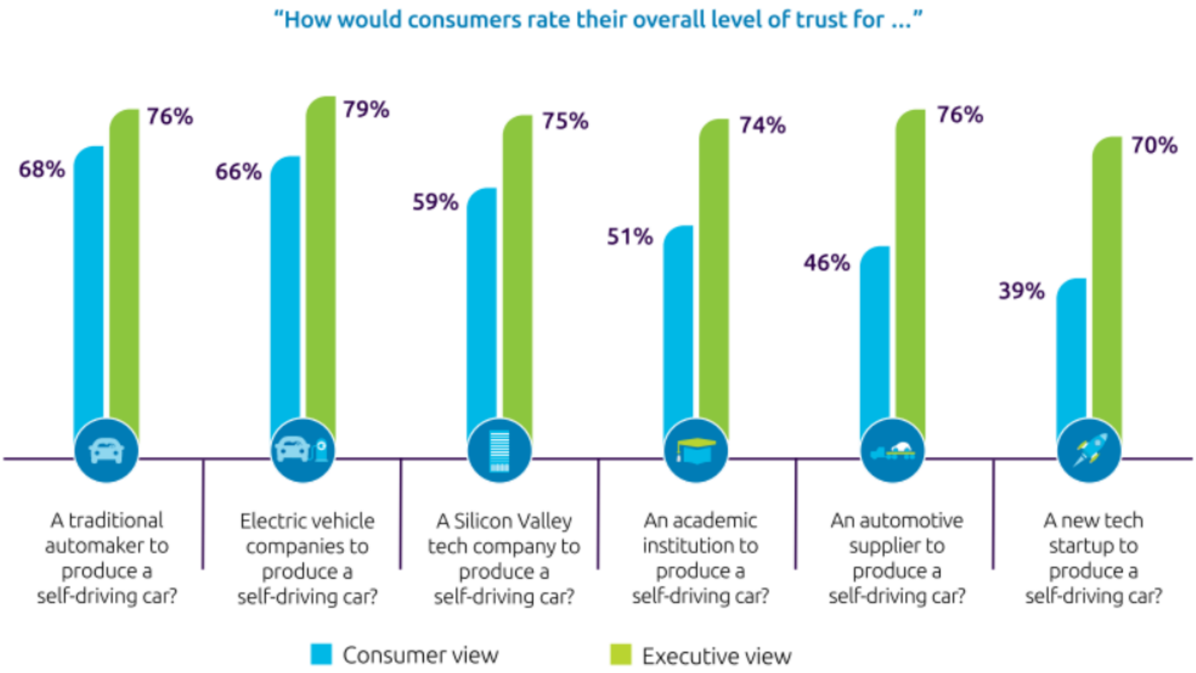
The cost of autonomous driving and autonomous vehicles directly affects the willingness to use the technology. Survey participants in France and Germany are more likely to use autonomous vehicles or buses if transport costs decrease (Othman 2021; Kaltenhäuser et al. 2020). The willingness to pay for advanced technologies differs between nations. Regarding both autonomy and safety, people from the USA and Germany are less willing to pay for the features compared to Chinese respondents in the survey, who are the most willing to pay among all included countries (Deloitte 2022). Besides monetary aspects, the overall acceptance of autonomous vehicles differs between countries, too, and is found when studying various factors that influence the perception of survey respondents (Nastjuk et al. 2020).

The factors determining the acceptance of or the intention to use autonomous vehicles in private ownership and shared autonomous driving differ. Motamedi et al. (2020) find that "personally owned users' intention will be more impacted by perceived usefulness, trust, and compatibility, whereas shared-use users' intention will be impacted more by perceived ease of use. Among all the factors, perceived safety is the only one which has a similar effect in both the full driving automation concept models." (p. 306). Regarding the shared use of autonomous vehicles, external factors may play a role that are irrelevant to the private use of autonomous vehicles. Xiao and Goulias (2022) show that the majority (67%) of survey respondents in California strongly (34%) or somewhat (33%) agree that they are unlikely to use shared autonomous mobility services, because they do not want to be in a vehicle with strangers. The finding suggests that the acceptance of autonomous on-demand mobility services may differ between pooled usage (meaning more than one party uses the vehicle at the same time) and individual usage (only one party is present in the vehicle). Since shared and ideally pooled vehicles are, however, favorable from an environmental and traffic flow perspective, it is important to look at the factors hindering people to use shared autonomous vehicles, when aiming at the adoption of shared autonomous mobility services. Several studies show that experiencing non-autonomous on-demand mobility services and public transport in general positively affects the position towards shared autonomous services (e.g. Xiao and Goulias 2022; Acheampong and Cugurullo 2019). This could serve as a link to foster the future usage of shared autonomous vehicles.

The attitude and acceptance of consumers is generally not steady over time, including the position towards autonomous vehicles (Narayanan et al. 2020). Besides own experiences, information that is spread through the media is shown to have a large influence on the acceptance (Anania et al. 2018). On the one hand, media coverage of the safe application of autonomous vehicles might increase trust and thus the willingness to use autonomous vehicles, on the other hand, the coverage for instance of single accidents with autonomous vehicles could negatively influence the diffusion of the technology.

The so far mentioned studies assess the acceptance of people towards autonomous vehicles regarding the technology and its deployment, which is expected to shape future autonomous mobility markets. The public acceptance of the supplying institutions might also have an influence, especially on the structure of the supplying value chains. Figure 36 shows the results from a survey conducted by Capgemini Research Institute (2019) regarding the question, how respondents would "rate their overall level of trust for" different organizations to produce a self-driving car. In the internationally conducted survey, the authors distinguish between the responses of consumers and those of executives from the broad field of autonomous driving. The questions aim at the expectations of consumers and executives who might produce a self-driving car. Thus the term "trust" here does not directly cover the trust in terms of the safety of the vehicles, but the trust in the ability of the organizations to introduce an autonomous vehicle to the market. However, the two questions might also be, at least to some extent, connected.

Figure 36: Trust of consumers and executives in different organizations to produce a self-driving car



Source: Capgemini Research Institute (2019)

The results show that consumers differentiate much more between the given varieties of organizations with regard to their potential ability to produce a self-driving car compared to executives. Traditional automakers are most trusted by consumers to produce a self-driving car, followed by electric vehicle companies and Silicon Valley tech companies. Consumers and executives both have the least trust in new tech startups to produce such a vehicle. While the overall acceptance of autonomous vehicles plays a role when it comes to the general introduction of the technology, value chain gains materialize for the firms whose vehicles and services are then demanded. If trust and perceived safety as two important and subjective determinants of the public acceptance vary among the offering organizations, acceptance could have a direct impact on future market shares.

5.6.4 Implications

The legitimacy of autonomous driving has to be considered in respect to the technology of autonomous vehicles and to the usage patterns of autonomous vehicles. Many firms, governments and organizations explicitly express their favor of an early introduction of autonomous driving. They want to foster the economic success of the respective country or firm but also the societal benefits that may arise from the implementation of autonomous driving. The latter is to be achieved for instance by shared autonomous driving concepts that replace many private vehicles and improve urban environments. Firms, whose revenues are dependent on the number and length of trips might profit from that concept rather than firms that are reliant on the quantity of sold cars. Automotive firms with their current business models and hardware-providing roles in offering robotaxi services, rather belong to the latter group. Depending on the individual strategy and introduction of service-offers, eventually, their priority might be on the introduction of the autonomous vehicles rather than on the diffusion of autonomous mobility services.

While the environmental benefits from autonomous driving materialize more (or at all) when autonomous vehicles are shared and thus used on a service base, customers lack the willingness to actually be in a vehicle with strangers. When governments start to intervene in that matter, market shapes and roles of firms may be affected. Examples of regulation would be measures that prevent the unlimited entrance of vehicles into city limits and thus foster shared mobility services rather than privately owned vehicles, or quotas on market shares of public transport firms that are expected to act more in favor of the common benefit. Overall, the acceptance of individuals stands partly in contradiction to the before mentioned preferences of governments and firms. Besides the reservation towards shared usage, few want to be the first to use the technology, which makes it crucial to attract first movers and might entail further involvement of government bodies to act as independent guarantors of safety. Safety and trust are central parameters in the acceptance of customers and firms that are trusted to provide safe products and services, are expected to have an advantage over others.

Discussion on both, environmental effects and customers attitudes, are still very hypothetical since the technology is not yet implemented. While legitimacy does not seem like a large challenge on an abstract level now, restraints among customers could lead to smaller market volumes and determine patterns of usage.

6 Integrated innovation system analysis: Interactions and intermediate results[17]

In the preceding chapters, concepts from the innovation system analysis were used in order to assess the current and future roles of the automotive and ICT sectors in the provision of autonomous driving and to derive implications on future value chain configurations. The aim was to enrichen the perspective on the international industrial transformation and to grasp the interplay between the two participating sectors by taking on the comprehensive and systemic viewpoint of innovation system research. The key assumption, which the analysis departs from, is that there is a strong linkage between the participation of actors and sectors in the innovation process of a product or service and their future role in the providing markets or value chains.

The preceding analysis of current and potential future roles of the automotive and ICT sectors in the provision of autonomous driving elaborated on the status quo in sectoral and national activities and suggested implications on further development. The interaction of the two sectoral systems within the development of autonomous driving is understood as the determining dynamic that may shape the implementation of the technology and thus the transformation of the value chain. The identified interactions between the sectoral systems are displayed in section 6.1. In the following section 6.2, the findings from the integrated innovation system analysis (sectoral analysis, functional analysis, analysis of sectoral interaction) are summarized. The intermediate findings build the base for the subsequent scenario-building process and macroeconomic simulation of potential effects on the German economy.

6.1 Interaction between the sectoral systems

The provision of autonomous driving requires the merger of technologies and concepts from the automotive and the ICT field. This requirement means that there has to exist exchange between the two fields or systems. The function “Interaction between sectoral systems” in the integrate analysis of autonomous driving development aims at the structured analysis and systemization of the interfaces and types of relationships that represent the interaction of the two systems (Breitschopf et al. 2023). Throughout chapters 4 and 5, the exchange and the interaction has been implicitly considered by distinguishing between the roles the automotive and the ICT sectoral systems play in the innovation system of autonomous driving. Thus, the newly introduced function has itself many interrelations to the other functions in the concept of functional innovation systems.

Understanding the interactions of the two systems in the innovation process is crucial when one wants to transfer insights from the status quo of autonomous driving development to the future system that will provide autonomous driving. The process of developing the technology and its implementation goes hand in hand with the process of back and forth between the industrial systems in finding, but also pursuing their roles. The dynamics between the two systems are considered to have a large effect on the future distribution of power and market shares and thus determine revenues and value added.

[17] Parts of the chapter have been published in Grimm and Walz 2024.

In the following, partly already presented information on the development process of autonomous driving is revisited and consolidated with regard to the characterization of the patterns of system interaction. The aim is to draw insights into how the interaction between the two sectoral systems may influence the future structure of autonomous driving provision.

6.1.1 Interfaces and relationships between the systems

The analysis of the interaction between the automotive and ICT sectoral systems departs from the identification of interfaces and relationships between the systems. The approach draws from the framework to asses inter-system interactions, introduced by Breitschopf et al. (2023). Interfaces in inter-system interactions are understood as elements that are shared by all considered systems. In the thesis, these are the automotive and ICT sectoral systems. Actors, institutions, infrastructure, technology, knowledge, natural resources, or intermediate goods and services can be interfaces (Breitschopf et al. 2023). Relationships describe the relation, the two systems have with regard to or through the interface. The relationships are considered to be either competing, cooperative or symbiotic, integrative, spill-over, or neutral. Two systems would compete, for instance, over scarce inputs or they would cooperate in non-rivalry manners using the same infrastructure. An integrative relationship describes the situation when one system provides structures such as intermediate goods, which the other system depends on. Furthermore, a rather unintended passing on or repurposing of knowledge or a technology, would be described as a spill-over between the two systems. Finally, interfaces can also exist in neutral relationships, where two systems co-exist without affecting each other's functioning. In the following, only the interfaces and relationships between the two sectoral systems in the context of the development of autonomous driving are considered. The framework was initially developed to analyze the interaction between socio-technical systems, however, its principles appear useful to structure the interaction between two systems within a, what one could call, shared innovation process. The following assessment of interactions partly builds on a case study on the interaction of the automotive and ICT systems, presented in Breitschopf et al. (2023)[18].

The innovation system of autonomous driving and everyone participating in that process aim at the technological development of autonomous vehicles and their implementation. This process requires the co-development of organizational structures, business models, regulatory frameworks, etc. to apply the technology in a secure and favorable manner. Since the implementation cannot be conducted without having the functioning technology, the technology of autonomous vehicles can be considered the core piece and initial interface of the automotive and ICT systems, engaging in autonomous driving. There exist different relationships between the automotive and ICT systems via the common technology, that both of them work on. Initially, when looking at the full concept of autonomous vehicles, one could consider the overall relationship rather competing, since firms from both sectors compete in terms of velocity in the R&D progress, aiming to be the first to bring autonomous driving to the streets. When one divides the technology of autonomous vehicles into its many parts, the picture changes. Firms that work on the development of the same technological parts would still be considered competing, however, firms that focus on different parts also currently cooperate in developing components together. Examples on the growing role of partnerships and collaborations have been presented in section 5.2.4. Furthermore, also integrative relationships exist in the complex assembly of an autonomous vehicle, since for instance ICT firms rely on automotive firms providing vehicle hardware for prototypes and test vehicles. Also, the display of patent

[18] The case study on the interactions of the automotive and ICT systems in Breitschopf et al. (2023) was conducted by the author (Anna Grimm) of the dissertation

citations among the different technological components and patenting sectors, as introduced by Meng et al. (2019), and shown in section 5.2.3, suggests spill-overs on the interface of technology. It shows that while the most prominent relationships are probably those between industrial actors, it is also individuals such as researches or institutions such as university chairs or research institutes that interact from the two systems on the interfaces of technology and knowledge by collaborating in research projects and by integrating published knowledge from the other field in the own research.

The relationships between the sectoral systems with regard to the interface of the technology or the technological knowledge appear to be diverse and they seem to change in the course of time. This dynamic evolution of and changes in relationships is probably due to the fact, that autonomous vehicles are still in the development stage. While some years back it seemed more like a very competitive landscape of a few firms trying to develop the technology as a whole, the number of firms and the number of cooperative development projects has increased over time. In the future, there might occur another shift from cooperative relationships towards more integrative relationships, after joint development projects were successful and ended. Then, the technologies are beyond the development stage and ready to be produced on a large scale. Complementary solutions, developed in cooperative development projects, then have to be integrated in supply chains.

Besides the technology of autonomous vehicles itself, also the application in form of autonomous driving services is a concept that both sectors participate in developing and implementing. The pilot projects that are already introduced or announced in providing robotaxi services, suggest cooperative relationships within partnerships. This was shown in section 5.2.4, where all presented partnerships include one firms that provides the mobility platform, one the automotive hardware and one the autonomous driving technology. Considering the partnerships as individual units, they in turn compete with each other. However, since partnerships are mixed, crossing sectoral borders, this would not necessarily be classified an inter-system interaction.

Next to the interfaces and relationships that arise in relation to the autonomous vehicle, the two systems increasingly share neutral interfaces, for instance, with regard to institutions. An example are the regulatory bodies that develop and publish traffic and transportation laws and are in charge of vehicle admission. The ICT sectoral system has for long been independent of these institutions. Aspects of data security or cyber law are fields that also have an increasing relevance for the implementation of autonomous driving and that both system have to cope with. Many of the fields in the legal and institutional sphere, however, are changing and expanding a lot in order to provide the suitable frameworks for the so far unknown and partly unregulated technology of autonomous driving. These interfaces are not so much elements of one system that then plays a role for the other system, where the experienced system might have an advantage in. They are new for both sectors and are established in the evolving overlap of the systems. Also, these interfaces are considered framework conditions, that both of the sectoral system have to cope with, but with a neutral relationship, since the interaction does not imply any distinguishing impact on the two systems' functioning.

Some other and quiet common interfaces exist with regard to the infrastructure. For instance, when considering labor markets a form of infrastructure, the two sectoral systems firms' compete in attracting experts with similar skills. The competition with regard to a trained workforce is intensified by the shortages in labor markets as shown in section 5.5.2. The interface of the workforce also implies interaction between the education and research bodies of the two sectoral systems, since the education and university programs increasingly merge.

The two sectoral systems face several interfaces with regard to autonomous driving. These interfaces and the relationships that are observable now, are likely to change in the course of time. Especially when the technology passes the development stage and will diffuse. The operation of an autonomous mobility system will probably give rise to other interfaces and relationships. One could be unforeseeable spill-overs to other sectors that are affected by autonomous driving.

6.1.2 Implications

Simply speaking, the two systems interact because their competencies are both needed in order to develop the technology of autonomous vehicles and the concept of autonomous driving. Through the merger of the competencies, the sectoral lines become increasingly blurry and a new digitized mobility system may arise in the intersection of the two sectoral systems. The interaction between the two established automotive and ICT sectoral systems can shape, first, the extent to which they themselves dissolve in the digitized mobility system, and second, the characteristics of the new digitized mobility system. Characteristics here refer to whether the emerging system is rather influences by the fundamental patterns of the automotive sectoral system or the ICT sectoral system.

With regard to the future configuration of the system providing autonomous mobility and its value chain, it is especially the interaction between the industrial subsystems of the automotive and ICT sectoral systems that is important. For one, there are relationships between the producers or suppliers of parts and components from the two sectoral systems. For the other, the relationships between the large automotive OEMs and the ICT so called tech giants, are expected to have a large influence on who will lead the value chain at the top.

Competition between the large automotive and ICT actors in providing the full concept of autonomous driving means that they want to provide the same thing. This in turn implies that they either provide it simultaneously, which leaves everyone with smaller market shares, or that some are forced to exit the market. If actors from both sectors would want to provide autonomous driving, it necessarily means that both have to somehow include the knowhow of the other, since autonomous driving can only be provided by combining the two fields. An inclusion in turn means that they either integrate the other product component or service into the upstream value chain or by integrating the knowledge, which means generating the knowhow, themselves. An integration of one or the other into the value chain, however, would imply that they are probably no longer competing on the downstream, final provision of autonomous driving. This chain of arguments only holds when looking at the provision of the full concept of autonomous driving. As shown in chapter 5.4.1, it is probable that two types of partial markets will form the autonomous driving market: For one there will still be the market for private autonomous vehicles and for the other, the market for autonomous driving services.

In case that the firms from the automotive and ICT sectors would target either one of the markets, for instance, the automotive OEMs rather the private autonomous vehicle market and ICT tech-giants rather the (shared) autonomous driving service market, competition may prevail but not on the interface of the vehicle technology. The competition would rather arise on the interface of the customers that they are targeting and thus be about the sizes of the private and the mobility service-oriented markets.

While the private autonomous vehicle provision does not require the mobility service “component”, the autonomous driving provision requires the integration of a vehicle, which brings one back to the interface of the autonomous vehicle. Assuming, that an ICT brand firm provides the autonomous driving service, chances are that they outsource the production, as they do with the production of their other products such as smartphones, too. Then, the competition on the interface of the autonomous vehicle is no longer between the automotive OEMs and the ICT tech-giants, but between the automotive OEMs and evolving contract manufacturers, that have their roots in producing white label products for ICT brands. With the introduction of electric vehicles, vehicle manufacturing became easier and the market entry barriers into the vehicle market sink. While some contract manufacturers have announced the production of electric vehicles, they are not yet known for participating actively in the innovation process of autonomous vehicles or announcing cooperations. Contract manufacturing of vehicles by non-automotive producers has not yet exceeded the announcement stage.

Both, automotive OEMs and contract manufacturers would probably not produce the autonomous vehicles and all their components themselves. The current, established value chains of automotive OEMs consist of hundreds of suppliers that are integrated in the automotive value chain. Assuming this principle to prevail, both, automotive OEMs and contract manufacturers, would face several interfaces in form of technological components to the automotive and ICT suppliers. On these interfaces, they have to, or already have, established integrative or cooperative relationships.

For many parts and components such as sensors, electric parts, interior furnishings and so on, the relationships are mostly integrative: they are intermediate goods that are traded along the supply chain. In the established automotive value chain, the combustion engine was the center piece of the vehicle, and the production has usually stayed with the OEMs themselves. Through the transformation to electric power trains, the shift in value creation and complexity of that center piece is one of the key issues that automotive OEMs and suppliers deal with right now. The technology of autonomous driving could be another one. There are firms that only focus on the development of the autonomous driving technology that can then be integrated into a vehicle. The mentioned examples of partnerships in providing robotaxi services, between platform providers, automotive hardware producers and autonomous technology suppliers suggest that the autonomous driving technology can be considered to be a system component that can be integrated into the hardware of other producers. It remains unclear, whether there will be one common concept of who and how the autonomous driving technology will be integrated in the vehicle. Following the example in robotaxi partnerships, where the autonomous driving technology is provided by a separate firm, autonomous driving providers could act as a supplier or partner to vehicle manufacturers. Another principle could be, that automotive OEMs develop and implement the technology in their own vehicles themselves. This strategy could be drawn from the example of Mercedes-Benz, who introduced the S-Class with Level 3 automated driving functions (Mercedes-Benz Group 2021). The future configuration will probably depend on the technological feasibility as well as on individual strategies. With external autonomous driving providers, new questions with regard to the branding and power structures in value chains arise. Here one should distinguish, again, between the private autonomous vehicle market and the autonomous driving service market.

In the private autonomous vehicle market, the power distribution between a vehicle manufacturer and the autonomous driving function supplier would determine, whether the relationship is rather integrative or cooperative. This would imply, that the technology will either be supplied from an upstream technology provider in a classic supplier-buyer relation or that the autonomous technology provider, from a value chain perspective, is more on the same stage as the vehicle manufacturer. In the latter case, when the autonomous driving technology is the center piece and develops into a determinant for sales, the continued existence of automotive brands could, in the most extreme case, be in question. In rather integrative relationships, or when the automotive firms developed their own technology, no large changes to the value chain principles are expected. However shifts in value added along the stages of the value chain still have to be determined.

In the autonomous driving service market, the existence of and relationship between the potentially external autonomous technology providers and the hardware producers could also have effects on the future value chains and forms of the supply side. With the autonomous technology being external, competition between automotive hardware suppliers and contract manufacturers would not be about the ability to provide for that technology. Furthermore, the firm constellations who provide, for instance, robotaxi services could be more flexible, alternating the different options of platform, vehicle and autonomous technology providers. Constellations would consist of three partners instead of only two, if the autonomous technology was integrated into the vehicle by the hardware supplier.

While the preceding paragraphs tried to introduce some potential pathways with regard to the implications that inter-system interaction may have on the value chain configuration in future autonomous driving, of course, one could think of others that exist in parallel. The examples illustrate the relevance that the inter-system interactions have on shaping the future system. Explicitly considering the ongoing inter-system interactions and thinking about the future evolution gives hints on more and less consistent combinations. This thus narrows down the space of likely parallel pathways and prepares the scenario-building process in chapter 7.

Overall, one can conclude that both systems, including all their different components or institutions, have to extend their knowledge into fairly new fields. That becomes especially obvious for the industrial players that prominently develop the technology and concepts of its implementation. Therefore, interactions, that affect the value chains, are largely observed among the industrial subsystems of the automotive and ICT systems. All types of relationships, including cooperation and competition over system-boundaries, are identified and it is shown that the interactions underlie dynamic changes in the course of time. Moving towards a currently non-existing new, integrated autonomous mobility system might eventually turn inter-system interactions to intra-system interactions.

6.2 Intermediate results of integrated innovation system analysis[19]

In the following, the first three proposed research questions from the introduction (chapter 1) are revisited. The sectoral and national perspectives on the development of autonomous driving are in focus when answering the questions. Central findings on the potential division of roles between sectors and nations in the future mobility value chain are pointed out and uncertainties are discussed. The abbreviations in the brackets indicate the function (Figure 4), from which the findings are drawn

What are the key characteristics of the automotive and ICT sectors that may influence their participation in the development of autonomous driving?

The participation in autonomous driving development can be broadly divided into the technological development of the autonomous driving functions and the development of accompanying business models such as shared autonomous vehicle usage. With regard to the technology, actors from both sectors have their sector-specific and relevant core competencies (automotive sector: vehicles, sensors, steering, etc.; ICT sector: data (especially image) processing, platform operations, etc. (S1, S2)). However, both have to generate new knowledge. The sectoral knowhow can explain the partly complementary engagement of the two sectors' actors in the development of autonomous driving (F2).

[19] The summary of intermediate results of the innovation system analysis is adopted from Grimm and Walz 2024.

Despite recent efforts to open up to the service market, the automotive sector can be classified rather product-oriented. In the ICT sector, software and service offerings are more common, also in combination with hardware, such as smartphones. Regarding the accompanying business models, ICT players, which are often already active in the platform economy, can draw from their implementation knowledge and customer base (S1, S2).

The automotive sector finds itself in a transformation that fundamentally changes its core product and source of revenue: the vehicle. The players' efforts aim at the securement of market shares in a changing mobility market. The automotive transformation goes beyond the automation of driving functions but includes the electrification of the powertrain, too, presenting parallel innovation pressure on the automotive sector (S2). For the ICT sector, the development of autonomous vehicle technologies and autonomous driving implementation is rather a classic innovation process, where new solutions are developed and, at least partly, known methods are applied to a new field: vehicles. The manufacturing of vehicles can be outsourced in the form of established business partnerships with contract manufacturers (S3). Furthermore, the existence of the ICT sector itself is not challenged by the rise of autonomous vehicles. The players have the possibility to enter an additional, new and evolving market without the pressure to obtain existing market shares.

Are there any differences in the activity of the automotive and ICT sectors and different countries in the development and provision of autonomous driving?

The automotive country Germany ranks high with regard to assisted and autonomous driving technology patents over the past 15 years, while the USA and China lead in new firm foundations. The latter increase their patenting activity. Especially the USA have become active with regard to patents targeting the full concept of autonomous vehicles (F1, F2). The implementation of testing and pilot projects is feasible in all analyzed countries (F3). However, pilot robotaxi services are mainly provided in the USA and China, where mostly domestic firms engage (F4). Most of the analyzed automotive firms engage in autonomous driving technologies, the integration of the components and hardware provision to robotaxi services. ICT firms mostly focus on technological components, digital environment and communication solutions and platform provision. New firms with a sole focus on the autonomous driving technology evolve in the interface of both sectors (F1). Despite a certain overlap, this suggests partly complementary engagement in relation to different components needed for autonomous driving implementation and requires cross-sectoral collaborations. These partnerships are currently prominent in the provision of robotaxi services (F4). The external funding structure of mostly ICT startups or startup-like affiliates of large ICT firms presents the chance to receive large amounts of funding (F1, F5). However, the structure also represents a high dependency on capital providers.

What are the main factors and how may they influence the potential reconfiguration of value chains and the division of tasks between the automotive and the ICT sectors? What does that imply for the national industrial landscapes?

Five central factors are identified that may shape the future autonomous mobility markets. First, the share of privately owned versus shared autonomous vehicles (F4) influences the success of targeted business models as well as market potentials and determines the distribution of power along the value chain. The distribution of autonomous vehicles to private customers, seemingly targeted by the automotive OEMs, leaves them in the position of lead firms. In the provision of autonomous mobility services, platform providers gain direct customer contact and they could potentially push back the vehicle manufacturers by one stage. In addition to that, the platform economy is known for the evolution of large, monopoly like providers. The agglomeration of market and supply chain power can contribute to market restructurings. However, studies on the future usage of autonomous vehicles suggest the coexistence of both types of business operations, privately owned and shared autonomous vehicles (F4).

Second, the differing mobility behavior and acceptance of autonomous driving suggest a further differentiation of regional markets and imply the requirement towards autonomous vehicle and mobility providers to meet these market specifics (F4). For example, Chinese respondents seem more open towards new mobility solutions which might foster the implementation of autonomous driving in China (Heineke et al. 2021). In contrast, the very active firms from the USA might be increasingly challenged by domestic customers that are clearly oriented towards private car ownership. The fragmentation of regional markets can also be driven by the future technological requirement details formulated by national governments (F3).

Third, technological bottlenecks and the provided infrastructure might define future areas of implementation (F3). While pilot projects suggest the feasibility within delimited areas or city limits, a widespread and continuous implementation of autonomous driving might be on another timeline. Automotive firms that also target the step by step automation of vehicles, might experience a broader diffusion of their new technologies in the near future.

Fourth, individual strategic firm decisions, technological improvements or even technological leadership and the success of cooperations may influence the competitive standing of industrial players and in turn the prevailing mode of sectoral interaction (FI). This is heavily intertwined with the acceptance of customers and the form of autonomous driving implementation. After a phase of high investments and many new foundations, the field seems to have entered a phase of consolidation, which is expressed in the forming of partnerships and mergers but also decreasing investments in new firms.

Fifth, the attractiveness of individual firms to attract capital but also workforce (F5) seems crucial to their success (and in turn also influences the competitive standing). Many markets face increasing labor shortages and skilled workers are sought-after by firms from both the automotive and the ICT sector. Furthermore, the development of autonomous driving has for some years been a prominent field prospering from high investments. Persistent and large future funding requirements leave the steering power over the success of especially ICT newcomers to external investors. Firms from the automotive sector face parallel investment needs with regard to the decarbonization of mobility, which might be more pressing due to regulatory standards.

For automotive oriented countries like Germany with less entrepreneurial activity in digital solutions, the continued existence of privately owned vehicles would equal fewer changes to a so far successful industrial landscape. In the private car market the incremental, increasing automation of driving features up to fully autonomous driving over the years is feasible, a core competency of the automotive industry. In contrast, countries with high entrepreneurial activity, large and running platform companies and robotaxi pilot projects such as the USA or China are likely to profit from a higher degree of servitization and fully autonomous driving offers. There, domestic platform firms have good access to the national mobility market and may occupy the evolving mobility service market. In addition to that, cooperations with national automotive manufacturers strengthen the capture of market shares from established foreign manufacturers such as German OEMs in China.

Either way, the portion of digital components and services along the value chain is expected to increase. Especially large automotive manufacturers and suppliers from the automotive industry expand their digital competencies in-house or acquire firms with fitting knowhow, which makes them to some extent persistent to the transformation. However, individual components are likely to be provided by new firms also from the ICT sector that enter the mobility value chain.

So far, automotive innovations have, at least in variations, been implemented in vehicles in all major automotive markets. Fully autonomous driving will eventually diffuse only in markets where it is accepted and wanted by customers. Also, meeting country specifics might be more challenging. The differing openness towards new technologies and the current mobility behavior suggest more fragmented international autonomous driving markets. Large domestic markets that appear to be open to new solutions, such as China, might be in advantage due to larger sales potential, so are the domestic providers. This would imply challenges to domiciled foreign manufacturers such as German OEMs. However, at the moment this applies mostly to large cities, since the gap to rural areas in terms of infrastructure and potentially acceptance is large.

Overall, the automotive and ICT sectors' interactions on the interface of autonomous driving have led to what one could name a light coupling. The innovation process requires competencies from both sectors and while players aim at expanding their knowledge in new fields, inter-sectoral dependencies and cooperation persist. Since the coexistence of vehicle and service-oriented mobility markets seems likely, lead firms from the automotive and ICT sector will probably coexist. An upstream and punctual integration of the two sectors in either direction along the mobility value chain has already been implemented, while a full integration of one sector into the other does not become apparent.

While some implications on the interrelation of influencing factors could be drawn, many uncertainties prevail. The field of autonomous driving is very dynamic and examples, such as the de-investment of Volkswagen and Ford in Argo AI (Korosec 2022), show how quick fundamental decisions are made and rolled back. The timing of the technological development success (F2) and co-evolution of regulation with regard to a certified safe application of autonomous vehicles remain unclear. Legitimization does not yet significantly affect the development process but might become an increasing problem, for instance in the occurrence of accidents caused by the autonomous driving technology (F6). Potential environmental rebound effects through the implementation of autonomous driving might enhance regulation by governments that may interfere with the firms' implementation strategies (F6). The same applies to potential market regulation in the case of unwanted monopolistic structures or industry policy engagement in protecting national markets (F4, F6). Finally, prospective modelling studies in many cases build on the self-assessment of respondents on their expected acceptance of autonomous vehicles, which can easily change based on a range of influencing factors (F4, F6).

7 Scenarios for the German industry in the global autonomous driving context

The development and future implementation of autonomous driving has the potential to disrupt the automotive market by changing principles of mobility, business models and the landscape of active industrial players. For countries with a strong automotive but weaker ICT industry, such as Germany, shifts in the value chain towards ICT firms could result in a loss in market shares and revenue and thus affect economic prosperity.

In order to assess these potential effects, chapters 4 - 6 aimed at understanding the status quo of autonomous driving development, activities of players and countries and the interplay between the automotive and ICT industries. Therefore, an extensive analysis of the structure of the automotive and ICT sectors and on the innovation system of autonomous driving was conducted. The analysis focused on the interplay between the automotive and the ICT sectors in Germany, USA, and China. The integrated innovation system analysis, combining sectoral, technological and interaction perspectives, described differences and similarities in the engagement between regions and the automotive and ICT industries in the field of autonomous driving. As a result, insights on potential changes in the value chain were derived and the most influencing factors that may drive further developments were identified. The described changes and potential developments are subject to a high degree of uncertainties and reveal that several pathways of future development are plausible. As described in section 2.2.1, scenario-building methods have been long established in order to cope with uncertain futures. Building heavily on the insights from the integrated innovation system analysis in the previous chapters, chapter 7 develops four scenarios on the potential future of the German industry's engagement in the provision of autonomous mobility in the global context of the new technology's diffusion until 2050. The approach that is chosen to build the scenarios is explained in section 3.2.

The following sections describe in detail the process of scenario-building. Section 7.1 presents the underlying understanding of the setting in which the scenarios are developed and draws the connection between the scenario storylines and the macroeconomic analysis in chapter 8. Section 7.2 explains how the factors were derived in an iterative process and presents the chosen set of factors. Finally, the developed scenarios for 2050 are described in section 7.3.

7.1 Objective of the scenarios

After analyzing and understanding the status quo of autonomous driving development and the industrial landscape, the objective of the scenario-building process and modelling is to shed light on the potential effects different development pathways may have on the German economy. The leading question of the scenario-building process is (research question 4, chapter 1): How could the future autonomous driving market develop up to 2050 and which strategies of the German automotive industry are imaginable? In the following step (chapter 8), the key characteristics of the scenarios are quantified and complemented by other framework figures in order to model the potential development of the indicators GDP, value added, and employment in Germany until 2050. Generally, scenarios should be plausible, consistent and be useful in the context of the research objective (European Foresight Platform 2023). In order for the scenarios to be useful, the subsequent processing in the economic modelling task is explicitly taken into account in the design of the scenario development process.

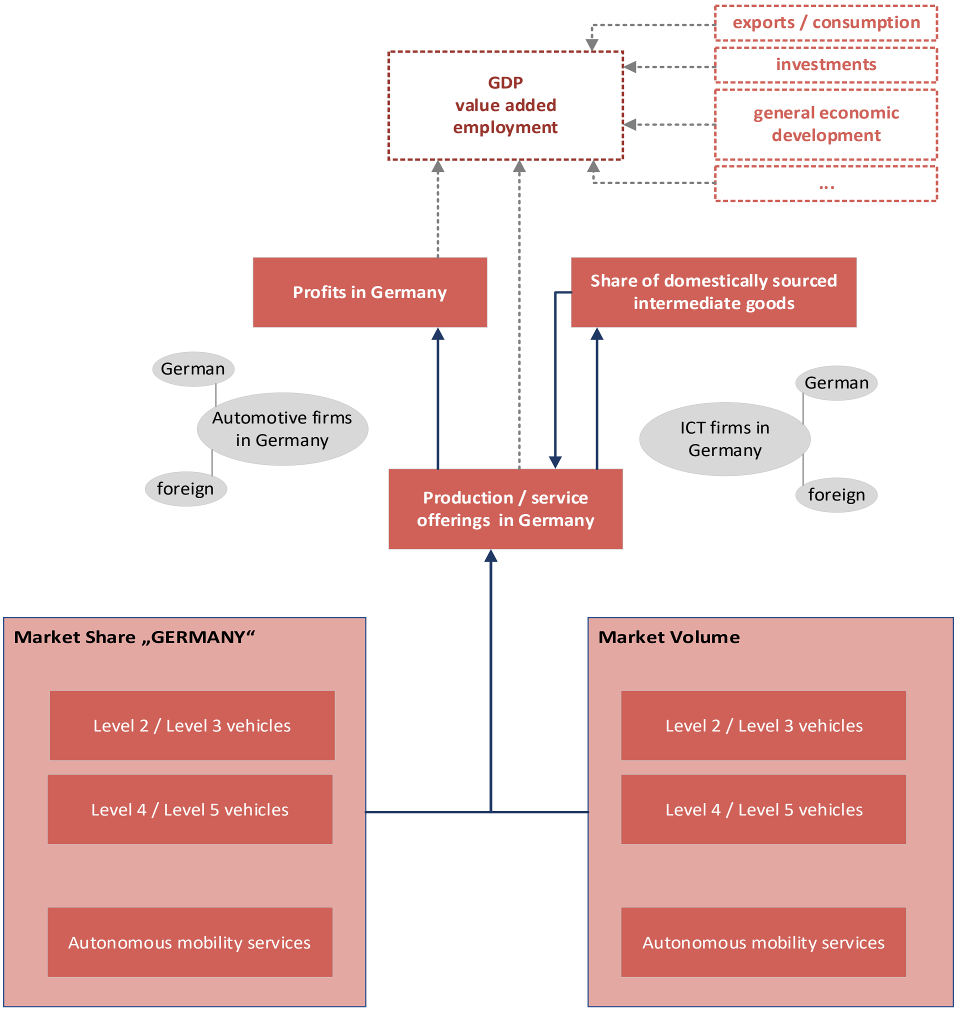
In global markets, economic activity and the success of industry branches or individual firms is dependent on different factors on the demand and supply side as well as general, global conditions.

Within the thesis, the focus is on the implications of a changing industrial landscape for the German economy due to the evolution of autonomous driving. The German industrial landscape might eventually supply autonomous vehicles and mobility services to domestic and international markets and meet international demand. While the development and implementation of autonomous driving is just one of several trends influencing the German industry, an overall assessment of the various transformations (electrification of the powertrain, circular economy measures …) in the automotive industry is beyond the scope of the thesis. The subsequent explanations all focus on the distinct developments in relation to autonomous driving.

Macroeconomic effects on the German economy, induced by the autonomous driving industry's performance can be measured by indicators such as GDP, value added or employment. Figure 37 displays the simplified understanding of the interrelation between market volume, market shares, and economic indicators, assumed in the thesis. The elements on the top right, bordered by dotted lines, indicate the categories of impulses that are used in the simulation (chapter 8) in order to translate the scenario characteristics in the model (see section 3.2.3 for description of the modelling approach). Changes in the GDP, value added and employment (top of Figure 37) are, in the scope of the thesis, driven by the economic activity of the autonomous driving industry. The economic activity is understood as the production of goods, the offering of services and the generated profits in Germany (center of Figure 37). That includes the activity of German automotive firms operating in Germany, the activity of foreign automotive firms operating in Germany, the activity of German ICT firms operating in Germany and the activity of foreign ICT firms operating in Germany. This understanding follows the production or output approach in national accounts (including input-output tables), where "a resident unit is regarded as constituting an institutional unit in the economic territory" (eurostat 2013, p. 27; Statistisches Bundesamt 2016). In case of German multinational firms, production or activities abroad are not considered to be part of the German economy. It is pointed out that the described understanding might neglect the existing profit-relations between the headquarters of multi-national firms and their subsidiaries. Profits that are generated abroad might still be transferred and invested in the home country through intercompany billings. The limitations are already mentioned here in order to shape the expectations towards the delineation of the qualitative scenarios.

Economic activity related to autonomous driving in Germany is understood to be driven by an international market volume and the market share that the industry in Germany has in supplying the market (bottom of Figure 37). Furthermore, it is influenced by the share of domestically versus internationally sourced intermediate goods that are used in German production. The considered global market for autonomous driving consists of automated vehicles (Level 2 and 3) and autonomous vehicles (Level 4 and 5) as well as autonomous mobility services. The market volume is mainly determined by the demand for the products and services (bottom right of Figure 37). The demand in turn is influenced by many individual factors such as the acceptance of the technology but also by market conditions such as regulatory frameworks, prices, or the political climate. The market share of Germany in supplying automated and autonomous vehicles and autonomous mobility services includes the market shares that German-based automotive and ICT firms have in supplying the market (see above paragraph on the institutional unit in the economic territory).

Figure 37: Simplified scheme of the understanding of autonomous driving's economic impact on Germany



Source: Own representation

With the described general understanding of the autonomous driving's economic impact on Germany in mind, the scenarios for the German industry are derived. The developed, qualitative scenarios should allow to think about quantitative implications of the scenarios for Germany. The final goal of the thesis is to translate these scenarios into quantitative impulses and to model the scenarios in a macroeconomic simulation model up to 2050 (chapter 8). The aimed at scenarios are useful for the further assessment, if they are formulated in a way that allows for projections on the development of German market shares and global market volume (bottom of Figure 37).

7.2 Influencing factors

"Building the System and Identifying the Key Variables", that's how Jouvenel (2000) described one of the first steps in prospective procedures or scenario-building. As mentioned before, the innovation system analysis, conducted in the preceding sections has already established the systems in focus: the overlap of the automotive and ICT sectoral systems, the technological system of autonomous driving and the various regional or national system, namely Germany, USA, and China. The innovation system analysis allowed for the identification of the key factors that drive the development of autonomous driving and the potential future configuration of a new mobility value chain in both, the sectoral and regional dimension. These identified key drivers are now revisited in order to derive the scenarios of German engagement in the provision of autonomous driving.

In an iterative process, factors were selected that directly or indirectly drive either the development of the overall autonomous driving market volume or influence the market shares of the German industry (Figure 37). The detailed process is displayed in Figure A 2. It departed from the collection of driving factors from the innovation system analysis for a first long list of influencing factors. Table 9 shows the final short list of factors and provides brief description of the factors. The factors are arranged by the TIS-function the innovation system analysis from which they were derived. One additional framework factor on the overall trade climate was added.

Table 9: Factors and their description (I/IV)

Function	Factor	Description	No.
Framework conditions	**Trade climate**	Recent decades have been marked by the major vehicle markets Europe, USA and China. However, vehicle market volumes and shares in sales of German OEMs appear to stagnate or even decrease, especially in China. Current market dynamics might indicate shifting mobility target markets for German firms. Furthermore, changing trade regulations can pose the need for domestic production in the target markets which results in the shift of production sites from Germany or Europe to e.g. the USA or China.	1
Sectoral structure	**Premium orientation of German OEMs**	German OEMs have been targeting the premium vehicle segment but also the middle and mass segment. Recent announcements of German OEMs (especially Mercedes-Benz and BMW) suggest a shift towards high premium cars. The sale of premium cars promises higher margins but fewer car sales and shifts market shares when measured in the number of sold cars.	2
	Occupation of German firms with other challenges besides automation (electrification etc.)	Companies with limited resources have to prioritize among different fields of interest. The automotive sector is challenged by large investments in other fields such as the modernization of production sites and the electrification of the powertrain. Investment needs (both financial but also with regard to human resources) in other fields possibly limit the available resources for the development of autonomous driving, which in turn influences the success and timeline of market introduction of the new technology.	3
	Role of contract manufacturing in autonomous vehicle field	In the ICT value chain, brand firms often do not manufacture their products themselves but outsource the production to contract manufacturers. Contract manufacturers such as Foxconn, that is known for manufacturing the iPhone for Apple, have introduced white label electric vehicle models that they do not aim to sell themselves but to automotive players. The availability of contract manufacturers with reliable products has the potential to challenge the automotive OEMs business core. A shift from popular vehicle brands towards white label vehicles might come along a monopolistic position of large manufacturers.	4

Table 9: Factors and their description (II/IV)

Entrepreneurial activity	**German automotive engagement in Software, Services, and Hardware**	Findings on the engagement of firms from the automotive and ICT sectors suggest a certain complementarity along sectoral borders. Currently, automotive players seem to be more active in the development of the full concept of automated vehicles and hardware components, while ICT players show more activity in providing software components and mobility services. The future division of markets for intermediate and final goods and services between the automotive and ICT sector is central in determining their shares of mobility revenues. In each of the three fields software, services and hardware, the automotive and ICT firms might put more or less focus and gain larger or smaller market shares.	
		Software (operating systems for cars, vehicle communication, data processing, imaging etc.)	5
		Services (mobility services, infotainment solutions and other aftersales services)	6
		Hardware (classic components such as seats, chassis etc. and also new components such as sensors)	7
	Focus of German automotive engagement on Level 2 / Level 3 vehicles	Automotive firms engage in both, the development of incremental advancements in assisted and increasingly automated driving and the full concept of autonomous vehicle, while the large ICT players rather focus on the latter. These foci might stay the same but can also shift and determine which market segments might by supplied by whom.	8
	Development of ICT landscape in Germany	Germany neither ranks high when it comes to the absolute number of active firms in autonomous driving nor with regard to new foundations - especially in the ICT field. Activity is rather present with established automotive firms, partly large OEMs and suppliers. The implications of the division of roles between the automotive and ICT sectors in the provision of autonomous driving for Germany are dependent on the success of ICT and automotive in Germany. While the automotive industry already plays a large role, the ICT industrial landscape is not as elaborated when it comes to relevant ICT players in the mobility market.	9
Knowledge development and diffusion	**Readiness of autonomous driving technology**	Advances in the development of automated and autonomous driving and its components are the backbone of the future implementation in the markets. Especially the step from Level 4 to Level 5 autonomous driving, however, poses additional challenges to guaranteeing secure operations. Current robotaxi pilot projects run on Level 4 technologies. The abidance on Level 4 would imply that robotaxi services will only be available in limited zones and for regular routes within urban or in rural areas. While this makes robotaxi services attractive for every day routines, longer routes between cities or places might not be available on a service base. As long as Level 4 dominates, there might still be a stronger demand for (assisted or automated) vehicles in private possession.	10
	German advances in the development of autonomous vehicles (full concept)	Advances in the development of automated and autonomous driving and its components are the backbone of the future implementation in the markets. From the individual firm perspective, considerable differences in the innovation capacity of automotive and ICT firms might allow one or the other to materialize first mover advantages and to secure market shares.	11

Table 9: Factors and their description (III/IV)

	Production and distribution ability	While the development of a new technology and the provision of prototypes is one challenge, the large scale production and distribution of the final product is another. Having access to adequate and high quality production capacities and distribution networks for autonomous vehicles is a key requirement to actually monetarize the competitive advantage a firm might have through technological leadership in developing the prototypes.	12
Guidance of the search	**Admission of automated vehicles and autonomous driving (international regulation vs. national differences)**	Testing activities and pilot projects run based on special permits in different countries. While the first regulatory frameworks have already been passed in national governments, there is not yet a comprehensive admission for autonomous vehicles – not on the national and especially not on the international level. Especially questions with regard to the accountability of vehicle manufacturers in the case of an accident are not yet answered legally. The timeline on which admission and further regulation will be available determines the diffusion of the technology. The existence of an internationally valid framework for admission would influence the degree to which product portfolios of autonomous vehicle providers have to be adjusted to the individual markets.	13
Market formation	**Diffusion of automated and autonomous vehicle technologies**	The timeline on which assisted, automated and autonomous driving is available and will diffuse on the large scale is the key factor that determines short-, middle- and long-term effects on the providing industries. Both, the successful sale of autonomous vehicles and its components but also the provision of robotaxi services are influenced. This factor is heavily driven by many other factors such as the engagement and success of individual firms as well as the progress in admission rules. The timelines might differ between different countries.	14
	Market shares of privately owned vs. shared autonomous vehicles	The market shares of privately possessed autonomous vehicles and shared autonomous vehicles are influenced by factors such as the acceptance of customers. The two modes require different types of business models (vehicle sales vs. mobility services) and might be provided by different types of firms. Therefore the market shares are expected to heavily influence the position of the German automotive sector that so far focuses mostly on the vehicles themselves rather than mobility services. Due to different market characteristic and differing customer attitudes towards different business models, market shares might differ between countries.	15
	Monopolistic power of ICT platform providers for autonomous mobility services	Successful firms or brands from the platform economy such as Airbnb, Amazon, Google, or Uber have reached partly monopolistic positions. Platforms that provide autonomous driving services might as well reach such a status. This can have various implications. Few firms might finally supply the whole service market. However, these races to the top often require large investments and price competition in the first years, which are often not profitable. Monopolistic mobility platform providers would eventually have large negotiating power towards supplying vehicle manufacturers, leaving them with smaller margins compared to private customer sales.	16

Table 9: Factors and their description (IV/IV)

Resource mobilization	**Financial investment capacities of established automotive and ICT companies**	Established firms have to manage their financial resources and to strategically decide which development projects they attribute what amount of available resources. Available resources depend, for one, on current revenues. Furthermore, the established firms considered offer large portfolios of products and services (in contrast to dedicated autonomous driving startups). Investments in the development of autonomous driving are thus always in competition to other development projects. Also, stakeholder interests might affect the technological focus of firms. Investments in development are likely to influence the timeline on which the technology of autonomous vehicles reaches market readiness. Differences may arise between individual firms, sectors, and countries.	17
	Availability of human resources	Labor markets for IT specialists and engineers, next to other fields, are tense in all considered countries. The lack of the needed workforce is expected to be a key challenge for the upcoming decades. A larger availability of needed workforce in different countries may result in competitive advantages for the countries' industry. Furthermore, the attractiveness of individual firms or sectors may vary and in turn influence competitive position of individual firms or sectors.	18
Creation of legitimacy	**Public acceptance of autonomous vehicles and autonomous shared mobility services**	The acceptance of the public towards autonomous driving will determine whether, when, where and how autonomous driving will enter the market. Acceptance is driven by various factors such as the cost, the perceived usefulness or safety and trust in the new technology. The acceptance towards autonomous driving and shared autonomous mobility services differ. Also, cultural aspects play a role and citizens from different countries show a differing openness towards autonomous driving.	
		Acceptance of **autonomous vehicles**	19
		Acceptance of **autonomous shared mobility services**	20
	Cost of autonomous driving	The cost of autonomous driving is one among various factors that affects the acceptance of autonomous driving. It is one factor that the providing industry can influence directly. At the same time, the cost of autonomous driving also determines the revenues and margins of the industry.	21
	Regulation of autonomous mobility	Studies on the future effects of autonomous driving on the mobility system predict different outcomes and affected fields. Environmental concerns are discussed (e.g. increase in km travelled, decrease in public transport usage …) as well as effects on traffic flows or land availability. The regulatory body on the communal, regional or national level may introduce measures to steer the implementation and usage of autonomous driving. These can have direct effects on the markets sizes but also indirect effects on the public attitude towards autonomous driving.	22

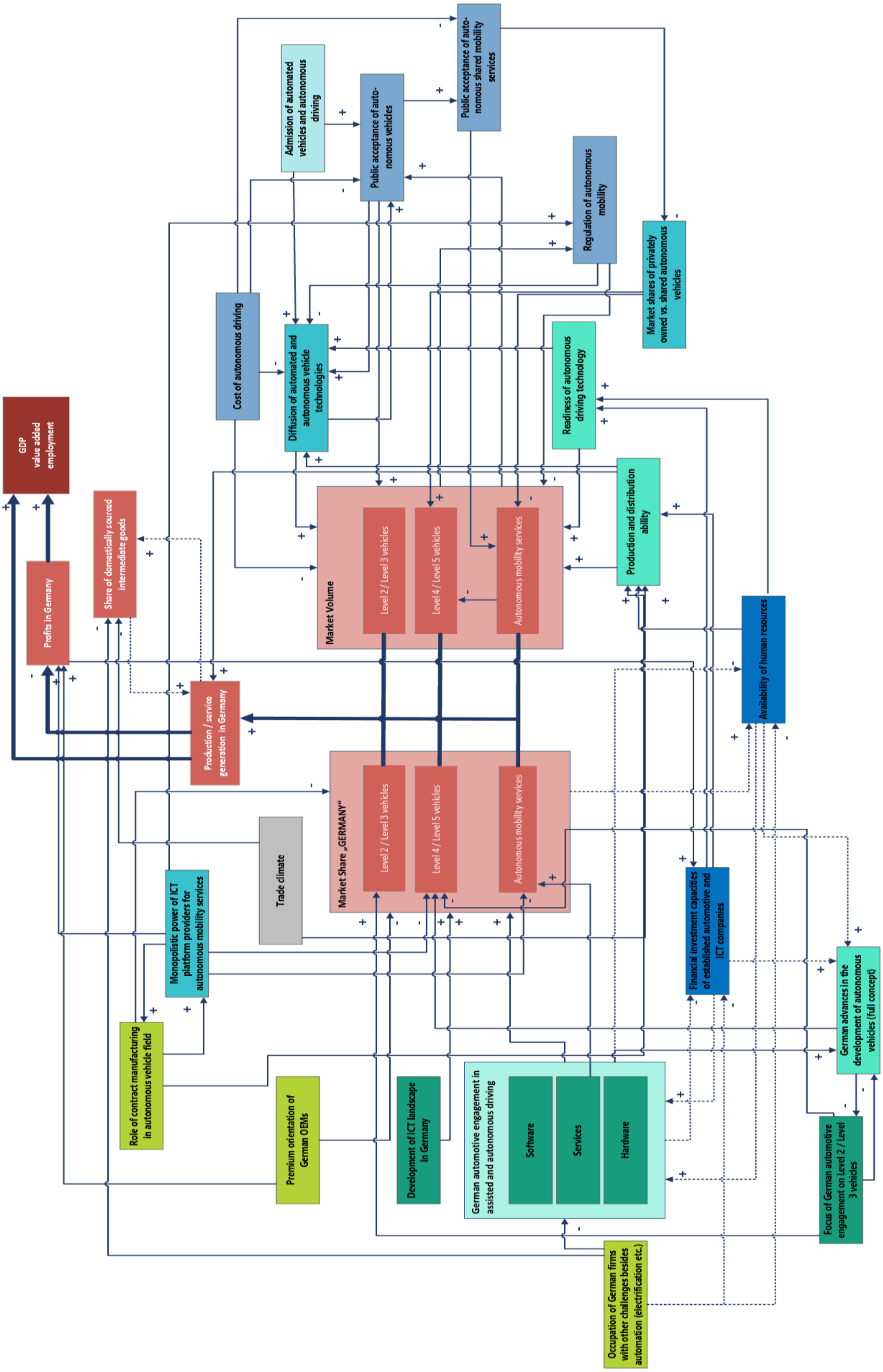
Source: Own representation

With the aim to secure the consistency of the findings and avoid missed factors, many loops were included during the process of deriving a final list of relevant factors. A causal loop diagram (CLD) was developed in order to check the plausibility of the selected factors (Haraldsson and Bonin 2021). The final CLD is displayed in Figure 38. The center shows the core of the simplified scheme of interrelations determining the changes in the German economy, as already displayed in Figure 37. The factors (green and blue colored boxes) were arranged and rearranged around the "economic core" during the process. The color of each indicator's box refers to the TIS-function in the integrated innovation system analysis that the factors is derived from. Interrelations between factors and the economic parameters are displayed as arrows, the plus and minus signs indicate whether the assumed influence is positive or negative.

The CLD helped with identifying the factors that actually influence the economic activity in Germany with regard to autonomous driving and the interrelations between factors. Also, substitutes could be subsumed and considered as one factor, additional factors were added and less relevant factors were dismissed. Furthermore, the strength of the interrelations between factors and economic parameters were rated quantitatively and independently from the first development of the CLD. Figure A 3 in the Annex shows the interrelation-matrix. In the matrix, the interrelations were labeled -2 (strong negative influence), up to 2 (strong positive influence). The interrelation between all of the factors but also between the economic indicators was rated. Figure 38 of the CLD contains only the strong interrelations, but leaves out weak interrelations for better clarity in the display.

The independent filling out of the matrix was used as another cross-check of the CLD and in turn the list of factors. In an iterative process, consistency was reached. The final list of factors was then discussed in three interviews with six experts from the transport, industrial innovation and industrial dynamics and macroeconomic impact-assessment fields (see Table A 2 for details on experts).

Figure 38: Causal Loop Diagram (CLD) of interrelations between influencing factors and economic parameters (strong influence)



Source: Own representation

7.3 Scenarios

To each of the selected factors, two or three development alternatives until 2050 were assigned. The definition of alternative developments was made based on the generated knowledge from the innovation system analysis on what developments seem plausible (see requirements to scenario-building, section 2.2.1). For each factor, there is a more ambitious and a less ambitious alternative. For some factors a third alternative development was assigned that is considered to be moderately ambitious or that differentiates between the development in different countries or sectors. The scenarios are configured by consistently combining one alternative per factor (see Figure 39 and Figure 40). For example, it is likely that a quick diffusion of autonomous vehicles comes along a high acceptance of autonomous vehicle technology in the population. This combination is considered to be consistent. To combine the quick diffusion with low acceptance is rather inconsistent.

The interrelation matrix, described above (Figure A 3) did not only help to verify the selected factors and their relations in the first instance. It was also used as a point of departure in the subsequent scenario-building process. Based on the rating of influences that one factor has on all other factors and parameters, the overall influencing power of the factor was determined by summing up the absolute values (row sum). For the scenario-building, the factors were chronologically arranged according to their influencing power. The alternative development of the factor that has the largest influence on all the other factors was assessed first, and so on. For example, the availability of different types of resources to a firm is considered to have a high influence on many other factors (see Figure A 3, row sum). The selection of the alternative development B (limited resources for German industry) for the factor (see Figure 40) is thus likely to have a strong influence on the selection of alternative developments of other factors. For example, it is unlikely that the German industry will invest largely in new development projects when facing limited resources. By setting the alternative development for the most influencing factors at the beginning, the consistent selection of the subsequent alternative development for other factors is considered to go more smoothly. It helps in assuring the consistency and plausibility of the scenarios during the development process (see requirements to scenario-building, section 2.2.1).

The three factors "Occupation of German firms with other challenges besides automation (electrification etc.)" (3), "Financial investment capacities of established automotive and ICT companies" (17), and "Availability of human resources" (18) all influence how much resources and thus capabilities the German industry has to approach the field of autonomous driving. Varying the factors internally between scenarios (e.g. high financial capacities but low availability of human resources versus low financial capacities but high availability of human resources) did not seem to yield interesting differentiations, since the outcome would be similar: limited engagement of the German industry in the provision of autonomous driving. Therefore, the selection of the alternative developments for the three factors influencing the general access to resources was conducted in a parallel way: either there was access or there was none.

Table 10: Overview of factor-groups (market-share-related / market-volume-related)

Factors, influencing the role of German industry in the provision of autonomous driving	**No.**	**Rank**	**Factors, influencing the global market framework development**	**No.**	**Rank**
Access to resources			Cost of autonomous driving	21	4
a) availability of human resources	18	1			
b) occupation with other challenges	3	2			
c) financial investment capacities	17	3			
Monopolistic power of ICT platform providers for autonomous mobility services	16	6	Trade climate	1	5
German automotive engagement in Hardware	7	7	Public acceptance of autonomous shared mobility services	20	10
Focus of German automotive engagement on Level 2 / Level 3 vehicles	8	8	Regulation of autonomous mobility	22	11
German advances in the development of autonomous vehicles (full concept)	11	9	Admission of automated vehicles and autonomous driving (international regulation vs. national differences)	13	14
Role of contract manufacturing in autonomous vehicle field	4	12	Diffusion of automated and autonomous vehicle technologies	14	16
German automotive engagement in Software	5	13	Market shares of privately owned vs. shared autonomous vehicles	15	17
German automotive engagement in Services	6	15	Public acceptance of autonomous vehicles	19	18
Premium orientation of German OEMs	2	19	Readiness of autonomous driving technology	10	21
Development of ICT landscape in Germany	9	20			
Production and distribution ability	12	22			

Source: Own representation

After developing the first set of scenarios, it stood out that the alternative development of some factors would heavily influence the overall outcome of the scenarios (e.g. trade climate, global diffusion of autonomous driving technologies), overshadowing differentiations made in the assumptions on the development of the industry's engagement. This observation was confirmed in the expert rounds. In order to differentiate between different framework developments and different forms of industry engagement and especially to study the interrelations, the list of factors was split into two sets. One set contains all factors that influence the role of the German industry in the provision of autonomous driving (left side of Table 10). The other set contains all factors that influence the global market framework development (left side of Table 10). For each of the sets, distinct scenarios were derived. By combining different scenarios of each of the two sets, one is able to compare the outcome of a certain industry engagement in different framework developments and vice versa.

The perspective takes up the understanding that factors can drive the economic development either through influencing German market shares or through determining the market volume, as indicated in Figure 37 and Figure 38. At the same time, it makes the simplifying assumption that there is no interdependence between the market volume and the market shares. This means that the activities of an individual firm or several firms in a country do not influence the development of the global market volume.

The factors are chronologically arranged per set by their rank that was derived from the interrelation matrix (section 7.2, Figure A 3). The process of combining the factors' alternative developments were then carried out again in order to build two scenarios for each set of factors. The scenario sets are referred to as the "market framework condition scenarios" and the "German industry positioning scenarios".

Figure 39 displays the market framework condition scenarios as two scenario pathways. One scenario is called "Autonomous driving uptake" (scenario A) and is indicated by the gray rings. Scenario A combines more ambitious alternative developments, found in the column of alternative A and one moderate alternative development, found in the third column, alternative C. The moderate alternative is chosen with regard to the cited studies in section 5.4.5 that suggest that autonomous mobility services are more likely to coexist with privately owned autonomous vehicles in contrast to dominating mobility systems.

The other scenario is called "Moderate automation of mobility" (scenario B) and is indicated by the dotted gray rings. Scenario B combines less ambitious alternative developments, found in the column of alternative B and one moderate alternative development, found in the third column, alternative C. Here, it is assumed that the regulation on the admission of autonomous vehicles in Germany will not fall back behind the ambitions of other countries, while the least favorable development would be that Germany does have a strong competitive disadvantage.

Figure 39: Market framework condition scenarios ("Autonomous driving uptake" (scenario A) / "Moderate automation of mobility" (scenario B))

Factor	No.	Rank	Alternative A	Alternative B	Alternative C
Cost of autonomous driving	21	4	Cost of components decreases, only small surcharge after 2030	Cost of autonomous driving technology remains high (surcharge up to 20% of vehicle price), however cost advantage of autonomous mobility services compared to conventional mobility	
Trade climate	1	5	In a persistently globalized world, German OEMs and large suppliers stick to their internationally spreaded production sites. Multinational firms have access to international markets, regarding both, the offering of products and services.	Protectionist measures of the USA and China let German OEMs and suppliers shift production sites from Germany into these countries and reduce domestic production and exports from Germany. Multinational firms have very restricted access in offering (mobility) services abroad.	German OEMs and suppliers reduce their international appearance due to increasing political tensions and decreasing market shares, especially in China. Exports to foreign markets are still ongoing. That results in lower total vehicle production but steady to increasing domestic production.
Public acceptance of autonomous shared mobility services	20	10	High acceptance internationally	Low acceptance internationally	Low acceptance in Germany, but higher in China and USA
Regulation of autonomous mobility	22	11	Regulatory support internationally	Strict and restrictive regulation internationally	Strict and restrictive rules in Germany, support in China and USA
Admission of automated vehicles and autonomous driving (international regulation vs. national differences)	13	14	A quick realization of an international admission framework for highly automated and autonomous vehicles until 2030 allows for firms to supply markets with similar regulatory requirements. Product portfolios can be rolled out without a lot of adjustments to individual markets	No international agreement is reached. Countries rely on their individual regulatory frameworks. Germany fails in providing reliable regulation.	No international agreement is reached. Countries rely on their individual regulatory frameworks. Major markets allow for automated and autonomous driving.
Diffusion of automated and autonomous vehicle technologies	14	16	Quick everywhere	Slow everywhere with long dominance of automated vehicles on Level 2++ / Level 3	Slow in Germany / Europe; especially quick in China and major US cities
Market shares of privately owned vs. shared autonomous vehicles	15	17	Shared mobility solutions / mobility services dominate	Private vehicles dominate	Coexistance
Public acceptance of autonomous vehicles	19	18	High acceptance internationally	Low acceptance internationally	Low acceptance in Germany, but higher in China and USA
Readiness of autonomous driving technology	10	21	Level 4 autonomous driving is reached and rolled out.	Level 4 autonomous driving remains in niches. Majority of vehicles contains lower automation levels.	

Source: Own representation

Figure 40 maps the scenario pathways for the two German industry positioning scenarios. One scenario is characterized by "successful digital modernization" (scenario 1) and displayed by the turquoise dots. Scenario 1, in parallel to scenario A, combines more ambitious alternatives for the German industry. They are found in the left column (alternative A). At some points, they were combined with moderate assumptions on the alternative development. For example, it was assumed that German automotive firms would not have an incomparable breakthrough in the development of autonomous driving technology but rather be as successful as other players.

The other scenario sketches a more "bumpy adaptation to autonomous mobility" (scenario 2) and is indicated by the yellow dots. Scenario 2, in contrast to scenario 1, combines the less ambitious alternative for the German industry, found in the column of alternative B.

Figure 40: German industry positioning scenarios ("Successful digital modernization" (scenario 1)/ "Bumpy adaptation to autonomous mobility" (scenario 2)) (I/II)

Factor	No.	Rank	Alternative A	Alternative B	Alternative C
Access to resources a) availability of human resources b) occupation with other challenges c) financial investment capacities			Automotive and ICT firms are not heavily influenced by shortages	Limited resources hinder engagement of German automotive firms	
	18	1	Overall tense situation on the market for experts	Trouble in attracting experts especially for German automotive, international ICT/automotive good	
	3	2	German OEMs and suppliers suceed in providing emission free vehicles and components. The needed adaption of production sites for the manufacturing of electrified vehicles is joined with the modernization of production equipment and processes.	German OEMs struggle in providing emission free vehicles on a large scale. Both, financial and human resources are tied up in the development and build up of production of emission free vehicles.	
	17	3	Available investment capacities for automotive and ICT	Automotive faces tense financial situation, ICT does not	
Monopolistic power of ICT platform providers for autonomous mobility services	16	6	No monopolistic structure, different firms offer autonomous driving services.	Monopolistic international market. Major ICT platform providers offer services in Germany and abroad.	Monopolistic individual markets dominated by domestic ICT firms in China and USA, not so much in Germany.
German automotive engagement in Hardware	7	7	Established automotive supplier structure of German automotive sector persists. OEMs and suppliers enlargen their product portfolios according to new demands and offer integrated hardware and the accompanying software solutions.	New providers of specific new components, such as LiDAR sensors and the related control software) enter the supply chain. The "classic" components stay with established suppliers.	New components and "classic" components stay within the automotive sector's focus, however German suppliers are not as successful as Chinese and American suppliers.
Focus of German automotive engagement on Level 2 / Level 3 vehicles	8	8	German firms keep on focusing on both, assisted and autonomus driving. International ICT firms give up on their autonomous vehicle technology projects and foucs on service provision as well as add on services in vehicles.	German firms focus on assisted / partly automated driving. International ICT firms stick to their focus on fully autonomous driving.	German firms keep on focusing on both, assisted and autonomus driving. International ICT firms stick to their focus on fully autonomous driving.

Figure 40: German industry positioning scenarios ("Successful digital modernization" (scenario 1) / "Bumpy adaptation to autonomous mobility" (scenario 2)) (II/II)

German advances in the development of autonomous vehicles (full concept)	11	9	German automotive firms have a break through in the development of autonomous vehicles.	Foreign ICT firms have a breakthrough in the development of autonomous vehicles, while German automotive firms do not.	No considerable differences between different players.
Role of contract manufacturing in autonomous vehicle field	4	12	Contract manufacturers have trouble in rolling out the production of vehicles and leave the market.	Contract manufacturers suceed in offering emission free and "ready-for-autonomous-driving-integration"-vehicles (sucessful development and production roll out) and find customers in ICT brands.	
German automotive engagement in Software	5	13	German automotive sector, partly in cooperation with domestic ICT firms, succeeds in providing autonomous driving software. German OEMs develop their own operating systems for their vehicles (high investment, time intensive, but data sovereignity). Foreign automotive OEMs and ICT players are "normal" competitors.	German automotive sector does not succeed in software-related fields and relies on the integration of foreign ICT. German OEMs outsource IT-system provision to ICT-Players (market-ready, worldwide market presence, research capacity).	German automotive sectors collaborate with autonomous driving software providers. Integration of software solutions for operating systems by automotive and ICT-Players (example Mercedes - Google: automotive operating system but maps by Google).
German automotive engagement in Services	6	15	Players from the German automotive sector engage as platform providers in offering mobility services on the international level. That may happen individually or in a joint project. International ICT players engage internationally.	German automotive sector does not engage. International ICT players engage internationally.	German automotive sector engages in Germany as a mobility service provider. International ICT players engage internationally.
Premium orientation of German OEMs	2	19	German OEMs supply all segment, following their strategies of the past.	German OEMs target the premium segment	
Development of ICT landscape in Germany	9	20	Growing ICT in Germany, focus software solutions for autonomous driving technologies	No considerable growth of ICT in Germany	Growing ICT in Germany, focus mobility services platforms
Production and distribution ability	12	22	Production and distribution capacities are no issue for active firms in different countries.	Production and distribution capacities are an issue for active firms in Germany.	Production and distribution capacities are an issue for all active firms.

Source: Own representation

The set of factors and alternative developments would allow for the combination of additional alternative scenarios. Studying more than the combination of two scenarios per set of factors would be beyond the scope of the thesis. The given scenario pathways allow to assess different developments in the positioning of the German industry and the development of market framework condition. Furthermore, the focus of the thesis is on the sectoral tensions between the automotive and ICT sectors. The innovation system analysis in chapters 4 to 6 does not suggest that one sector or country will eventually oust all others. Scenarios of interest are such that include the co-existence of German automotive industry and international ICT / automotive industry. Plausible alternative developments are defined accordingly and some more moderate alternatives are included in the scenario pathways, as described above. Therefore, there is no worst case ("Germany loses its overall role as automotive location") and best case ("Germany provides vehicles and platforms internationally") scenario. The selection of the scenario thus fulfills the requirement that scenarios should be built, focusing on the in issue in question (see section 2.2.1, European Foresight Platform 2023).

The storylines of the chosen scenario pathways can be summarized as displayed in Figure 41. At the top, there are the two market framework condition scenarios. These are referred to as scenario A and scenario B. At the bottom the German industry positioning scenarios are described. These are referred to as scenario 1 and scenario 2. The two scenarios per set can be combined in order to obtain four scenarios that allow for the comparison of different German industrial engagement in varying market frameworks. These four scenarios are referred to by scenario A-1, scenario B-1, scenario A-2, and scenario B-2.

Scenario A-1 combines an ambitious German autonomous driving industry with a world of quick autonomous driving diffusion and liberal markets. Scenario B-1 combines an ambitious German autonomous driving industry with a world of slower autonomous driving diffusion and protectionist markets. Scenario A-2 then links a more restricted German industry with a world of quick autonomous driving diffusion and liberal markets. Scenario B-2 finally matches a restricted German industry with a world of slower autonomous driving diffusion and protectionist markets.

Referring to the fourth research question, formulated in chapter 1, the market framework scenarios present two alternatives on how the future autonomous driving market could look like up to 2050. The two industry positioning scenarios display potential strategies of the German automotive industry. The development alternatives and configuration of scenario pathways build on the insights from the integrated innovation system analysis in chapters 4 - 6 and the derived scenarios are further assessed in chapter 8. The scenarios are quantified and potential effects on the German economy until 2050 are estimated. The analysis focuses on the deviation between scenario A-1 and scenario A-2 as well as between scenario B-1 and scenario B-2. The scenarios A-1 and A-2 differ in terms of the industrial strategy, while the market framework development is held constant. This means that the overall potential market volume is the same, the difference lies in the realized market shares of the German industry. The same is the case for the comparison of scenarios B-1 and B-2. Given a specific market development scenario, the macroeconomic assessment thus allows to assess the difference in the effect the two positioning options of the German automotive industry would have on German economic indicators.

Figure 41: Overview of scenarios sets for cross-combination

Market framework conditions

Scenario A - Autonomous driving uptake

Decreasing cost for autonomous driving technology, the quick realization of an international admission framework, regulatory support of autonomous mobility services and an overall acceptance of autonomous vehicles and services lead to a quick diffusion of autonomous vehicles. Level 4 autonomous driving allows for autonomous mobility services. These services claim moderate market shares and coexist with privately owned autonomous vehicles. In a persistently globalized world, multinational firms have access to international markets, regarding both, the offering of products and services.

Scenario B - Moderate automation of mobility

High prices of autonomous driving technology, countries' individual admission laws of autonomous vehicles, strict international regulation of the implementation of autonomous driving and an overall low acceptance leads to a slow diffusion of autonomous vehicles. For long, Level 2 / 3 vehicles dominate the markets and Level 4 autonomous driving is only found in niches. Automated and autonomous vehicles are mostly in private possession. International mobility markets are marked by protectionist measures of the national government with regard to products and especially mobility services.

Scenario A-1 **Scenario B-1** **Scenario A-2** **Scenario B-2**

Scenario 1 - Successful digital modernization

In the purple scenario, the German OEMs and suppliers engage actively in the provision of assisted and autonomous driving. The firms focus on both, the classic and new hardware components as well as the related software. German firms (automotive and ICT) provide their own software solutions, including autonomous driving software and operating systems by OEMs. German firms compete with international ICT and automotive firms.

Also, the expansion of production capacities does not propose a challenge and German OEMs are not challenged by contract manufacturers. German OEMs stick to the provision of vehicles in all segments.

The overall focus of the German industry is on the development and manufacturing of vehicles and worldwide sales. German firms do not provide mobility services, such as robotaxi platforms, internationally. They partly supply the German market.

Scenario 2 - Bumpy adaptation to autonomous mobility

In the yellow scenario, German automotive firms face a lot of their resources (financial and human) being tied up in other projects. German OEMs focus on incremental advancements in assisted driving, while international ICT firms keep on working on autonomous vehicles and are rewarded with a breakthrough. The advanced assisted driving functionalities are implemented in premium segment vehicles by German OEMs, the vehicle class that German firms increasingly focus on.

The expansion and modernization of German production capacities remains a challenge. Contract manufacturers enter the automotive market. They engage in cooperation with autonomous driving technology providers, ICT platforms and ICT brands. The German industry does not engage in the provision of mobility services.

German suppliers maintain their internationally recognized position in the provision of high quality classic hardware components, while new components are supplied by new firms.

German industry positioning

Source: Own representation

8 Simulations for Germany

The scenarios, developed in the previous section and derived from the integrated innovation system analysis, are assessed in a macroeconomic simulation in order to gain a better understanding of the scale of effects that may be induced by different forms of autonomous driving development. The focus lies on the variation between the scenarios, rather than the absolute effects. The simulation aims at a better understanding of how different modes of engagement of the German automotive industry in a given global market development may influence the economic situation in Germany. The description of the modeling approach can be found in section 3.2.3. The leading questions are: How do different industrial strategies of the German automotive industry influence the overall German economy until 2050? What effects can be expected in terms of the development of gross domestic product, value added and employment?

In the following, section 8.1 describes the process of translating the scenarios into impulses. The results of the simulation are presented in section 8.2, section 8.3 provides a discussion of the results and shortcomings.

8.1 Translation of the scenarios into impulses

The scenarios on the German industry's engagement in autonomous driving, derived in chapter 7, are based on 22 factors and their alternative developments. In the macroeconomic simulation, the scenarios are not translated completely, but a selection of important and distinguishing characteristics between the scenarios is made. Many of the factors directly or indirectly influence the success of the German industry in the sales of automated and autonomous vehicles and the provision of mobility services. Therefore, mainly the effects from the production of passenger vehicles in Germany, as well as the offering from autonomous mobility services are considered. The potential revenue from new business models in the field of vehicle connectivity and the generated data are left out. The reduction of complexity towards the outcome of the scenarios is already introduced in the short description of the scenario sets in Figure 41. The translation of the scenario into impulses follows the main characteristics that are named in the description.

Table 11 provides an overview of the chosen indicators that are used in order to translate the scenario characteristics into quantitative impulses. On the left hand side, the key characteristics of the market framework condition scenarios (scenario A and scenario B, top) and the German industry positioning scenarios (scenario 1 and scenario 2, bottom) are summarized. On the right hand side, the indicators are listed. The conducted derivation of the quantitative value of each of the indicators is described in the following section 8.1.2.

The quantitative analysis focuses on the differences between the scenarios on autonomous driving and the engagement of the German industry in it. However, the automotive industry and mobility system are influenced by a large variety of other factors beyond the automation of vehicles and mobility systems. Examples are the electrification of the powertrain, the introduction of environmental and social standards in the supply chain, an increasing focus on recycling or the implementation of curricular economy principles. Within the analysis, the development of these outside-of-scope factors are not considered. This decision was made in order to present results that can be explained by the differing characteristics of the scenarios in relation to autonomous driving and are not driven by other factors.

Table 11: Translation of scenario characteristics into indicators

Scenario A – "autonomous driving uptake"	Scenario B – "Moderate automation of mobility"	Indicator
Quick diffusion of autonomous vehicles	Slow diffusion of autonomous vehicles	→ New vehicle registrations in Germany → Automation levels
Decreasing cost for autonomous driving technology	High prices of autonomous driving technology	→ Surcharges for automated and autonomous driving technology
Coexistence of autonomous mobility services and privately owned vehicles	Dominance of privately owned autonomous vehicles	→ Vehicle mileage in Germany → Share and price of autonomous mobility services
Persistently globalized world	Protectionist measures	→ Export volume
Scenario 1 – "Successful digital modernization"	**Scenario 2 – "Bumpy adaptation to autonomous mobility"**	**Indicator**
Focus on all vehicle segments	Focus on premium vehicles	→ Market / production share of German OEMs in small, middle class, premium segment and different levels of automation
Engagement in all automation levels	Focus on L2/L3 assisted driving	→ For both, German and international markets
Germany provides their own software solutions	German automotive industry purchases from foreign software providers	→ Market share of German firms in software components For both, German and international markets
German suppliers provide classic and new components	German suppliers provide classic components	→ Market share of German firms in new hardware components For both, German and international markets
German OEMs partly supply the German autonomous mobility services market	German OEMs do not engage in autonomous mobility services at all	→ Market share of German OEMs in autonomous mobility services

Source: Own representation

8.1.1 Projections in the literature

The definition of the development of the indicators, forming the impulses, is based on quantitative projections in the literature. Table 12 presents an overview of quantitative parameters that were used in or were the result of scenario studies that focus on the development and implementation of autonomous driving. Detailed information on quantitative parameters of such projections are mostly found in reports rather than journal articles. In the literature review, the focus was on scenario publications that were published no earlier than 2017 and published either in English or German language. Furthermore, studies that focus on Germany, Europe, USA, China or on the global development were considered. Such studies were selected that include projections on parameters that equal the needed indicators given in Table 11 or that can be used in order to estimate an indicator. In the table, the white cells contain projections for Germany, the regional scope of other projections is indicated in the table.

Overall, only a few studies provided numbers on parameters such as future autonomous vehicle registrations, the share of autonomous mobility services, or technology costs. Hardly any studies report the full set of needed parameters. Also, many numbers remain vague such as the global revenue potential for software components in autonomous vehicles.

The qualitative scenarios in section 7 are derived based on the insights from the integrated innovation system analysis. Thereby the focus was on sound scenario storylines rather than concrete values for alternative developments. Some of the publications in Table 12 are used in the innovation systems analysis, too, and are thus indirectly considered in the scenario development. Other publications in Table 12 focus on quantitative estimations but lack the explicit discussion of the underlying industrial dynamics that lead to the estimations. These studies are introduced at this point and have not been part in the integrated innovation system analysis or scenario-building process, respectively. The studies are used in order to gain an understanding of the quantitative scale of potential developments. The definition of impulses can thus be understood as a matching between the key characteristics of the scenarios with quantitative projections.

The collection in Table 12 shows large variations in the projections of the parameters in different studies. Even the results within individual studies partly differ a lot between the defined scenarios and authors point out the large uncertainties in the development of autonomous vehicles (e.g. Alonso Raposo et al. 2018; McKinsey & Company 2023). Furthermore, many studies are hardly comparable since they use different indicators (e.g. autonomous vehicles registrations vs. autonomous vehicle stocks vs. autonomous vehicle travel). The majority of studies projects the development of automated and autonomous driving up to the year 2030. In the years up to 2050, there remain many data gaps. Due to the given data base, there was the need to combine different data sources and approximate and simplify the developments with regard to individual indicators.

Table 12: Overview of autonomous driving projections in the literature (studies, press) (I/II)[20]

Variable	2025	2030	2035	2040	2050
Total vehicle stock	~45M cars [12]	~45M cars [12] Europe: 200M cars (-25% (-80M) vs. 2017) [6] USA: 212M cars (-22% vs. 2017) [6] Chin: 276M cars (+50% vs. 2017) [6] globa: 1.5B cars [8]	-3M cars vs. 2019 (in cities) [1] ~44M cars [12]	~42M cars [12]	global: 1.45-1.55B cars [17]
Vehicle registration	~3.25M cars [12] Europe: 16-19M cars (+18-39% vs. 2015) [5] global: 93M cars and LCV (+4M vs. 2019) [11]	1.460-1.676M (small/compact), 0.886-1.071M (middle), 0.258-0.326M (premium) [9] ~3.45M cars [12] Europe: 24M cars (+34% (+6M) vs. 2017) [6] USA: 22M cars (+20% vs. 2017) [6] Chin: 35-38M cars (+30% vs. 2017) [6] global: 102M cars and LCV (+13M vs. 2019) [11] 102M passenger vehicles [19]	-25,000 (+0.7%) vs. 2019 (in cities) [1] ~3.6M cars [12]	1.280-1.650M (small/compact), 0.743-1.061M (middle), 0.189-0.306M (premium) [9] ~3.55M cars [12] global: 120M cars [18]	1.100-1.624M (small/compact), 0.600-1.050M (middle), 0.120-0.285M (premium) [9] Europe: 18-21M cars (+33-52% vs. 2015) [5]
Car sales revenue	Europe: 445-610B € [5]	China: 50-60B $ profit pool [3]			Europe: 500-665B € [5]
Assisted vehicle registration	Europe: vehicle travel: 51-10% (L2), 49-14% (L3) [5] global: 23% (L1), 43% (L2), 1% (L3) [11]	vehicle stock: 24-26% (L1), 7% (L2), 1% (L3) [9] global: 18% (L1), 52% (L2), 10% (L3) [11] stock: 150M (L3 highway-pilot) [8] delayed/accelerated case (~): 15/16% (L1), 22.5/18% (L2), 24/33% (L2+), 2.5/8% (L3 traffic jam), 1.5/3% (L3 highway pilot) [13]	global: delayed/accelerated case (~): 14/12% (L1), 4/1.5% (L2), 37/20% (L2+), 3/3.5% (L3 traffic jam), 7/2% (L3 highway pilot) [13]	vehicle stock: 13-15% (L1), 1% (L2), 1% (L3) [9]	vehicle stock: 2-8% (L1) [9] Europe: vehicle travel: 0-34% (L2), 1-62% (L3) [5]
Cost for assisted vehicle technology	1,500-2,000 $ (L2+) [13] Europe: 1,000€ (L1), 5,600€ (L2), 6,800€ (L3) [5]	220-270€ yearly revenue highway-pilot, 440-530€ yearly revenue city-pilot [8] global: 33-41B € revenue (L3 highway-pilot) [8]			Europe: 0€ (L1), 1,700€ (L2), 2,000€ (L3) [5]
Autonomous vehicle registrations	vehicle stock: ~4.2M, ~9% [12] Europe: vehicle travel: 0-23% (L4), 0-35% (L5) [5]	~5% (highway-pilot, L4) [10] vehicle stock: 1% (L4) [9] ~8.5M, ~19% [12] Europe: 12.5M cars and light vehicles (L4-5), 7.3M for moblity services, range of absoute share of autonomous vehicles in vehicle stock (up-/downside scenario): ~11-65% [6] USA: ~8M cars and light vehicles (L4-5), ~4M for mobility services [6] China: ~18M cars and light vehicles (L4-5), ~12M for mobility services [6] global: 2% (L4) [11] stock: 30M (L4 city-pilot) [8] delayed/accelerated case (~): 0/8% (L4 highway pilot) [13]	560,000 (in cities) [1] vehicle stock: ~12.3M, ~28% [12] global: delayed/accelerated case (~): 7/47.5% (L4 highway pilot), 0/4% (L4 highway pilot) [13]	~22-26% (highway-pilot, L4), ~9-17% (city-pilot, L4), ~0-2% (door-to-door-pilot, L4) [10] vehicle stock: 18-23% (L4) [9] ~15M, ~36% [12] China: 40% of total [3]	~22-26% (highway-pilot, L4), ~21-27% (city-pilot, L4), ~6-16% (door-to-door-pilot, L4) [10] vehicle stock: 28-34% (L4), 6-7% (L5) [9] Europe: vehicle travel: 2-29% (L4), 2-86% (L5) [5]
Autonomous driving system cost	5,000 $ + [13] (L4) Europe: 8,100 € [5] China: 8,000 $ [3] 10,000 $ (L4) [14]		10,000 € (total: 35,000€) [1]		Europe: 2,400 € [5]

20 The following abbreviation are used in the table: T = thousand, M = million, B = billion
The following abbreviations are used in the table and the following sections: L0 = Level 0, L1 = Level 1, etc.

Table 12: Overview of autonomous driving projections in the literature (studies, press) (II/II)

Variable	2025	2030	2035	2040	2050
Revenue potential from autonomous vehicles	Europe: 65-160B € (self-driving software and hardware linked to new vehicle sales) [5]	China: 15-20B $ profit pool [3] global: 13-16B € (L4 city-pilot) [8] 273B $ (2020-2030) [15]			Europe: 40-60B € (self-driving software and hardware linked to new vehicle sales) [5]
Software revenue potential	global: 33B $ (Software for ADAS and HAD), 15B $ (Infotainment, connectivity, ...), 5B $ (OS, middleware) [11] ~13B $ (Software, Automotive AI) [16]	global: 42B $ (Software for ADAS and HAD), 18B $ (Infotainment, connectivity, ...), 7B $ (OS, middleware), automotive software growth 2019-2030: 9.4%/year [11] 15B $ (New software), 210B $ (Connectivity) (2020-2030) [15]			
Electronics / Hardware revenue potential	global: 1B $ (LiDAR), 6B $ (Camera), 6B $ (Radar) [11] ~6B $ (Hardware, Automotive AI) [16]	global: 10B $ (LiDAR), 8B $ (Camera), 10B $ (Radar) [11] 41.5B $ (Autonomous hardware components), 7.2B $ (Autonomous driving chips) (2020-2030) [15]			
Share of shared autonomous mobility services	5% shared autonomous vehicles, 95% private [12] Europe: 40-80% private vkm (fleet: 35-80% L0-3, 0-5% L4-5), 20-60% mobility service vkm (fleet: 7-28% L0-3, 12-53% L4-5) [5]	5% pkm L4 mobility services [2] 8-15% pkm autonomous mobility services, 3-8% pkm private autonomous cars [7] 15% shared autonomous vehicles, 85% private [12] Europe: 25% mileage travelled in autonomous mobility services, 56% of autonomous vehicle registrations as shared vehicles, 44% private autonomous vehicles, range of absolute share of shared autonomous vehicles in vehicle stock (up /downside scenario): ~6%-42% [6] USA: 24% mileage travelled in autonomous mobility services, 12% private autonomous vehicles [6] China: 13% pkm autonomous, 11% private, **2% mobility services** [3] ~40% mileage travelled in autonomous mobility services, ~10% private autonomous vehicles [6]	32% of trips [1] 18% shared autonomous vehicles, 82% private [12]	17% shared autonomous vehicles, 83% private [12] China: 66% pkm autonomous, 55% private, **11% mobility services** [3]	Europe: 10-70% private vkm (fleet: 5-69% L0-3, 1-35% L4-5), 40-90% mobility service vkm (fleet: 7-27% L0-3, 3-90% L4-5) [5]
Revenue potential mobility services		Europe: 1.4B € [4] China: 25-30% of profit pool [3] global: 1.5-2.2T $ [7]	16.7B € / year (1/6 of new vehicle sales in Germany today) [1]	China: 1.1T $ market value [3]	
Data monetization / connected car		275-410€ per vehicle and year for in-car e-commerce, entertainment, data analysis, data sales etc. [8] global: 450-750B $ [3] 113-177B € [8]			

Sources in Table 12

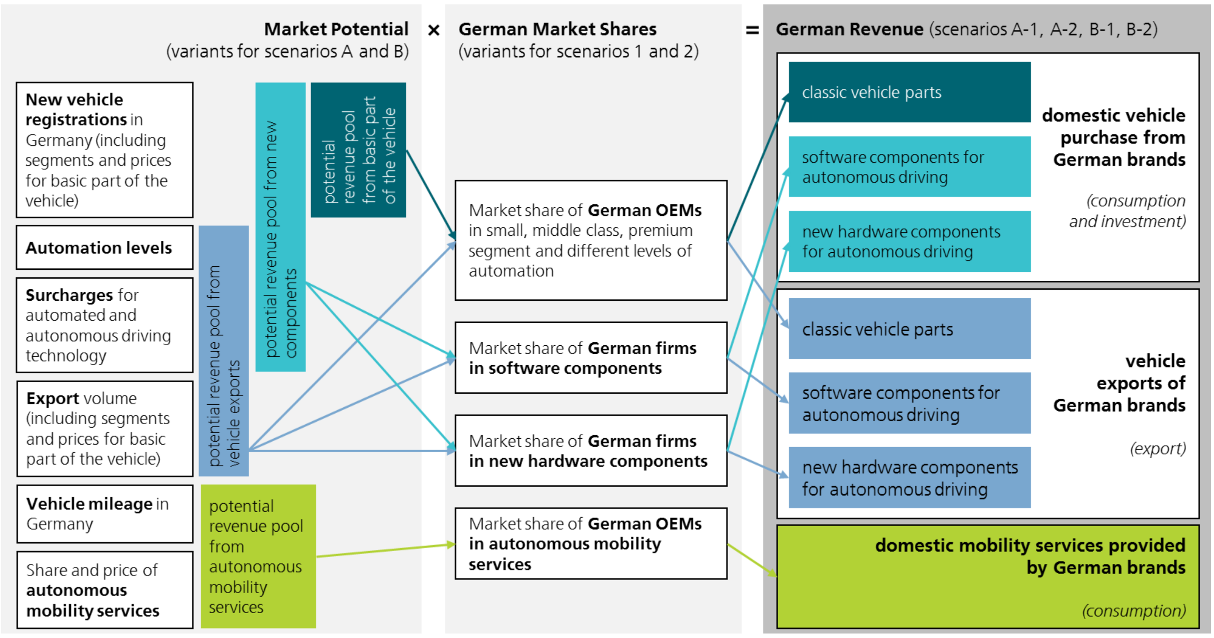
[1] Deloitte (2019a)
[2] IPE Institut für Politikevaluation GmbH et al. (2019)
[3] McKinsey & Company (2019c)
[4] McKinsey & Company (2019b)
[5] Alonso Raposo et al. (2018)
[6] pwc (2017-2018)
[7] Bratzel and Tellermann (2018)
[8] Bratzel and Tellermann (2022)
[9] Krail et al. (2019)
[10] Altenburg et al. (2018)
[11] Burkacky et al. (2023)
[12] Kaltenhäuser et al. (2020)
[13] McKinsey & Company (2023)
[14] KrASIA (2021)
[15] Asselin-Miller et al. (2017)
[16] Proff et al. (2019)
[17] International Transport Forum (2023)
[18] Bloomberg Finance (2017)
[19] International Energy Agency (2023)

Source: Own representation

8.1.2 Definition of impulses

In the following, it is explained how the scenario characteristics are translated into quantitative impulses for the macroeconomic simulation and what procedure is chosen to derive the estimation of individual indicators. If current data is used, it usually refers to the year 2019 in order to exclude structural effects that were potentially induced by the COVID-19 pandemic or Russian aggression in Ukraine. Figure 42 provides an overview of the relevant indicators (already mentioned in the right column of Table 11) and how they are combined in order to build the impulses for the four scenarios.

Figure 42: Estimation of indicators and generation of impulses



Source: Own representation

The impulses, used for the macroeconomic simulation, are based on the German industry's revenue from domestic vehicle purchases, the revenue from exports and the revenue from domestic mobility services until 2050. The components of the impulses are displayed in the dark gray box on the right of Figure 42. For vehicle sales, both domestic and exports, it is distinguished between revenue from the basic parts of a vehicle (or a hypothetical non-automated vehicle to which automation functions can be added), revenue from software components, and revenue from new hardware components. Domestic demand for vehicles is distinguished into private demand and corporate demand. Private demand falls into the final demand category consumption, while corporate purchases are considered to be investments. The impulses are derived by multiplying the respective total market potentials (box in the left) and the German market shares (box in the middle), as indicated by the arrows. For the two market framework scenarios A and B, the indicators new vehicle registrations, automation levels, surcharges for autonomous driving technology and export volumes are estimated in order to derive the potential revenue pools from the domestic demand for and export of (automated) vehicles. These are combined with the estimated market shares of German firms in the provision of classic vehicles parts as well as software and new hardware parts in the domestic market and with regard to exports, as defined by the industry positioning scenarios 1 and 2. Analogically, the potential revenue pool from autonomous mobility services in scenarios A and B, derived using the indicators vehicle mileage, share and price of such services, is combined with the market shares of German OEMs in the German market in scenarios 1 and 2.

Sections 8.1.2.1 and 8.1.2.2 outline the procedure of how the development of the indicators was derived for the framework and industry positioning scenarios, respectively. Sections 8.1.2.3 summarizes the full set of impulses and section 8.1.2.4 described the translation into macroeconomic impulses. Throughout the sections, it is repeatedly referred to the literature, mentioned in Table 12.

The derivation of impulses aims to meet the scenario key characteristics, developed in chapter 7. Due to the lack of a consistent data source from transport research that assesses scenarios that resemble the transport scenarios in the thesis, a variety of data sources is used. While the scenarios from chapter 7 themselves are built such that they are consistent (e.g. lower prices correspond with higher levels of automation), the combination of distinct quantitative indicators might not be entirely consistent. For example: Does the assumed lower cost for autonomous driving really correspond to the exact dynamic of diffusion of autonomous vehicles? Covering that would require the introduction of elasticities and, in the best case, a systemic transport modeling of the scenarios. This lies beyond the scope of the thesis. The weakness of the approach from the transport research perspective is pointed out.

Furthermore, the scenarios A-1, A-2, B-1, and B-2 are built on the assumption that one can combine framework (A and B) and industry positioning scenarios (1 and 2) independently (see section 7.3). This approach is chosen in order to allow for a direct comparison of different forms of industrial engagement in Germany in a given market environment. The assumption on independency is followed throughout the definition of the impulses. However, interdependencies may exist between the activities of an industry, embedded in a country and for example the domestic market development. In order to account for some key issues with regard to the uncertainties in the estimations and the interdependence between the scenario sets, sensitivities are considered. The key issues and chosen indicator developments for sensitivities are described in section 8.1.2.5.

8.1.2.1 Framework market conditions (Scenarios A / B)

Absolut number of new vehicle registrations in Germany

Only a few studies provide projections on vehicles sales in Germany until 2050 (see Table 11). Krail et al. (2019) study the impact of autonomous vehicles on transport emissions in Germany, using the transport model ASTRA (ASsessment of TRAnsport Strategies). The authors display the development of the vehicle fleet in Germany until 2050 and distinguish between vehicles segments (small, middle-class, premium) and shares of automation levels in registrations per year. Upon request, the authors provided the unpublished, underlying data on new vehicle registrations, which provide the same details. Their data is used, since it is, to the best knowledge of the author, the only source that differentiates between segments. This differentiation is needed in order to later implement the German automotive industry's strategy in scenario 2 to focus on premium vehicles only.

Krail et al. (2019) consider two scenarios. In scenario 1, private vehicles dominate. Scenario 2 displays a world, in which mobility services play a large role. In scenario 1, new vehicle registrations stagnate and later decrease slightly. Furthermore, moderate levels of automation are reached. In scenario 2, new vehicle registrations decline remarkably until 2050 and automation levels are higher. The scenarios do not perfectly fit the logic of scenario A (more ambitious diffusion of automation technology, coexistence of private and shared autonomous vehicles, significant price reduction) vs. scenario B (slow diffusion of vehicles, focus on low automation levels, private vehicle domination, lower price reduction) in the thesis. Therefore, the data from Krail et al. (2019) is understood as the base development dynamic that is adjusted by changing e.g. the scale of a specific automation level share later on.

Registrations up to 2050 as in scenario 1 Krail et al. (2019) are used in both **scenarios A and B**. It is assumed, that the coexistence of private and shared autonomous vehicles in **scenario A** does not necessarily reduce vehicle stocks and registrations. Registrations in Germany are estimated to be at 3.1 million vehicles in 2030 and decline to 3 million vehicle in 2050 (see Table A 3 for details).

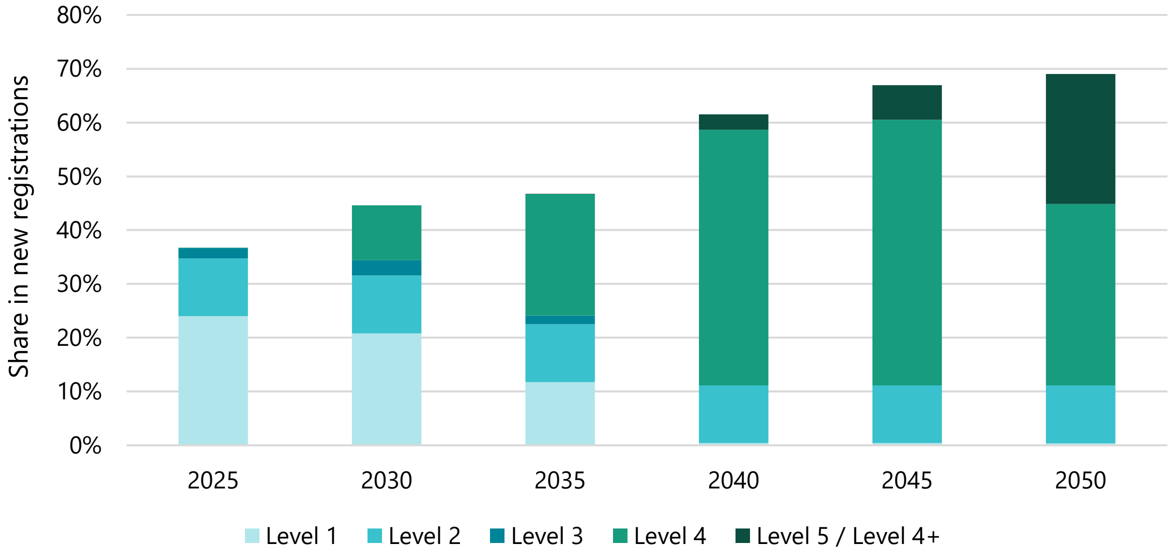
Automation levels of new registrations

For the ambitious autonomous driving scenario (**Scenario A**), numbers on automation levels as retrieved from Krail et al. (2019) in scenario 2 are used as a basis and combined with the almost steady new registrations from scenario 1.

Scenario 2 in Krail et al. (2019) projects an increase of the share of L5 vehicles in the vehicle stock that reaches 7% in 2050. Given the current development in technological advances and expert assessments, it remains questionable whether L5 autonomous driving will actually be implemented. Market forecasts such as McKinsey & Company (2023) or Altenburg et al. (2018) introduce different sublevels of the automation levels (L4 highway pilot and L4 urban pilot or L4 highway-pilot, L4 city-pilot and L4 door-to-door-pilot, respectively), which partly blur the line between L4 and L5 vehicles with regard to the required technological components. Therefore, even though the introduction of L5 is questionable, the shares of L5 vehicles in the market projections are included in Scenario A in order to project potentially rising costs of advanced L4 vehicles.

The given levels of automation in scenario 2 of Krail et al. (2019) are lower than the current share of low automation levels in sales (McKinsey & Company 2023). In comparison to other studies, the projections can be considered in the middle field. With regard to medium-term sales of L2 and L3 vehicles, the numbers are lower than comparable studies (Burkacky et al. 2023; Bratzel and Tellermann 2022; McKinsey & Company 2023). McKinsey & Company (2023) propose that especially L2 (L2+) will be a main driver of short- to medium-term growth in automation levels. In line with Krail et al. (2019), L3 automation will probably only play a smaller role, and the major shift will be from L2 directly to L4 (pwc 2017-2018; McKinsey & Company 2023). In order to include the more positive projections for L2 vehicles and overall shares of automated and autonomous vehicles in other studies, additional sales of L2 vehicles are added to the automation sales timeline, retrieved from Krail et al. (2019). The simplified assumption is made, that the share of L2 vehicles per segment remains on their 2025 levels. Furthermore, the moment of L4-5 vehicles reaching a share of 50% in registrations is pushed to after 2040 by delaying the steep increase of L4 automation in the small vehicle segment. Small vehicles play an important role in mobility services that have higher market shares in scenario 2 in the study compared to **scenario A** in this thesis. Figure 43 displays the considered projections of automation levels in new car registrations in **scenario A**, aggregated over all vehicle segments.

Figure 43: **Projection of automation levels in new car registrations in Germany – Scenario A**

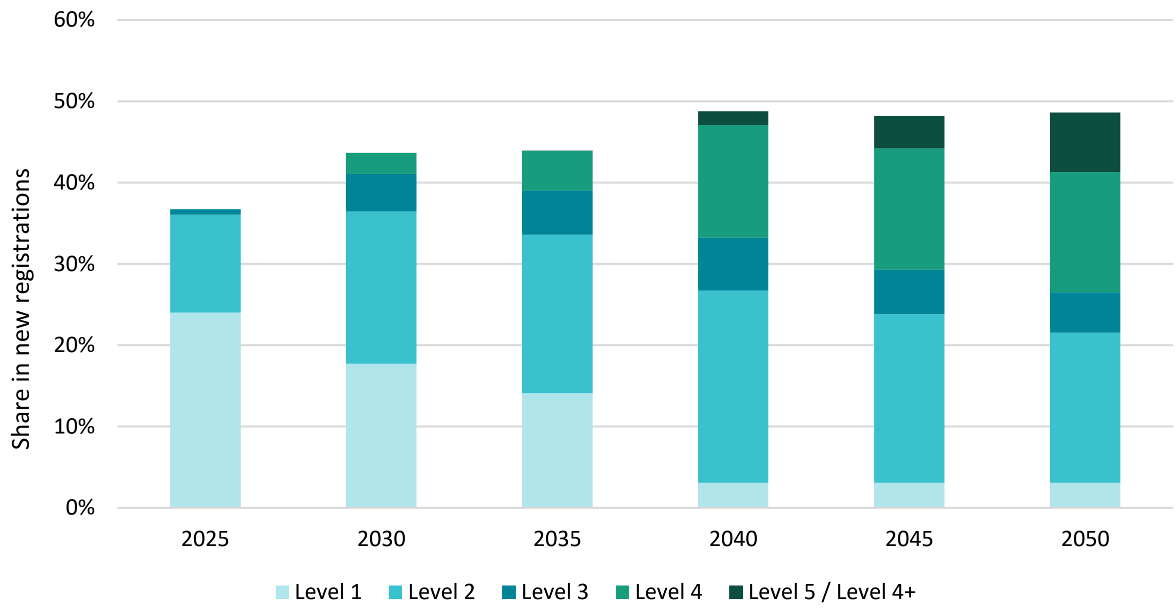


Source: Own representation

The scenario with lower automation levels (**Scenario B**) builds on the numbers from Krail et al. (2019) scenario 1 as a starting point, due to the mentioned good fit of time coverage and disaggregation in vehicle segments. In comparison to other scenarios that aim at the display of a slow diffusion of automation levels, the considered timeline shows lower L1-L3 automation levels and higher L4-5 levels. In addition to that, the total share of automated vehicles in the stock (2050: 36%, L1-L5) are comparably low.

Alonso Raposo et al. (2018) suggests higher and persistent shares of L2 (L2+) and L3 automation in vehicle travel that reach up to almost 100%. Compared to more recent studies (that, however do not consider the years 2050), these numbers in the low uptake scenario seem to be rather high (McKinsey & Company 2023; Burkacky et al. 2023; Bratzel and Tellermann 2022). In order to adjust the considered base time line (Krail et al. 2019, scenario 1) to the average characteristics of slow diffusion scenarios in the literature and thus my considered **scenario B** storyline, the overall level of automation is increased (up to 50%) in new registrations. Furthermore, L4-5 registrations are partly substituted with L2-3 registrations within the vehicle segments. Figure 44 maps the derived automation levels in **scenario B**.

Figure 44: Projection of automation levels in new car registrations in Germany – Scenario B



Source: Own calculations

Surcharges for automated and autonomous driving technology

The potential German revenue pool from vehicle sales in the two **scenarios A and B** is estimated by multiplying the new registrations with average prices for new vehicles in Germany and surcharges for the projected automation levels. It is distinguished between the revenue pool from the classic vehicle components or L0 vehicle and the revenue pool from surcharges from automation levels L1-L5.

A L0 vehicle is considered to be the base vehicle, to which automation technologies, according to their automation levels (L1-L5), are added. In order to derive the L0 price, current average prices for small, middle-class and premium cars in Germany in 2022 as provided by Wittich (2022) are used. The current average prices are considered to be in 2022 € price levels and are deflate to 2019 price levels. Currently, already a lot of vehicles contain assisted driving functions on the levels 1 and 2. In approximation of the current L0 vehicle price, the L1 surcharges, retrieved from Krail et al. (2019) are subtracted from the vehicle prices per segment. These adjusted prices (small: 20,693€ , middle: 37,282€, premium: 81,789€) represent the steady base prices for L0 vehicles up to 2050 and are not varied between the two **scenarios A and B**.

The revenue pool from automation functions is derived by multiplying the projected number of vehicles with certain automation levels with the according projected surcharge. These surcharges are also collected from Krail et al. (2019). In their report, the authors publish prices at the point of introduction of the automation levels in the different market segments. The introduction prices do not vary between their scenarios. Given the years of introduction of the automation levels in the segments, the surcharge per automation level, segment and year can be estimated.

In **scenario A,** automation surcharges for premium vehicles are estimated, using three data points that are retrieved from the authors elaborations (e.g. L4: 5,000€ (2025), 3,500€ (2035), 3,000€ (2050)). For the other vehicle segments, prices are linearly reduced to end up at the same surplus as the premium vehicles in 2050, due to limited data availability for other segments (e.g. middle L4: 3,952€ (2030, introduction L4 2029), 3,000€ (2050)). See Table A 4 in the Annex for detailed timelines.

For **scenario B** prices are reduced only half as much as assumed in scenario A. Surcharges are thus estimated by applying 50% of the reduction of surcharges that was realized in scenario A. The price reduction was distributed linearly from the point of introduction of each automation level until 2050 (e.g. premium L4: 5,000 € (2025), 4,000 € (2050)). See Table A 5 in the Annex for detailed timelines.

The defined prices apply to all vehicles. It is possible that the large scale provision of autonomous mobility services influences vehicle prices. In case an OEM uses its own cars in the provision of autonomous mobility services, prices are expected to be lower. Also, in case a whole fleet of vehicles is purchased by another autonomous mobility service provider, it is likely that discounts are applied. These effects are not considered in the derivation of the vehicles prices.

Export potential for the German industry

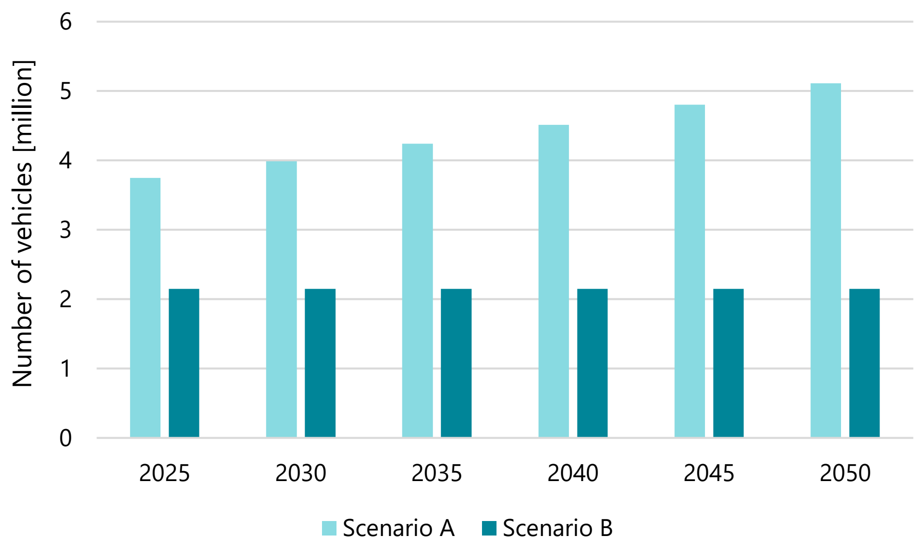
Scenarios 1 and 2 differ by the assumed international trade climate. In order to assess potential vehicle export volumes in the scenarios, projected international vehicle sales from the literature and the current German export structure are used. Long-term outlooks on the future sales of passenger vehicles are rare. Krail et al. (2019) assess the most important countries rather than the whole world. Other literature mainly focuses on the mid-term development until 2030 or 2040 (Burkacky et al. 2023; International Energy Agency 2023; Bloomberg Finance 2017). Both, Burkacky et al. (2023) and International Energy Agency (2023) expect global passenger vehicle sales to increase to around 102 million vehicles in 2030. In 2019, global passenger vehicle sales added up to 87-89M vehicles (International Energy Agency 2020; Burkacky et al. 2023). This suggests an annual growth rate of 1.25% or 1.46%, respectively. Using the lower growth rate (and 89 million vehicle sales in 2019, accordingly) in order to perpetuate the projected 102 million vehicle sales in 2030 to the year 2050 yields a bit over 130 million vehicle sales in 2050. This projection is a slightly lower compared to suggested 120 million vehicles sold in 2040 by Bloomberg Finance (2017) but is considered for development of global vehicle sales in **scenario A.**

In 2019, Germany exported 3.48 million passenger vehicles (Verband der Automobilindustrie 2023a). German passenger vehicle exports thus equal 3.91% of 89 million global vehicle sales in 2019[21]. Of the given German passenger vehicle exports, 2.15 million were exported to European countries (62%) (Verband der Automobilindustrie 2023a). Vehicle exports in 2019 were lower compared to the export record of 4.41 million passenger vehicles in 2016, but higher compared to post-COVID-19 years (2.65 million in 2020, 2.37 million in 2021, 2.65 million in 2022).

The trade climate in **scenario A** allows for international trade, while **scenario B** is marked by protectionist measures. In **scenario A**, the development of the export potential from Germany is set at the current share of 3.91% German exports in global vehicle sales (2050: 5.11 million). The implementation of protectionist measures is complex and may affect final products and intermediates in both, imports and exports. Within this thesis, only the effect on the exports of vehicles is studied. For a rough approximation, it is assumed that in a protectionist world, Germany would still be able to trade within the European single market. The large growing international markets are expected to be outside of Europe, therefore, the export potential in **scenario B** is set and held steady at the level of current German vehicle exports to Europe (2.15 million). Figure 45 displays the considered development of the German passenger vehicle export potential in **scenarios A and B**.

[21] 4% if referring to 87 million vehicles sold in 2019

Figure 45: German passenger vehicle export potential – Scenario A and B



Source: Own calculations

Revenue potential from mobility services in Germany

Given the projections on the share of autonomous mobility services in the literature, it is hard to derive suitable parameters for my scenarios. The given parameters (see Table 12) differ in terms of the chosen unit (passenger kilometers, vehicle kilometers, number of vehicles, trips), the focus on mobility services overall or only autonomous mobility services, the characteristics of studied scenarios, and the assumed diffusion of autonomous vehicles. Furthermore, no single study includes absolute kilometers and costs. On the other hand, there are only a few studies that directly provide numbers on the expected revenue pool from mobility services but lack a transparent calculation of the values. Within the thesis, the revenue pool from mobility services is estimated by combining several sources on vehicle mileage development, the share of autonomous mobility services and cost.

The 2019 German passenger vehicle mileage (in order to exclude negative effects of COVID-19 on transport), reported in vehicle kilometers (Kraftfahr-Bundesamt 2021), is taken as a point of departure. In order to adjust for expected growth in mileage due to the automation of vehicles (e.g. Alonso Raposo et al. 2018; Kaltenhäuser et al. 2020), a constant factor of growth is applied to the current mileage up to 2050. Kaltenhäuser et al. (2020) expect the vehicle mileage in Germany to increase by 20% between 2015 (constant mileage until 2021) and 2040. The increase is driven by the growing usage of shared vehicles (without distinction between autonomous and non-autonomous shared vehicles). Narayanan et al. (2020) show in their comprehensive literature review that most authors expect vehicle mileage growth due to autonomous mobility services to range between +2% to +29%. In **scenario A**, where private and shared usage of autonomous vehicle coexists, 20% growth in vehicle mileage in Germany between today and 2050 is assumed. In **scenario B**, vehicle mileage is considered to remain constant on 2019 levels.

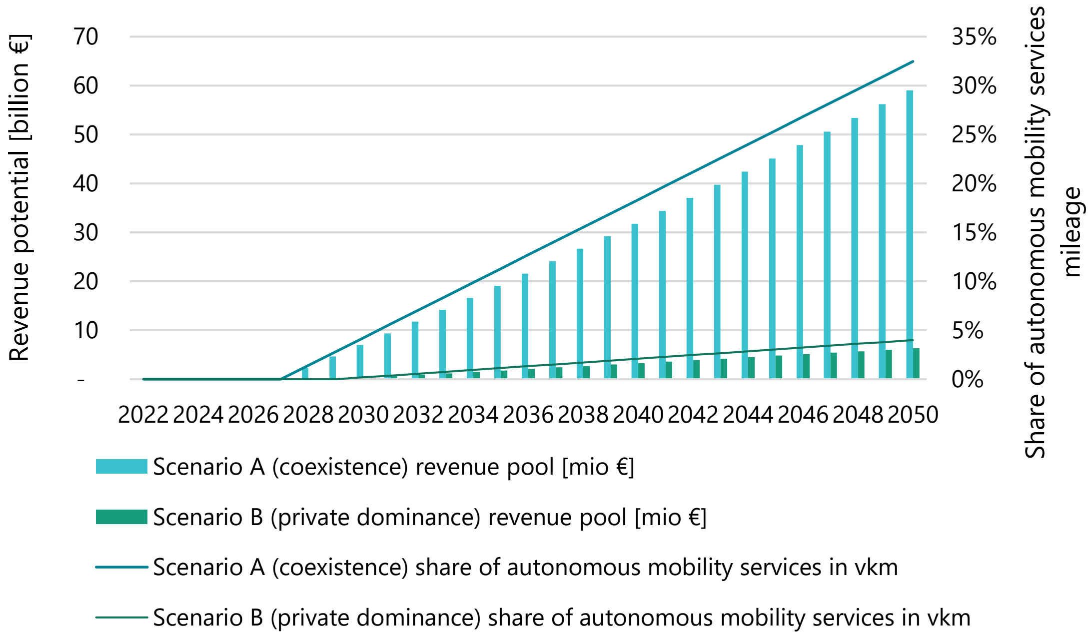
Projections on the share of autonomous mobility services in the literature are either given as the share of the vehicle stock (no relation to mileage) or in passenger kilometers and only cover the years up to 2030/2035. One study on the development on the European level cover both, autonomous vehicle shares in registrations and the mileage of autonomous mobility services up to 2030 (pwc 2017-2018). The approximation of shares in mileage of autonomous mobility services used in **scenario A** builds on their projections. Thereby, it is considered that the German development is parallel to the European development.

The projections show 51% autonomous vehicles in new registrations in 2030 (pwc 2017-2018). At the same time, the authors suggest 24% of vehicle mileage to be covered by autonomous mobility services. The considered timeline of autonomous vehicles registrations in **scenario A** in the thesis (see Figure 43) reach 51% autonomous registrations (L4-5) in 2044. Therefore, it is assume that the corresponding 24% of vehicle mileage with autonomous mobility services is reached in 2044. According to the defined timeline, the first introduction of L4 vehicles takes place in 2028. Interpolation between 0% autonomous mobility service mileage in 2027 and 24% in 2044 is used in order to calculate yearly shares in mileage and to project the shares up to 2050 (see Figure 46, line diagram on secondary axis). It is noted that the availability of autonomous mobility services relies more on the autonomous vehicle stock than new registrations. The chosen approximation might underestimate the share of autonomous mobility services in total mileage since the registration timeline leaves more time for the autonomous vehicle stock to build up. However, autonomous vehicles that are used for mobility services are expected to be replaced much faster, which partly compensates that effect.

Scenario B is characterized by private vehicle dominance and low acceptance for mobility services. Vehicle mileage, covered by autonomous mobility services, is assumed to be at only one third of the amount in scenario A, given the same share of autonomous vehicles in new vehicle registrations. In 2050, in **scenario B**, the share of autonomous new registrations is at 26% (L4-5). The high adaptation scenario A surpasses 26% new registrations of L4-5 vehicles in 2030 corresponding to an autonomous mobility service share of 13% of total vehicle mileage. Thus, a 4% mobility service share (one third of 13%) in total mileage is suggested to be reached in 2050 in **scenario B**. In order to obtain the development over the years, it is interpolated linearly from 0% in the year before the introduction of L4 vehicles (2030).

The overview of autonomous mobility service cost per km in various studies from Krail et al. (2019) suggests that the cost per km varies between 0.09€ and 0.58€ among the different studies. The majority lies between 0.15€ and 0.35€ per km. Also, Narayanan et al. (2020) find in their comprehensive literature review that most estimation vary between 0.19$ and 0.30$ per km. An average price of 0.25€ per vehicle kilometer is considered due to the long perspective up to 2050 and expected price decreases in the purchase of autonomous vehicles for mobility service providers. The real price remains constant in $€_{2019}$. It is not distinguished between different forms of autonomous mobility services. Figure 46 displays the potential revenue pool in Germany for **scenarios A and B**.

Figure 46: **Revenue pool and autonomous mobility services share in mileage in Germany – Scenario A and B**



Source: Own calculations

8.1.2.2 German industry positioning (Scenarios 1 / 2)

Share of German OEMs in the domestic market

Scenario 1 is marked by successful engagement of German OEMs in all segments and automation levels. Successful engagement is translated into the assumption that German OEMs can keep up their current market shares in vehicle registrations. In order to approximate the differences between the scenarios more accurately, market shares of German OEMs per segment are used. This is needed because **scenario 2** differentiates in engagement of OEMs in the different vehicle segments and the development of new vehicle registrations.

There is data available on the production of the automotive industry in Germany, but it does not differentiate between production for the domestic market and for exports, on the level of vehicle segments (only on the level of total production) (Verband der Automobilindustrie 2021). Therefore, the share of German OEMs in new vehicle registrations is used in order to estimate the German vehicle production for the domestic market. This entails the assumption that all vehicles of German brands that are sold in Germany, are also produced in Germany. The approach might overestimate German production, since vehicles for the German market are also produced in production facilities of German OEMs abroad (e. g. Eastern Europe).

The data on market shares by segment is not readily available but has to be calculated given data from the Kraftfahr-Bundesamt ("Federal Motor Transport Authority") in Germany. The available data contains information on the model series and brands that were registered in Germany (Table FZ11.1, Kraftfahr-Bundesamt 2020b). Detailed registration data from 2019 is used in order to grasp the pre-COVID19 structure in new registrations. The model series by German OEMs are selected (Audi, BMW, Mercedes-Benz, Porsche, Volkswagen)[22] including information the attribution to the 13 given segments by the Kraftfahr-Bundesamt. The numbers are then aggregated into the tree vehicle segments “small”, “middle”, and “premium”. Thereby, the definition of Krail et al. (2019) is used. Table 13 displays the market shares of the segments and of the German OEMs by segment. See Table A 6 for details on how vehicle models were assigned to OEMs and segments. The absolute number of total registrations and the division in the three segments differs slightly from the assumed vehicles registration development in Germany as provided by Krail et al. (2019) (small: 54%, middle: 35%, premium: 11%). The market shares, derived here, are used in combination with the described vehicle registration projections (section 8.1.2.1).

Table 13: Market shares of German OEMs in German new passenger vehicle registrations per segment (2019)

Vehicle segment	Total registrations in Germany	Registrations of German OEMs' models	Share of the segment in total registrations	Share of German OEMs (total registrations)	Share of German OEMs (within segment)
small	1,826,387	631,182	54.3%	18.8%	34.6%
middle	1,293,866	677,564	38.5%	20.2%	52.4%
premium	240,953	176,161	7.2%	5.2%	73.1%
total	**3,361,206**	**1,484,908**	**100%**	**44.2%**	

Source: Own representation based on Kraftfahr-Bundesamt (2020b)

In **Scenario 1**, the given market shares (last column of Table 13) are assumed to be constant until 2050. **Scenario 2** is marked by the focus of German OEMs on the premium segment vehicles and the automation level up to L3. In the scenario, German OEMs are expected to still produce some small and middle class vehicles eventually, but at a smaller amount and thus with smaller market shares (small: 10%, middle: 35%) in 2035. The share in registrations of premium vehicles is increased by about 10% to 85% until 2035. The given market shares from Table 13 are used for 2019 and it is interpolated linearly between 2019 and 2035. For the years between 2035 and 2050, the shares are held constant. German OEMs do not engage in vehicle registrations with automation levels 4 or 5. The given shares of German OEMs in the different vehicle segments are thus only applied to vehicles with automation levels up to L3.

Share of German vehicle exports in international markets

There is no data available on the vehicle exports by segment. Verband der Automobilindustrie (2021) provides number on the total domestic production of vehicles by segment in Germany (Table 14). The vehicle segments, as listed in the table, were aggregated according to the procedure described in above paragraph (“Share of German OEM in new vehicle registration”). The share of the segments in total vehicle production in Germany for both, the domestic market and exports,

[22] Foreign brands that are part of the VW group are not considered. Also, Opel that is part of Stellantis is not considered a German OEM at this point.

matches almost exactly the share of segments in registrations of German OEMs (from Table 13 the following shares of segments in the German OEM's new registrations can be derived: 43% small vehicles (631,192), 46% middle vehicles (677,564), and 12% premium vehicles (176,161)[23]). This implies that German vehicle production for the domestic market and German vehicle production for exports are similar with regard to the shares of the different vehicle segments. It should be noted that the total vehicle production in Germany contains production of non-German brands ins Germany such as Ford or Opel, also in data by Verband der Automobilindustrie (2021). Due to the lack of detailed data, the produced vehicles by those brands cannot be subtracted from total vehicle production in Germany. If their production differs in term of the segment shares, the real shares of the segments in the total domestic production of German OEMs may differ. It remains unclear, whether and on what scale that may lead to distortions.

Table 14: Passenger vehicle production in Germany (2019)

Vehicle segment	Total vehicle production in Germany	Share of the segments
small	1,918,160	42%
middle	2,080,853	46%
premium	565,901	12%

Source: Own representation based on Verband der Automobilindustrie (2021)

Despite the mentioned restriction, for further estimations it is assumed that the German OEMs' production for the domestic market and exports has the same structure with regard to vehicle segments produced. Thus, in **scenario 1,** German OEMs produce 43% small vehicles, 46% middle vehicles, and 12% premium vehicles for both the domestic and export market. These shares are held constant until 2050. The shares are used in combination with estimated potential exports in **scenario A** and **B** in order to derive export numbers by segment for each of the scenario combinations. The automation levels per segment are assumed to have the same structure compared to new vehicle registrations in Germany in **scenarios A** and **B**. Furthermore, the same vehicle prices and surcharges as in **scenarios A** and **B** are considered. **In scenario 1**, the calculated export potentials are fully exhausted. This means that in **scenario A-1**, the full 5.11 million vehicles are exported and in **scenario B-1**, 2.15 million vehicles are exported (see section 8.1.2.1, export potential).

Scenario 2 is characterized by the stronger focus on premium vehicles and on vehicles with automation functions up to L3. The assumed development of market shares of German OEMs in the domestic market (2035: small: 10%, middle: 35%, premium: 85%) can be translated into a production of 182,639 small, 452,853 middle, and 204,810 premium vehicles by German OEMs in 2035. This in turn equals a structure of 22% small vehicles, 54% middle vehicles, and 24% premium vehicles in German production in 2035. Again, these shares are used in combination with **scenario A** and **B** in order to derive potential exports by segment in each of the scenario combination with **scenario 2**. The automation levels per segment are assumed to have the same structure compared to new vehicle registrations in Germany in **scenarios A** and **B**. Furthermore, the same vehicle prices and surcharges as in **scenarios A** and **B** are considered. In **scenario 2**, the calculated export potentials are not fully exhausted. Only exports of vehicles of automation levels up to L3 are realized. This means that in **scenario A-2**, only 2.00 million vehicles are exported and in **scenario B-2**, 1.50 million vehicles are exported.

[23] The shares do not sum up to 100% due to rounding

The comparison of different vehicle export statistics from Germany suggests that vehicles that are exported to non-European countries have higher values (Verband der Automobilindustrie 2023a; Statistisches Bundesamt 2023a). Table A 7 in the annex displays the absolute number of vehicles exported and the value of those vehicles. Exports to European countries in 2019 account for 62% of exported vehicles, but only 57% of the value of exports. However, no numbers on the exported vehicle segments are available. Due to the lack of a suitable indication, it is assumed that exports have the same segment structure as the production of German OEMs for the German market. It is pointed out that by the chosen procedure, exports to Europe may be overestimated, while exports to non-European countries may be underestimated, which might underestimate the effects in combination with scenario B, where only the European market is supplied.

Share of German OEMs in mobility services

Autonomous mobility services hardly exist in the German market at the moment. Autonomous mobility services are considered to be carried out using robotaxis that may still resemble cars, and autonomous shuttles. Autonomous shuttles are usually defined to be larger and used in order to transport more people, often also on predefined routes. It is assumed that German OEMs, according to their product portfolio, would only engage in mobility services that are carried out in robotaxis. The relevance of robotaxis in comparison to autonomous shuttles can be approximated by looking at the numbers of both vehicle types. Deloitte (2019a) suggest that mobility services in German cities could be carried out using 560,000 robotaxis and 180,000 autonomous shuttles, which equals a share of almost 75% robotaxis. The current carsharing market in Germany is used in order to approximate potential market shares of German OEMs in providing mobility services. In the beginning of 2020, among the ten largest carsharing providers, there were private carsharing companies, companies that are backed by automotive OEMs, and subsidiaries of transport companies (Statista 2020). With regard to the number of vehicles in the carsharing fleet, OEM-backed carsharing accounted for 41% of the Top-10 carsharing suppliers (see Table A 8 in annex). Leaving aside the regional origin of the OEMs, running these carsharing platforms, the 41% market share is used as a proxy in order to estimate the potential market share of OEMs in the autonomous mobility service market. Taking into account the 75% share of robotaxis in mobility services and 41% OEMs share suggests a potential market share of 31% of the total revenue pool from autonomous mobility services. The market share of 31% is used as the market share of OEMs in **scenario 1**. Non-existent engagement of German OEMs in **scenario 2** is defined at 0% market share.

Share of German firms in components for autonomous driving – regional and sectoral origin

Scenario 1 and 2 differ in terms of the engagement of automotive OEMs and suppliers in the provision of new vehicle components and software. Therefore, the potential revenue from the surcharge for autonomous driving components needs to be split into their hardware and software parts. The used surcharges for automated and autonomous driving technologies do not allow for that differentiation (Krail et al. 2019). Projections in the literature mostly focus on estimating the market revenue potential and thereby distinguish between different components. Asselin-Miller et al. (2017) estimate the global market potential for connected and automated vehicle technologies to be 273 billion $ between 2020 and 2030. New software accounts for 15 billion $, autonomous hardware components for 41.5 billion $ and autonomous driving chips for 7.2 billion $. This corresponds to 24% software and 76% hardware shares in autonomous vehicle technology (leaving out the revenue potential from connectivity). Burkacky et al. (2023) project a global revenue potential of 42 billion $ (55%) from software for assisted and highly automated driving, 7 billion $ (9%) from operating systems and middleware, and 28 billion $ (36%) from hardware (cameras, radar, LiDAR) in the year 2030 alone. Proff et al. (2019) estimate a global market revenue potential from automotive artificial intelligence software of 13 billion $ and from automotive artificial intelligence hardware of 6 billion $ (68% and 32%, respectively).

The estimations differ largely and the definition of the components remains unclear, which complicates the comparison. Furthermore, the projected market revenue potentials as well as average prices for individual components are very uncertain. To demonstrate the wide range of even current price estimations, the costs for LiDAR equipment of running test vehicles are estimated between 35,000 – 100,000$ per vehicle (Grant and Lyu 2022).

For both scenarios, it is assumed that the projected market revenue potentials give a hint on the distribution of software versus hardware components in the surcharge for autonomous driving technology. The numbers from Burkacky et al. (2023) are used, which are in between the other two, to roughly approximate the distribution of autonomous vehicle surcharges to the fields of software (64%) and hardware (36%).

In **scenario 1**, German suppliers engage in both the provision of software and new hardware components. Due to the lack of evidence on the exact market share of the suppliers of such components, it is assumed that German suppliers maintain the same market shares as the German OEMs. In **scenario 2**, German suppliers only engage in the provision of the classic hardware component that are included as intermediates to the non-automated vehicles. Therefore, it is assumed that the potential revenue pool from automation technologies is not tapped by the German industry.

The revenue potential from the export of software and new hardware components is determined similarly. In **scenario 1**, German firms realize the same export potential as the manufacturers of vehicles. In **scenario 2**, German firms do not provide software or hardware components for exports.

8.1.2.3 Overview of indicators and their development

Sections 8.1.2.1 and 8.1.2.2 described in detail, how the scenario characteristics are translated into quantitative indicators and how their development is defined. Table 15 summarizes the results. The left column states the scenario characteristic in focus, the center column contains the chosen indicators, the right column describes the projected development of the indicator. The "scenario-pairs" (scenarios A and B, scenarios 1 and 2) are each mapped using the same indicators but different development paths. Scenarios are built by combining the market framework and the German industry strategy scenarios. Thus, the procedure yields four different scenarios and sets of impulses.

Table 15: Overview of the defined translation of scenario characteristics into indicators and development

Indicator - Market	**Scenario A – "autonomous driving uptake"**		**Scenario B – "Moderate automation of mobility"**	
	Scenario characteristic	**Development of indicator**	**Scenario characteristic**	**Development of indicator**
New vehicle registrations in Germany	Quick diffusion of autonomous vehicles	stagnation	Slow diffusion of autonomous vehicles	stagnation
Automation levels		quick diffusion, 57% L4-5 vehicles in new registrations in Germany 2050, first introduction of L4 vehicles in 2026		slow diffusion, 26% L4-5 vehicles in new registrations in Germany 2050, first introduction of L4 vehicles in 2030
Surcharges for automated and autonomous driving technology	Decreasing cost for autonomous driving technology	Decreasing surcharges, up to 70% price reduction	High prices of autonomous driving technology	moderate decrease in surcharges, half of the price reduction realized (vs. Scenario A)
Vehicle mileage in Germany	Coexistence of autonomous mobility services and privately owned vehicles	Increases by 20% until 2050	Dominance of privately owned autonomous vehicles	constant
Share of autonomous mobility services		32% of total vehicle mileage in 2050		4% of total vehicle mileage in 2050
Export potential	Persistently globalized world	Increasing global export potentials with 1% growth rate until 2050	Protectionist measures	Steady exports only within European single market
Indicator – Market share of German firms in...	**Scenario 1 – "Successful digital modernization"**		**Scenario 2 – "Bumpy adaptation to autonomous mobility"**	
	Scenario characteristic	**Development of indicator**	**Scenario characteristic**	**Development of indicator**
Small, middle class, premium segment and different levels of automation (German and international markets)	Focus on all vehicle segments	All segments: constant	Focus on premium vehicles	Small: declining, middle class: declining, premium: increasing
	Engagement in all automation levels	Applies to all automation levels	Focus on L2/L3 assisted driving	Applies only to automation levels up to L3, 0% market share for L4-5
Software components (German and international markets)	Germany provides their own software solutions	Software-related new components provided by German firms (100%)	German automotive industry purchases from foreign software providers	Software-related new components not provided by German firms
New hardware components (German and international markets)	German suppliers provide classic and new components	Hardware-related new components provided by German firms (100%)	German suppliers provide classic components	Hardware-related new components not provided by German firms
Autonomous mobility services	German OEMs partly supply the German autonomous mobility services market	German OEMs partly supply the autonomous mobility service market (31%)	German OEMs do not engage in autonomous mobility services at all	German OEMs do not supply the autonomous mobility service market (0%)

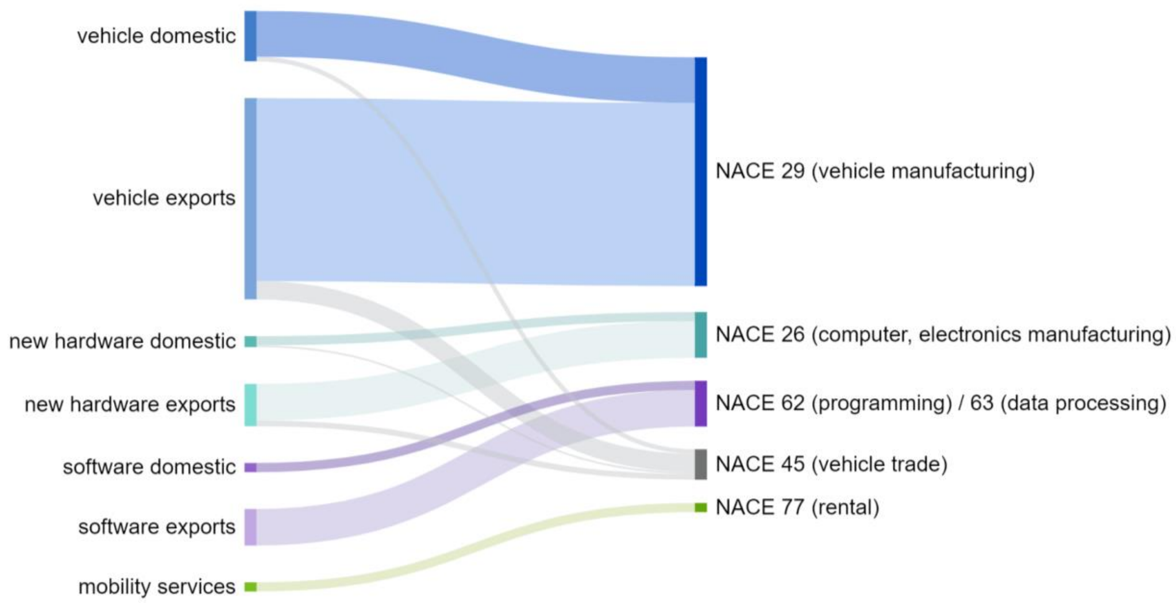
Source: Own representation

8.1.2.4 Assignment to affected industries and demand types

In the preceding sections, estimations on the development of revenue potentials for firms or, broader speaking, the German industry, have been conducted. The generated data on the development of indicators has to be translated into a statistical understanding of the economy in order to form impulses that can be used in the macroeconomic simulation model. In the translation, economic activities by firms are assigned to the economic activities in certain industries. These industries are classified by NACE system, as already introduced in section 4.1.3 (eurostat 2008). In the production account of the national account in Germany, the allocation of companies to economic sectors is made according to the focus of economic activity, measured by the contribution to gross value added (Statistisches Bundesamt 2019b).

Economic activity of OEMs is thus considered in the "Manufacturing of vehicles and parts"-industry. Impulses are, however, distributed among different industries according to a technological understanding of the origin of the vehicle component. E.g. the estimated demand for software is assigned to the industry branch "Computer programming, consultancy and related activities" (NACE 62) and "Computing infrastructure, data processing, hosting and other information service activities" (NACE 63). However, the software could also be offered by an automotive supplier or the OEM itself, which statistically needed to be assigned to the industry "Manufacture of motor vehicles, trailers and semi-trailers" (NACE 29). Splitting the production value among the required product-components helps to understand the demand for competencies and to include the relevant intermediate value chains. The procedure follows the final demand approach as described in Miller and Blair (2009). Figure 47 sketches the concept of assigning impulses to the different industries.

Figure 47: Concept of assigning impulses to industries



Source: Own representation

The revenue from domestic vehicles sales without the automation surcharges represents final demand for non-automated passenger vehicles. According to Kraftfahr-Bundesamt (2020a), in 2019, 34% of passenger vehicles in Germany are registered by private vehicle owners, while 66% of new vehicles are registered by commercial vehicle owners[24]. Commercial owners can be company cars, but also lessors. Using the given shares, 34% of the revenue is attributed to the consumption impulse, while 66% is attributed to investments. Both impulses are attributed to the "Manufacture of motor vehicles, trailers and semi-trailers" (NACE 29). Non-automated passenger vehicles (or the non-automated base vehicles) are considered to be produced with an input structure that is similar to the given input structure in the 2019 IOT.

The estimated impulses are calculated by using market prices. Hence, the monetary impulses represent purchase costs for vehicles, components etc. The simulation model that builds on an input-output table requires the impulses on the basis of production costs. Purchase costs include taxes, subsidies and trade margins, which need to be subtracted in order to derive production costs. The average trade margins and taxes per industry can be derived from the German input-output table and are displayed in Table 16. The subtracted trade margins are reassigned to the industry branch "Wholesale and retail trade and repair of motor vehicles and motorcycles" (NACE 45). The branch includes the "Wholesale trade of motor vehicle parts and accessories" (NACE 45.3.1), which is considered to include the trade of future autonomous driving technologies. Trade margins are not relevant for services.

Table 16: Trade margin and taxes according to German IOT 2019

	Trade margin	Taxes
Manufacture of computer, electronic and optical products (NACE 26)	**15.30%**	3.50%
Manufacture of motor vehicles, trailers and semi-trailers (NACE 29)	**9.20%**	2.90%
Computer programming, consultancy and related activities (NACE 62); Computing infrastructure, data processing, hosting and other information service activities (NACE 63)	**0%**	2.40%
Rental and leasing activities (NACE 77)	**0%**	2.10%

Source: Own representation based on Statistisches Bundesamt (2022)

The demand for automation technology in the field of software components in domestic vehicles sales is assigned to "Computer programming, consultancy and related activities" (NACE 62) and "Computing infrastructure, data processing, hosting and other information service activities" (NACE 63). While the software components for vehicles are actually intermediates to the manufacturing of vehicles, they are treated as final demand for reasons of simplification and straightforward representation of the effects. Since only those components that are built in sold vehicles are considered, the same share of consumption versus investment is considered.

Similarly, the demand for automation technology in the field of new hardware components in domestic vehicles sales is assigned to consumption and investment and attributed to the "Manufacture of computer, electronic and optical products" (NACE 26). The considered new hardware components include technologies such as sensors, cameras or control units which are all included in industry NACE 26.

[24] Number of passenger vehicles registered by private vehicle owners in Germany, 2019: 1.24M; Number of passenger vehicles registered by commercial vehicle owners in Germany, 2019: 2.36M; Kraftfahr-Bundesamt 2020a.

Foreign demand for German vehicles and components is attributed to the final demand category exports. The export impulses are assigned to the same industries as the domestic demand has been assigned to.

The revenue from mobility services is considered to be entirely generated by private demand and is thus implemented via a consumption impulse. The impulse is attributed to the industry "Rental and leasing activities" (NACE 77). The industry classification includes the rental of passenger vehicles without drivers among other products such as machines or other means of transport and immaterial goods. The rental of passenger vehicles is chosen to resemble the input structure of future operations of autonomous mobility services. The rental of vehicles accounts for about 50%[25] of the revenue in the industry branch of "Rental and leasing services" (Statistisches Bundesamt 2023c) and should thus largely determine the input structure. The high amount of depreciations, high shares of intermediate inputs from the industry branch itself, other economic services (that include the cleansing of vehicles) and insurance roughly resemble the industry split suggested for robotaxis in e. g. Sievers and Grimm (2019). The current input structure of the rental of vehicles may, however, underestimate the relevance of the operation of platforms. Table 17 gives an overview of the assignment of impulses to industries and demand types.

[25] Revenue of Rental and leasing activities (NACE 77) in Germany, 2019: 64.8B €; Revenue of sub-industry branch Rental of vehicles < 3.5t (NACE 77.11) in Germany, 2019: 31.4B €; Statistisches Bundesamt 2023c.

Table 17: Overview of the assignment of impulses to industries and demand types

	Impulse type	Industry
Revenue from **domestic vehicle sales** (without automation surcharge)	34% private: Consumption; 66% commercial: Investment	Manufacture of motor vehicles, trailers and semi-trailers (NACE 29) 9.2% trade margin: Wholesale of motor vehicles, motorcycles and related parts and accessories (NACE 45)
Revenue from **domestic automation technology** sales (**Software**)	34% private: Consumption; 66% commercial: Investment	Computer programming, consultancy and related activities (NACE 62); Computing infrastructure, data processing, hosting and other information service activities (NACE 63)
Revenue from **domestic automation technology** sales (**Hardware**)	34% private: Consumption; 66% commercial: Investment	Manufacture of computer, electronic and optical products (NACE 26) 15.3% trade margin: Wholesale of motor vehicles, motorcycles and related parts and accessories (NACE 45)
Revenue from **vehicle exports** (without automation surcharge)	Exports	Manufacture of motor vehicles, trailers and semi-trailers (NACE 29) 9.2% trade margin: Wholesale of motor vehicles, motorcycles and related parts and accessories (NACE 45)
Revenue from automation technology **exports (Software)**	Exports	Computer programming, consultancy and related activities (NACE 62); Computing infrastructure, data processing, hosting and other information service activities (NACE 63)
Revenue from automation technology **exports (Hardware)**	Exports	Manufacture of computer, electronic and optical products (NACE 26) 15.3% trade margin: Wholesale of motor vehicles, motorcycles and related parts and accessories (NACE 45)
Revenue from domestic **mobility services**	Consumption	Rental and leasing activities (NACE 77)

Source: Own representation

Based on the described procedure, the impulses for the four scenarios A-1, A-2, B-1, and B-2 are calculated and attributed to the different demand types and industries. The price basis €$_{2019}$ is considered, since often data points from 2019 are used. Other prices (e. g. vehicle prices in €$_{2022}$) are deflated, using GDP deflators provided by the German federal statistical office (Statistisches Bundesamt 2023b). Table 18 provides an overview of the used impulses in 5-year steps (2019-2050).

Table 18: Overview of the impulses 2019 – 2050 [€2019]

Impulse	Final demand type	Industry (NACE)	Scenario	2019	2025	2030	2035	2040	2045	2050
total domestic final demand (vehicles without automation surcharge)	consumption / investment	29	A-1	47,607	46,766	46,064	45,363	44,661	43,960	43,258
			A-2	47,608	42,723	27,271	16,986	11,588	11,101	10,797
			B-1	47,608	46,766	46,064	45,363	44,661	43,960	43,258
			B-2	47,608	42,723	35,596	30,323	25,223	22,511	20,596
total intermediate domestic demand SOFTWARE	consumption / investment	62/63	A-1	908	817	1,237	1,499	1,917	1,967	2,097
			A-2	-	-	-	-	-	-	-
			B-1	952	1,117	1,592	1,626	1,998	1,965	1,857
			B-2	-	-	-	-	-	-	-
total intermediate domestic demand NEW HARDWARE	consumption / investment	26	A-1	425	383	579	701	897	920	981
			A-2	-	-	-	-	-	-	-
			B-1	446	523	745	761	935	920	869
			B-2	-	-	-	-	-	-	-
total exports (vehicles without automation surcharge)	exports	29	A-1	108,623	117,009	124,490	132,449	140,916	149,925	159,510
			A-2	108,623	128,142	107,831	86,479	64,418	66,636	70,090
			B-1	67,117	67,117	67,117	67,117	67,117	67,117	67,117
			B-2	67,117	73,503	73,318	74,541	63,932	58,250	54,521
total exports SOFTWARE	exports	62/63	A-1	2,265	2,210	3,255	3,961	6,272	6,944	7,979
			A-2	-	-	-	-	-	-	-
			B-1	1,446	1,670	2,344	2,451	3,059	3,047	2,900
			B-2	-	-	-	-	-	-	-
total exports NEW HARDWARE	exports	26	A-1	1,060	1,034	1,523	1,854	2,935	3,250	3,734
			A-2	-	-	-	-	-	-	-
			B-1	677	782	1,097	1,147	1,432	1,426	1,357
			B-2	-	-	-	-	-	-	-
total service value mobility services	consumption	77	A-1	-	-	2,119	5,795	9,653	13,692	17,913
			A-2	-	-	-	-	-	-	-
			B-1	-	-	91	548	1,005	1,462	1,919
			B-2	-	-	-	-	-	-	-
trade with vehicles and vehicle parts	consumption / exports	45	A-1	16,632	17,408	18,247	19,092	20,145	21,079	22,111
			A-2	16,352	17,883	14,140	10,829	7,955	8,136	8,466
			B-1	12,008	12,165	12,193	12,132	12,145	12,068	11,972
			B-2	12,008	12,165	11,399	10,976	9,331	8,453	7,862

Source: Own representation

The production of vehicles for exports exceeds the production for the domestic market in all scenarios. Especially the deviation between scenario A-1 and scenario A-2 is large. The export quota in 2050 in scenario A-1 is 79%, in scenario A-2 it is 87% but absolute exports are just below 50% compared to scenario A-1. The lowest export quota in 2050 is expected in scenario B-1, where 39% of vehicle production are for the domestic market and 61% are exported.

The impulses for scenario A-1 and B-1 are usually higher compared to scenarios A-2 and B-2, since the engagement of the German industry in scenarios A-1 and B-1 is more ambitious. The only exception are vehicle exports from Germany in the early years. Scenarios A-2 and B-2 are characterized by a German industry that focuses increasingly on premium vehicles and that yields higher market shares in that segment. Furthermore, only vehicles with automation levels up to L3 are produced. In the early years, when automation levels over L3 are not yet widely diffused, scenarios A-2 and B-2 are marked by higher export values since the focus on more expensive premium vehicles pays off, while the are no missed export potentials in higher automation levels. In scenario A-2 this advantage is compensated already in 2030, as soon as vehicles with L4 automation levels are introduced. In scenarios B-2, the advantage persists with regard to exports until 2040.

The export impulse in the globalized framework scenarios for 2019 well matches the 128,109 million € value of passenger vehicle exports in 2019, reported by Statistisches Bundesamt (2023a). Both, the given impulse and the export statistics differ largely from information available on the foreign sales revenue of the German automotive industry. Verband der Automobilindustrie (2023b) report 282,700 million € foreign sales revenue in 2019. The difference contains the revenue from trucks, busses, vehicle parts and the revenue from non-German automotive OEMs that were not considered in the calculation of the impulses. The same argument can be applied in order to explain the majority of the differences between the vehicle production impulse and the reported domestic revenue of 153,400 million € in 2019.

The impulses displayed in Table 18 represent the development of final demand for passenger vehicles and mobility services over time and are fed into the macroeconomic simulation model ISI-Macro that follows a demand-led approach. One criticism of demand-led modelling approaches is the neglect of crowding out effects and the principle of basically unlimited investment possibilities (see section 2.2.2). This criticism can be met by including reciprocal financing mechanisms, such as a limited investment budget, in ISI-Macro. However, in case of the studied scenarios within the thesis, it is argued that counter-financing is not necessary. The argument builds on the following thoughts. First of all, domestic production of exports are stimulated by demand abroad and thus do not require counter-financing in Germany. Exports are the largest impulse in the comparison of the scenarios (see section 8.2.1). At this point, it is neglected that the upscale of production volume could require investments in production infrastructure which in turn might need to be counter-financed. The investment needs of German firms in order to meet future demand are beyond the scale of the thesis. Secondly, for the considerations on counter-financing of consumption and investment in vehicles, it is crucial to point out that scenarios 1 and 2 are compared within either framework scenario A and or B. By definition of scenario A, the total demand for vehicles in Germany is the same, regardless of whether industry strategy 1 or 2 is considered. The difference between A-1 and A-2 lies only in the assumed share of German industry and thus domestic German production, not in the level of total demand. However, the consumption level is held constant in the circular logic of the model. This means that the bottom-up consumption impulse is first subtracted from the endogenously determined consumption level. The remaining consumption budget is distributed across all industries in the economy. The bottom-up consumption impulse is then distributed to the directly affected industries. With regard to investments, the investment level is not fixed. Hence, the investment impulse flows into vehicles (corporate spending on cars) without being deducted elsewhere. Investment in vehicles is the only investment impulse considered. As described above, the overall level of expenditure on vehicles in Germany only varies between scenarios A and B. The comparison of A-1 and A-2 refers to the difference in German firms' market shares, not changes in the overall demand level and the investments therefore do not need to be counter-financed to account for additional expenditure.

8.1.2.5 Critical assessment of assumptions and sensitivities

Estimations on future development of the world market and industrial landscape providing autonomous driving until 2050 underlie a high degree of uncertainty. In the following, some central uncertainties in the estimation of the indicators are discussed. Furthermore, as mentioned in the beginning of section 8.1.2, sensitivities are introduced in order to gain a better understanding of potential deviation in the results given alternative definitions of the scenarios A-1, A-2, B-1, and B-2. Next to sensitivities that display variation in the assumed magnitude of selected indicators, some sensitivities challenge the assumed independence between the framework and industry positioning scenarios. All considered sensitivities are summarized in Table 19.

Domestic vehicle sales

Estimations on future sales are in general highly uncertain. For both market framework scenarios A and B, it is assumed that vehicle registrations in Germany develop equally until 2050. Scenario A is characterized by a coexistence of privately owned vehicles and mobility services. In scenario B, private vehicles dominate. The introduction of mobility services is often discussed by transport scholars regarding the potential replacement of privately owned vehicles by fewer shared vehicles. Following this thought, registrations in scenario A might be overestimated. However, simulations on the actual effect on the future vehicle stock vary heavily (Narayanan et al. 2020). Some studies suggest a smaller vehicle stock, where the driven kilometers per vehicle increase. Increased vehicle kilometers in turn suggest that vehicles have to be replaced more quickly. Thus, even a smaller vehicle stock might not necessarily come along fewer vehicle registrations. In addition to that, lower prices for autonomous vehicles in scenario A in comparison to scenario B might foster demand for vehicles, which could result in higher vehicle registrations in scenario A. It remains unclear, whether the different effects balance each other.

The diffusion of automated driving functions in both, scenarios A and B, is adopted from published scenarios in Krail et al. (2019) and roughly adjusted based on other studies. Published scenarios by transport researchers that apply transport system models are considered to consistently estimate interrelations between different parameters such as between technology prices and technology diffusion, based on elasticities. The procedure of combining different scenarios in the thesis might undermine this inner consistency between the values for individual parameters. The goal was to meet the scenario characteristics as closely as possible, which required the combination due to the lack of suitable published full scenarios. It is pointed out that the considered scenarios in the literature differ widely, too. The wide range of estimations suggests that the future diffusion of the yet to be fully developed technologies are uncertain.

The assumed development of vehicle registrations and automation functions in Germany for market framework scenarios A and B suggests that there is no interdependence between the engagement of the domestic industry and the number of sold (automated) vehicles. In scenario A-1 the diffusion of autonomous vehicles is considered to be quick and the German industry shows high activity in the field of autonomous vehicles. This situation might be surrounded by more engagement of the government in fostering both, the demand and supply side (programs to increase acceptance of autonomous vehicles, programs to foster autonomous driving development; both e. g. in robotaxi pilot projects and services). Also, as pointed out in section 5.6.3, the acceptance of autonomous vehicles is dependent on the perceived security of the technology. Given the general acceptance of society for autonomous vehicles in market framework scenarios A, even higher trust and in turn higher demand for domestic vehicles is imaginable in scenario A-1. Such reinforcing cycles between industry engagement and demand for autonomous vehicles could suggest higher market shares of German firms in autonomous vehicles compared to scenario B-1. Therefore, a sensitivity is introduced that assumes the same absolute number of vehicle registrations but higher vehicles sales of German OEMs and accordingly suppliers. The sensitivity *A1_A2_sens_revenue_boost* introduces an increase in the revenue from domestic vehicle sales by 10% in scenario A-1 (see Table 19). The same rationale could be assessed by reducing revenue in A-2 or B-1.

Vehicle exports

The development of international vehicle markets and the export volume of the German industry is dependent on many factors. In scenario A, the export potential for the German industry is considered to grow by 1% per year. On the one hand-side international markets still show growth-potential. On the other hand, for example, sustainability in the transport system has been increasingly discussed with regard to greenhouse gas emissions but also local pollutants. Especially large cities have been and are still suffering from smog and take measures that could also affect the rate of car ownership. Projections on the future global car fleet, such as provided in the current ITF Transport Outlook, suggest a discrepancy of 100 million vehicles between the two defined scenarios for decarbonizing transport in the year 2050 (current ambition: 1.55 billion versus high ambition: 1.45 billion) (International Transport Forum 2023). The international market development can have a large influence on the export-oriented German automotive industry, but is subject to uncertainties. In order to assess the effects of a saturated international vehicle market, the sensitivity *A1_A2_sens_export_global_saturation* is introduced (see Table 19). Here, in the market framework scenario A exports do not grow by 1% per year, but remain constant at 3.48 million vehicles between 2019 and 2050.

The implementation of a more protectionist trade climate in market framework scenario B consist of a limitation of German export potentials to the European market. This is considered a strong assumption. Also, in such a strictly protectionist world, it is likely that Europe imposes protectionist measures, too. This could imply higher export potentials to the European market for German firms, especially in combination B-1, where German firms actively engage in the provision of autonomous vehicles, despite a slower diffusion of the technology. In order to account for that potential interdependency, sensitivity *B1_B2_sens_European_export_boost* is introduced (see Table 19).

In addition to the level of exports of the German industry, also the structure is subject to uncertainty. The assumed similar shares of automation functions in sales of German OEMs to the domestic and the international markets might neglect the possible differing diffusion of autonomous vehicles in international markets. Furthermore, prices are held constant for domestic production and exports which probably overestimates exports to European countries and underestimates exports to non-European countries (see section 8.1.2.2 and Table A 7).

Regional and sectoral origin of intermediates

The implementation of impulses for vehicle production are divided into three parts: the "base" vehicle without automation functions, the software components for automated driving and the new hardware components for automated driving. The basic vehicles out of German production are considered to be produced with the current input structure according to the IOT 2019. The input structure refers to the sectoral and international origin of intermediate goods and thus includes for each intermediate sector the share of domestically and internationally sourced intermediates to the automotive industry. This assumption is made for both industry positioning scenarios 1 and 3. For the new components for automated driving functions, the scenario characteristics introduce different market shares in scenarios 1 (100% inputs to German automated vehicle sales, thus same market share as German OEMs) and 2 (0% input to German automated vehicle sales). The domestic input share of the NACE industries 26 (electronics / new hardware) and 62/63 (software) to the automotive industry (NACE 29) (see Table 17) is currently (IOT 2019) at 35% domestic input to the automotive industry from the electronics industry and at 87% domestic input to the automotive industry from the software industry (Statistisches Bundesamt 2022). Comparing the assumption in scenario 1 to the current share of domestic inputs form the two named industries illustrates that the high level of ambition in the translation of the scenario characteristic. The sensitivities *A1_A2_sens_new_components_import* and *B1_B2_sens_new_components_import* assess the effect that these lower domestic shares from the IOT 2019 for new components of automated vehicles technology could have in the industry positioning scenario 1 (see Table 19).

Next to the possible overestimation of the suppliers' revenue from sales to German OEMs in scenario 1, the current implementation neglects sale of vehicle parts of German suppliers to other OEMs. Especially abroad. This probably underestimates the revenue of German suppliers from new components for autonomous vehicles in industry positioning scenario 1. The neglected effect is considered to be especially large in market framework scenario A, where autonomous vehicles reach higher market shares. In sensitivity *A1_A2_sens_new_components_export* it is assumed that German new component suppliers export parts besides their intermediates to German cars in scenario A-1. A revenue increase of 50% from software and new hardware components in scenario A-1 is considered.

Mobility services

Autonomous mobility services are intensively discussed and studied, however, future the market size and prices of autonomous mobility services remain uncertain. The assumed price of 0.25 € in all scenarios lies in middle field of several studies' estimations (Krail et al. 2019; Narayanan et al. 2020). Compared to vehicle sales, the revenue potential of mobility services is small. Therefore, only to sensitivities are introduced explicitly that allow for the assessment of higher prices, while it is acknowledged that prices could also decrease. For the market framework scenario A, the estimated price of 0.37€ per kilometer, suggested by Bösch et al. (2018) (0.41CHF individual autonomous taxi, 0.9005 €/CHF average exchange rate in 2017 (exchange-rates.org 2017)) is considered. In addition to that, the share of German firms in the provision of mobility services is increased. In scenario A, the coexistence of privately owned and shares autonomous vehicles is assumed. It might be unlikely that in such an environment, the German industry does not offer any mobility services at all as suggested in scenario A-2. At the same time, the share of 31% in mobility services in scenario A-1 might be low. Therefore, the share in the provision of mobility services in scenario A-2 is set at the 31% market share in the original A-1 scenario. In scenario A-1, it is assumed that robotaxi services in Germany are fully provided by the German industry, equaling 75% market share. Sensitivity *A1_A2_sens_mobility_service_increase_price_share* thus combines the mentioned higher price of 0.37€ per km, 75% market share in scenario A-1 and 31% market share in scenario A-2 (see Table 19).

For the market scenario B, an even higher price of 0.50€ per kilometer (double the initial price) is introduced, due to the higher cost of autonomous vehicle technology. The sensitivity is called *B1_B2_sens_mobility_service_increase_price* (see Table 19). The increase in prices has the same effects in the quantitative simulation as an increase in the assumed usage of mobility services or the market share of the German industry. The chosen perspective on the German industry considered only the activities of industrial players. Other (public) firms or organizations, such as domestic public transport firms, are not included in the analysis. These firms could provide mobility services in autonomous shuttles or robotaxis, which would positively affect German value added and employment. The effects on the German industry are limited to the activities of industrial players.

Table 19: Overview of chosen sensitivities and their implementation

Sensitivity name	Implementation
A1_A2_sens_revenue_boost	**A-1:** Higher revenue (+10%) from domestic market
A1_A2_sens_export_global_saturation	**Framework scenario A:** Export potential does not grow by 1% per year, but remain constant at 3.48 million vehicles between 2019 and 2050
B1_B2_sens_European_export_boost	**B-1:** Higher revenue (+10%) from European exports
A1_A2_sens_new_components_export	**A-1:** German new component suppliers export parts besides their intermediates to German cars, revenue from software and new hardware components +50%
A1_A2_sens_new_components_import *B1_B2_sens_new_components_import*	**Industry positioning scenario 1:** German OEMs import software and new hardware components (87% domestic software instead of 100%, 35% domestic new hardware instead of 100%) for both, vehicles for domestic supply and exports
A1_A2_sens_mobility_service_ increase_price_share	**Framework scenario A:** Higher price of 0.37 € per km (instead of 0.25 €) in framework scenario A **A-1 and A-2:** Higher share of German automotive industry in provision of autonomous mobility services: 75% in A-1, 31% in A-2
B1_B2_sens_mobility_service_ increase_price	**Framework scenario B:** Higher price of 0.5 € per km (instead of 0.25 €)

Source: Own representation

8.2 Results

The macroeconomic simulation with ISI-Macro aims at a better understanding of how different modes of engagement of the German industry in a given global market development may influence the economic situation in Germany until 2050. Therefore, the deviation between the different modes of German engagement in a given market framework condition is studied. This means, given one alternative of the market framework condition scenarios, the industrial positioning scenario "successful digital modernization" is compared to the "bumpy adaptation to autonomous mobility" in Germany. In terms of the scenario definitions, scenario A-1 is compared to A-2, while B-1 is compared to B-2. In the figures, A1_A2 indicates the deviation between the industry's engagement in the high autonomous driving framework, B1_B2 presents the difference in the moderate automation scenario.

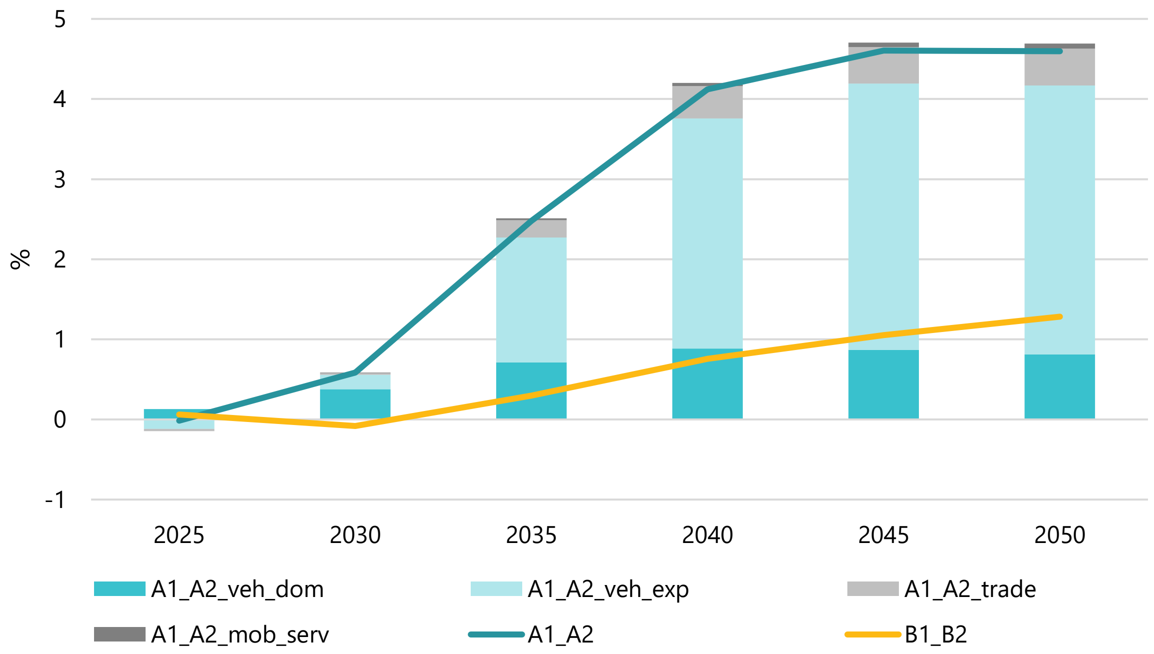
The aggregate effects from the deviation between A-1 and A-2 as well as B-1 and B-2 on German GDP and employment are displayed in section 8.2.1. Section 8.2.2 shows the detailed effects on individual industries in terms of GVA and employment. The perspective on industries allows to discuss the structural effects on the economy. The results on the sensitivity simulations, introduced in the preceding section, are assessed in section 8.2.3.

8.2.1 Overall effects on GDP and employment

The deviation between a different positioning of the German industry can, according to the simulation, amount to 4.6% in GDP in 2045. Figure 48 shows the relative deviation in GDP in A-1 versus A-2 and B-1 versus B-2 between 2025 and 2050. The deviation is much larger in the comparison of A-1 and A-2, as it would be expected by the much larger difference in impulses. Scenario A-1 profits from positive developments in exports, while at the same time the decline in revenue from vehicle sales in scenario A-2 is relatively larger compared to the development in scenario B-2 (see Table 18). The effect goes up 4.5% difference in GDP in 2045. The difference in GDP between B-1 and B-2 only yields 1.3% in 2050. Regarding both market framework scenarios, the difference between the industry's positioning grows in course of time. The negative deviation in 2030 in the comparison of B-1 to B-2 can be explained by the increasing exports of premium vehicles in B-2 (see section 8.1.2.4). The focus on premium vehicles pays off in the early years of the simulation, when the market for fully autonomous vehicles is not yet developed. In general, the successful focus on all automation levels of the German industry suggests higher economic prosperity. This effect is much stronger in a globalized and autonomous world, compared to a more restricted and less autonomous world.

In order to better understand the large differences between scenarios A-1 and A-2, the effect is split up in its components. *A1_A2_veh_dom* contains only the effect resulting from the production for the domestic market, while *A1_A2_veh_exp* displays the effect from the different realization of export potentials. *A1_A2_trade* shows the effects in wholesale, while *A1_A2_mob_serv* maps the effect from the engagement in mobility services in scenario A-1 versus no engagement in scenario A-2. The sum of the individual effects does not match the aggregated effect, when considering all impulses at once. This is due to the circular logic of the model that includes induced effects in the economy that rely on the overall growth of the economy.

Figure 48: GDP - relative deviation A-1 vs. A-2 and B-1 vs. B-2 (2025-2050)

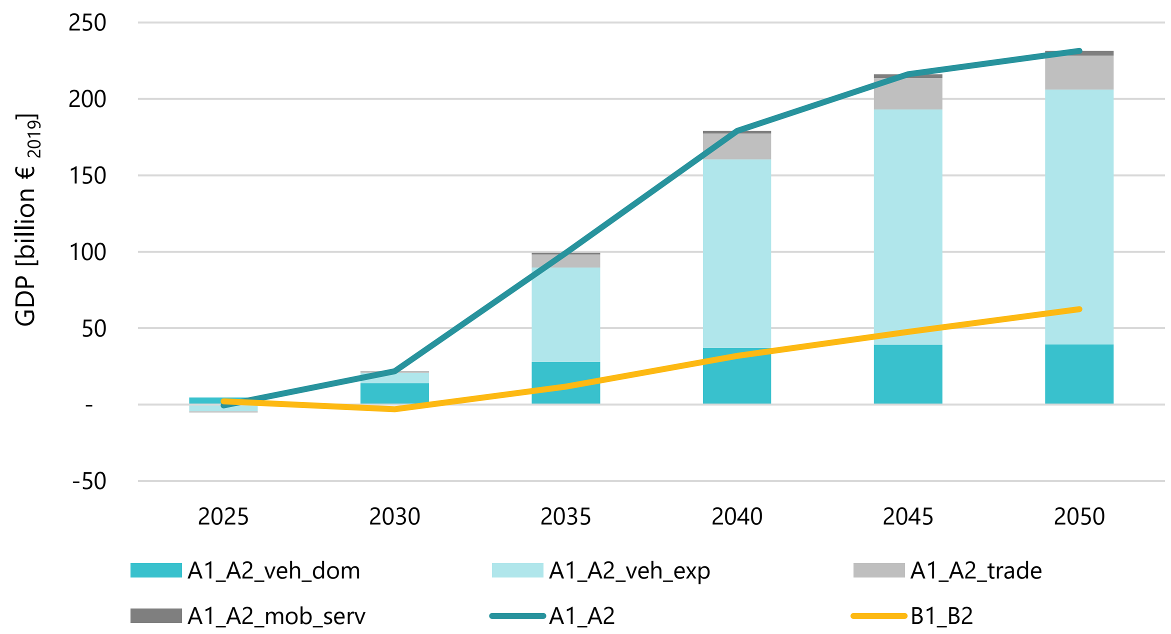


Source: Own calculations, ISI-Macro

The stacked columns clearly indicate the high reliance of the development of the GDP on the exports of vehicles from Germany. Around 3.3% of 4.5% deviation between the two scenarios in 2045 can be explained only by the difference in exports. The production of vehicles for the domestic market accounts for 0.9%, the trade of vehicles for 0.5%. The difference in the engagement of the industry in mobility services (A-1: 31% market share, A-2: 0% market share) accounts for less than 0.1% of the deviation in GDP. The higher realization of the potential profit pool from the sale of vehicles in A-1 heavily dominates the effects in the comparison to A-2.

Figure 49 displays the absolute deviation in GDP between the two scenario pairs. The figure resembles Figure 48 but shows another increase in absolute positive deviations between 2045 and 2050 which differs to the relative effect. The absolute increase is smaller than the underlying GDP growth, implemented in the model, which leads to the slight decline in the relative GDP effect. In absolute numbers, the deviation between scenarios A-1 and A-2 sums up to 216 billion € in 2045 or 231 billion € in 2050. The deviation between the two industry positioning scenarios in the protectionist world with slower automation adds up to 62 billion € in 2050.

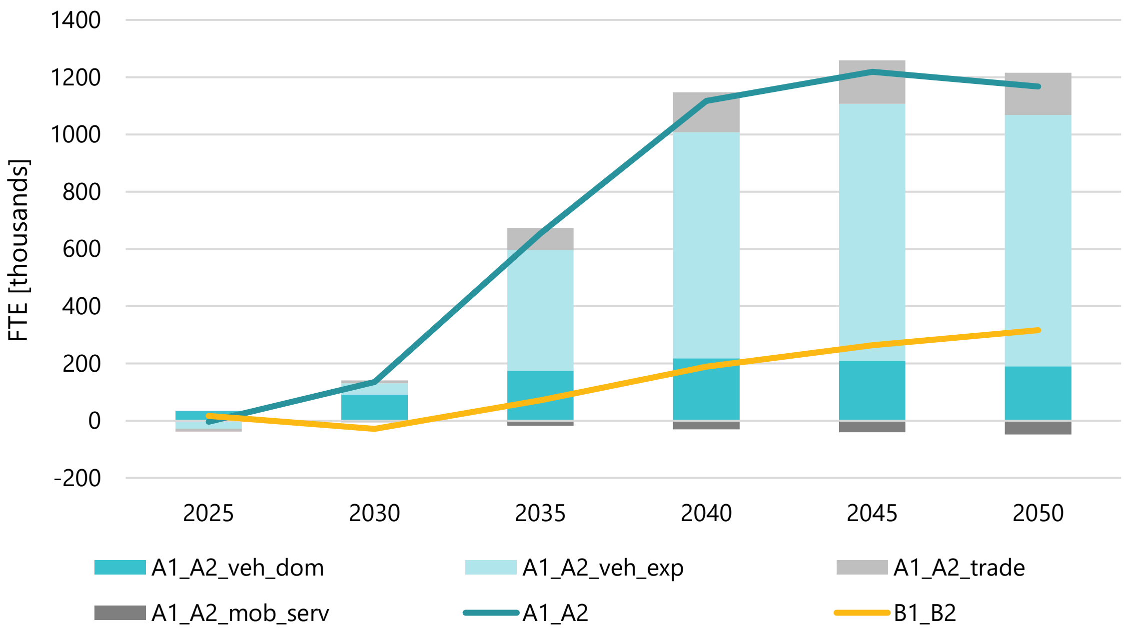
Figure 49: GDP - absolute deviation A-1 vs. A-2 and B-1 vs. B-2 (2025-2050)



Source: Own calculations, ISI-Macro

Figure 50 shows the absolute deviation between scenarios A-1 and A-2 and scenarios B-1 and B-2 in terms of labor demand. Labor demand is indicated by full time equivalents (FTE). The display is similar to the figure on the relative deviation in GDP and also contains the disaggregated effects between A-1 and A-2. The deviation in labor demand is the largest between scenarios A-1 and A-2 in 2045 with 1.2 million FTE. A slight decrease in the deviation of labor demand is observable between 2045 and 2050. The negative deviation between A-1 and A-2 regarding to mobility services can be explained by the underlying development of labor productivity. The small positive impulse of mobility services alone is overcompensated by the declining workforce, implemented in the model, due to increasing productivity per person or FTE. The deviation between B-1 and B-2 is largest in 2050, showing a difference of 316 000 FTE.

Figure 50: Labor demand in FTE - absolute deviation A-1 vs. A-2 and B-1 vs. B-2 (2025-2050)



Source: Own calculations, ISI-Macro

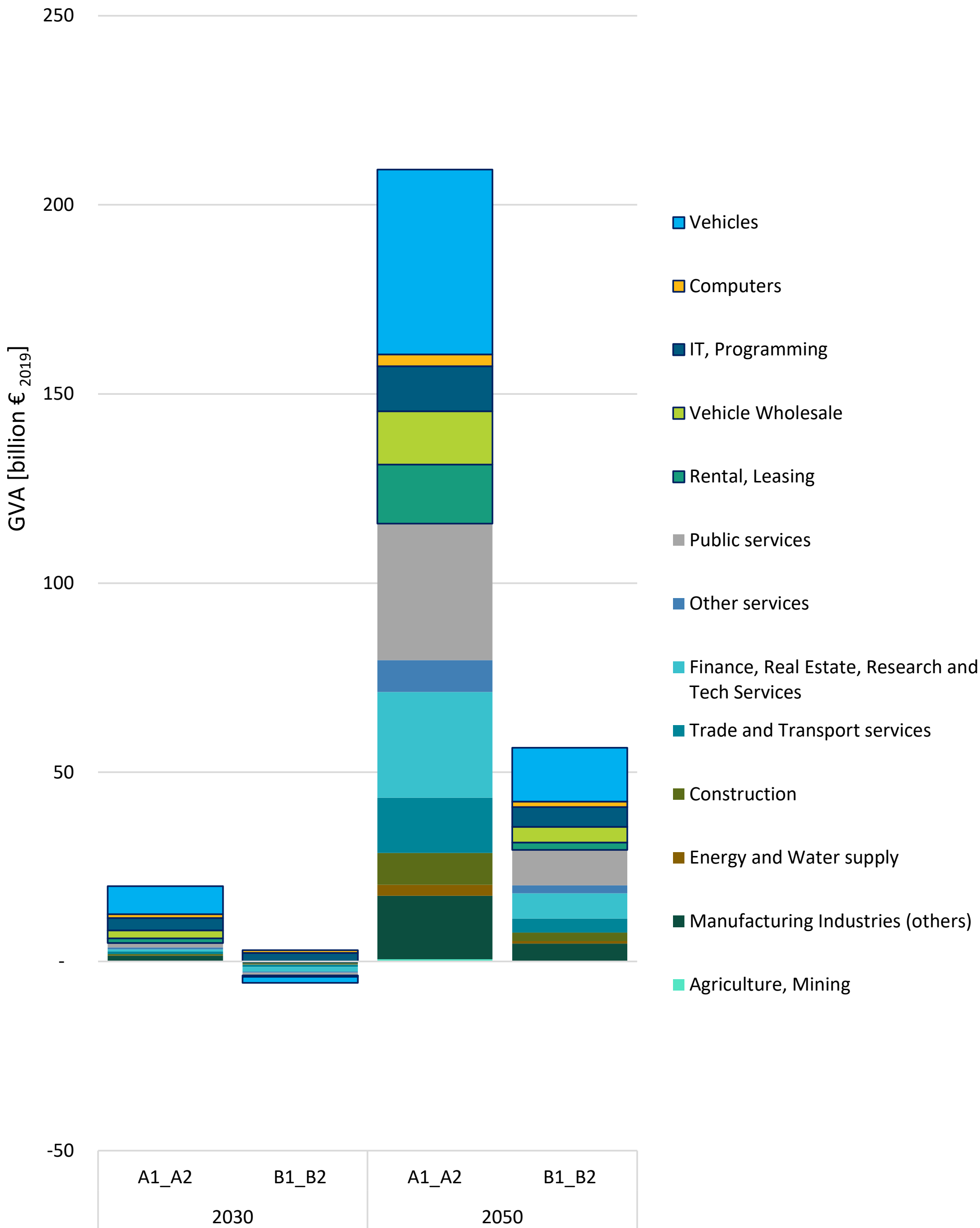
8.2.2 Detailed effects on industries

In order to better understand the effects on the German economy, the following results assess the effects of the scenarios more precisely on the industry level. Figure 51 and Figure 52 show the absolute deviation between the scenarios in terms of GVA and employment by industry, respectively. The industries, distinguished in the IOT are clustered into 13 industry groups for better clarity of the figure. Detailed information on the aggregation can be found in Annex Table A 9. The top five parts of the stacked columns, framed in black, represent the single industries that are directly affected by the impulses (see Table 17), namely the

- Manufacture of motor vehicles, trailers and semi-trailers (NACE 29), included in "Vehicles"
- Manufacture of computer, electronic and optical products (NACE 26), included in "Computers, Electronics"
- Computer programming, consultancy and related activities (NACE 62) and computing infrastructure, data processing, hosting and other information service activities (NACE 63), included in "IT, programming"
- Wholesale of motor vehicles, motorcycles and related parts and accessories (NACE 45), included in "Wholesale, Retail"
- Rental and leasing activities (NACE 77), included in "Other economic services (incl. Rental)"

Other effects result indirectly from the provision of intermediates or are induced by the large positive deviation in GDP. The figures display the deviation between A-1 and A-2 and between scenarios B-1 and B-2 for the two years 2030 and 2050. It should be noted that other industry groups partly contain a large number of industries such as the "manufacturing industries (others)", which contains 20 of 72 industries or "public services", which contains 11 of 72 industries.

Figure 51: GVA per industry - absolute deviation A-1 vs. A-2 and B-1 vs. B-2 (2030, 2050)



Source: Own calculations, ISI-Macro

In line with the overall effects on the German GDP, described in the previous section, Figure 51 shows much larger effects in 2050 than in 2030. In terms of GVA, the directly affected industries, which can also be affected indirectly and by induced effects, account for more than half of the overall effect on GVA for both scenario pairs. The deviation between scenarios A-1 and A-2 adds up to 210 billion € in 2050, the deviation between scenarios B-1 and B-2 adds up to 56 billion €. The difference between the sum of GVA in all sectors and the GDP includes product taxes minus product subsidies.

The structure of the affected industries is roughly similar, when comparing the deviations between the different industry positioning alternatives in the two market framework scenarios in 2050. In the less autonomous and protectionist market framework scenario B, the sum of effects in the directly affected industries is slightly larger (48% of total deviation) compared to the autonomous and globalized market framework scenario A (45% of total deviation). The deviation in aggregated GDP between A-1 and A-2 is larger compared to the deviation between B-1 and B-2. Therefore, larger induced effects are expected, which affect the overall economy in the comparison of A-1 and A-2 and can explain the slightly smaller share of the directly affected industries (45% of total deviation) in relation to the overall effect in GVA.

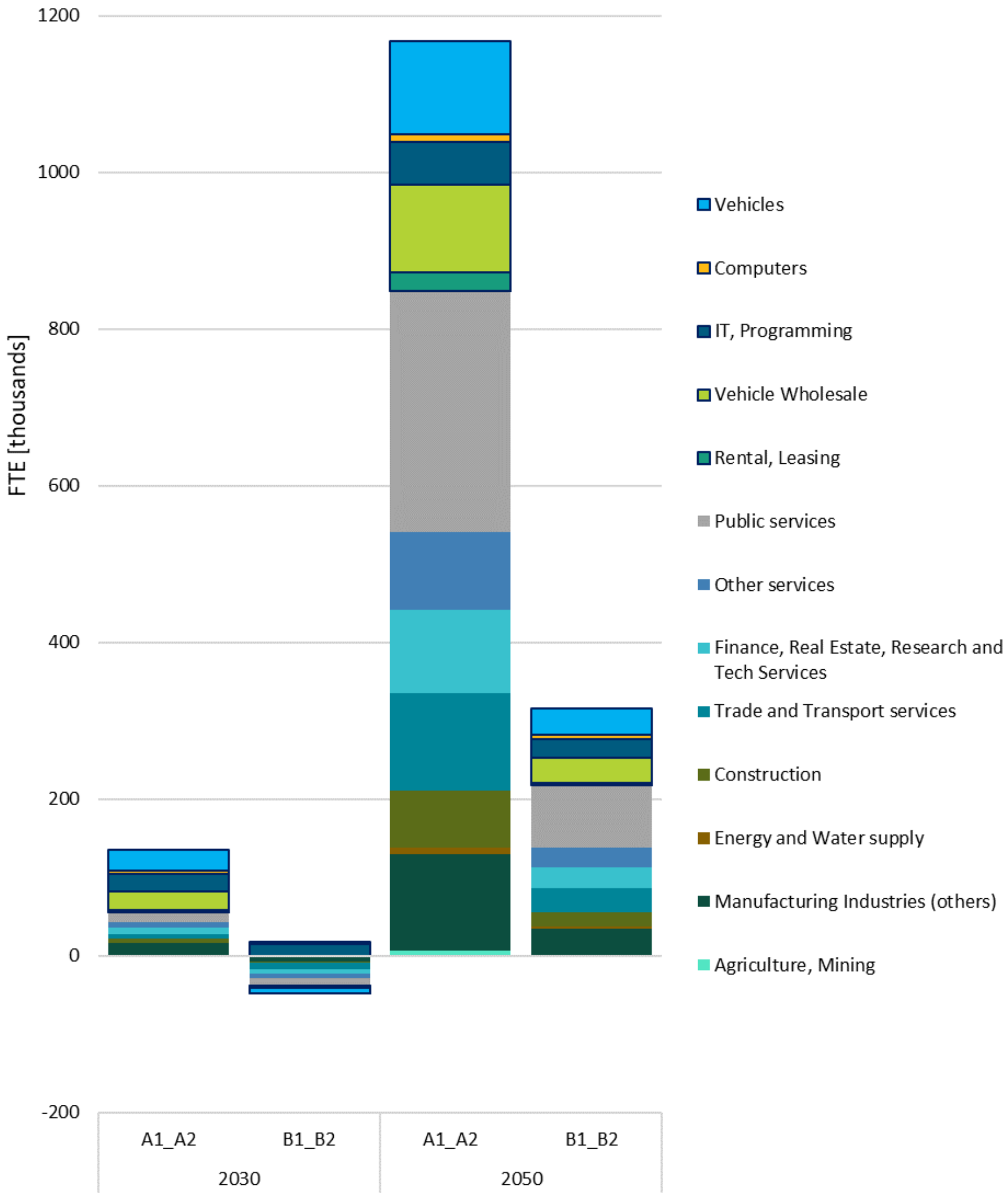
The production of vehicles itself represents about 23% (49 billion €) of the total difference in GVA between A-1 and A-2 and about 25% (14 billion €) of the total difference in GVA between B-1 and B-2 in 2050. The computer and electronics industry show the smallest effects regarding both scenario pairs. The effects in the rental and leasing industry vary the most between the two market framework scenarios. The deviation in the rental and leasing industry between scenario A-1 and A-2 accounts for a bit more than 7% of the total effect on GVA, while the deviation between scenarios B-1 and B-1 only reaches a bit more than 3%. The comparably strong effect can be explained by the large difference in the revenue from mobility services that is relatively larger than the differences in vehicle sales (see Table 18).

The industry groups of public services as well as finance, real estate, research and tech services show large effects while not being directly affected by the impulses. Especially effects in public services arise from the large deviation in the economic activity in general.

The display of the effects on labor demand per industry in Figure 52 roughly resemble the effects on GVA. However, the shares of individual industries differs due to varying employment intensities in affected sectors (how much employment per € production output). This explains for example the much larger effects in employment in public services, wholesale or other services. In general, service industries are more labor intensive than manufacturing industries. The total effects in labor demand equal the effects described in section Figure 50.

In terms of labor demand, the directly affected industries only account for 27% (317 600 FTE) of the total deviation between A-1 and A-2 in 2050 and 31% (98 500 FTE) of the total deviation between B-1 and B-2. The effects in the vehicle wholesale industry are much larger, compared to the effects in GVA and are close to the effects in the vehicle manufacturing industry itself (around 10%-11% in both market framework scenarios A and B).

Figure 52: Labor demand per industry - absolute deviation A1 vs. A2 and B1 vs. B2 (2030, 2050)



Source: Own calculations, ISI-Macro

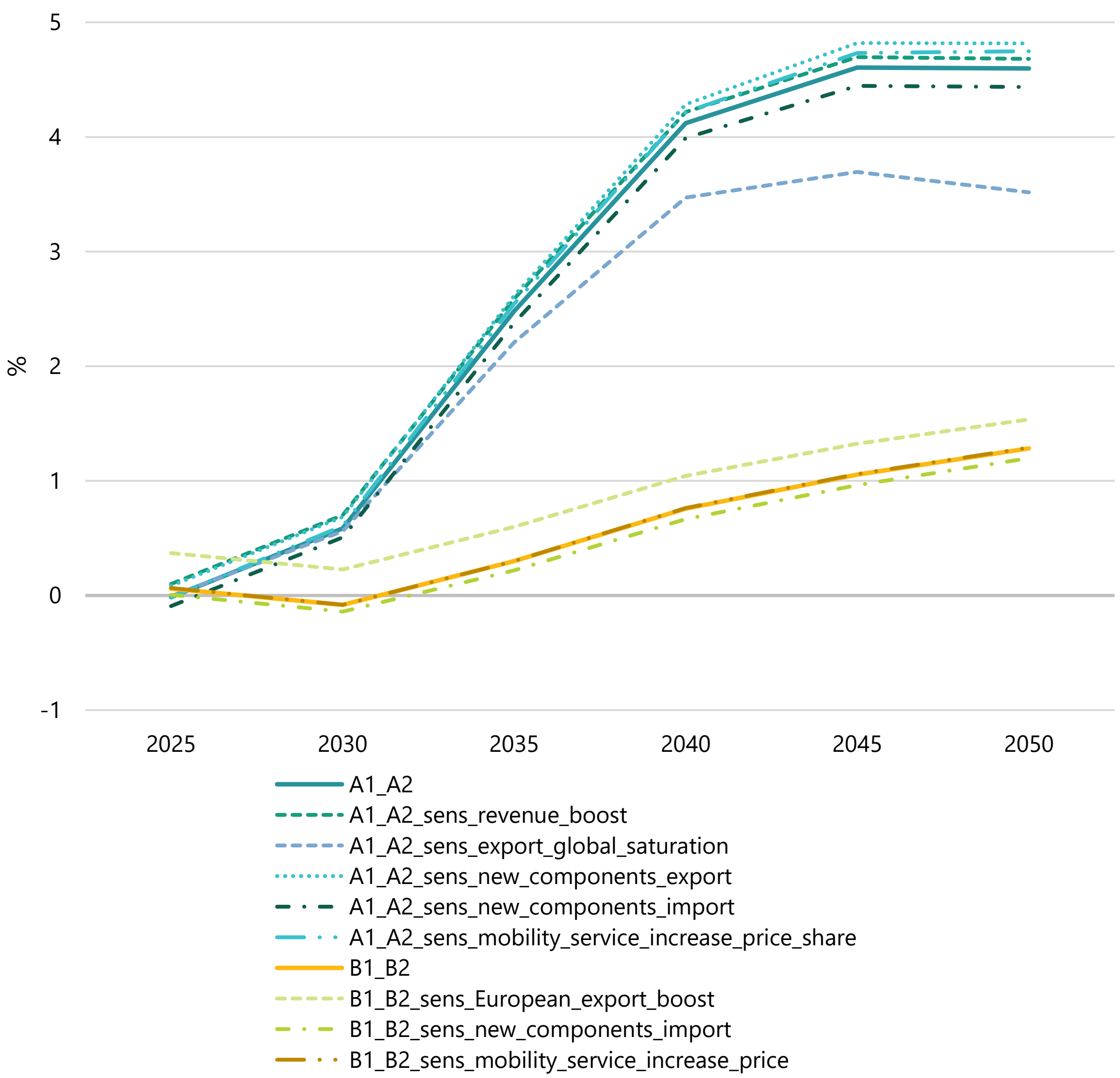
Indirect and induced effects on labor demand are much larger compared to the indirect and induced effects on GVA. Especially the service industries are strongly affected. The large deviation in industries, seemingly unrelated to the vehicle industry, illustrates the importance of considering indirect and induced effects in the economic assessment of large shifts in important industries to a national economy.

8.2.3 Sensitivity analysis

In order to gain a better understanding of the dependency of above described effects on the assumptions, made in scenarios A-1, A-2, B-1, and B-2, some sensitivities are assessed. The characteristics of the sensitivities are described in section 8.1.2.5. It is referred to Table 19 for an overview of the sensitivities and their implementation.

Figure 53 displays the development of relative GDP for the two scenario pairs in their basic configuration and the sensitivities. The two solid lines in turquoise and yellow show the deviation between A-1 and A-2, and B-1 and B-2 for comparison. All sensitivities of A-1 and A-2 are displayed in turquoise and blue shades. All sensitivities of B-1 and B-2 are displayed in yellow and green shades. Different line types are used for the sensitivities besides the different colors for better clarity. It stands out that all sensitivities range closely around their respective basic configurations. Between *A1_A2_sens_export_global_saturation* and *B1_B2_sens_European_export_boost*, the two most extreme sensitivities in the negative and positive sense, the difference is around 2% GDP in 2050.

Figure 53: GDP – relative deviation sensitivities A-1 vs. A-2 and B-1 vs. B-2 (2025-2050)



Source: Own calculations, ISI-Macro

A1_A2_sens_export_global_saturation shows the largest deviation in GDP effect from the basic configurations of A-1 and A-2. As mentioned in section 8.2.1, exports are the largest driver of the GDP effects, thus it is expectable that the GDP effects are most volatile to sensitivities, shifting export volumes. The sensitivity *A1_A2_sens_new_components_export*, allowing for the exports of new components by suppliers, marks the highest deviation between A-1 and A-2. Also, the effects of higher import shares in new components, as described by sensitivity *A1_A2_sens_new_components_import*, are comparably strong and are 0.25% lower than the basic deviation. Absolutely, this negative effect is also larger than the positive effect of the domestic revenue boost in *A1_A2_sens_revenue_boost*, which only accounts for about 0.1% more deviation in GDP. Also, the effect of higher prices in mobility services and a slightly larger difference in the market share between A-1 and A-2 exceeds the effects of a 10% increase in domestic vehicle revenue (see sensitivity *A1_A2_sens_mobility_service_increase_price_share)*.

In comparison to the basic configuration of B-1 and B-2, it is also the trade-related sensitivities that show the largest variations. *B1_B2_sens_export_boost*, which allows for 10% higher exports to the European market each year in a protectionist world, presents an almost parallel upward shift of GDP development. Similar to the sensitivity affecting component imports in A-1, sensitivity *B1_B2_sens_new_components_import* leads to lower deviation between B-1 and B-2. The sensitivity introducing the double price for mobility services, *B1_B2_sens_mobility_service_increase_price*, show almost similar effects compared to the basic configuration of B-1 and B-2.

Overall, the development paths still resemble the basic configurations and show the moderate effect variations in individual scenario characteristics have on the overall GDP effects. In all cases, changes in the export or import volumes have the largest effects.

8.3 Summary and discussion

The macroeconomic simulation in ISI-Macro compares the economic effects between the realization of one of the two industry positioning alternatives (scenarios 1 and 2) in a given market framework. The deviation between scenarios A-1 and A-2 compares the implications in a more ambitious autonomous driving market and a globalized world, while the deviation between scenarios B-1 and B-2 assesses the potential difference that results from the two industry positioning alternatives in a less ambitious autonomous driving market and protectionist world. The results of the simulation show that the different industrial strategies imply a much larger deviation in terms of GDP, GVA and labor demand in a world that develops according to market framework A. In market framework B, where automation diffuses slower and foreign trade is on a lower level, the difference in economic indicators is smaller when comparing the two potential industrial strategies. The results quantitatively substantiate the logical conclusion that the industrial strategy of German with regard to autonomous driving is more crucial in a world that drives autonomously and trades internationally.

8.3.1 Discussion of results and implications

The results can be put in relation by comparing them to the current role of the automotive industry in Germany. In 2019, around 820 000 people were directly employed in the automotive industry. In addition, around the same amount are considered to be employed in the production of intermediate products and services (Statistisches Bundesamt 2019a). This adds up to at least around 1.6 million employees in Germany (4%), related to the automotive industry.

The German automotive industry accounted for around 4% of German GDP in 2019 (Statistisches Bundesamt 2023b). GVA in the automotive industry was 136.61 billion € in 2019. This means, the overall deviation in GVA between scenarios A-1 and A-2 of 210 billion € in 2050 are larger than the total contribution of the German automotive industry to GDP in 2019. However, the deviation in

GVA in the analysis here include not only the effects in the automotive industry itself but indirect effects and induced effects in other industries. The deviation in the vehicle manufacturing industry alone accounts for around 49 billion € in 2050 (see Figure 51).

In scenario A-1 in 2050, around 1.87 million vehicles are produced for the domestic market and 5.11 million for exports, adding up to around 6.98 million vehicles that are produced in Germany. In scenario A-2 in 2050, only around 1.04 million vehicles are produced for the domestic market and 2 million for exports, adding up to only 3.04 million vehicles that are produced in Germany. The difference in German vehicle production is thus almost 4 million passenger vehicles. In 2019, the domestic production of passenger vehicles in Germany was 4.66 million vehicles. Hence, the difference in the absolute number of vehicles between scenario A-1 and A-2 corresponds to 85% of total production in 2019. While 85% of 820 000 directly employed persons in the automotive industry equal 700 000 employees, the deviation between A-1 and A-2 in terms of labor demand only adds up to 118 200 FTE (see Figure 52). The seeming understatement of the effect on the vehicle industry partly results from the research focus in the thesis. Within the scenarios, the focus is on passenger vehicles only, while the German production of vehicles includes other vehicles such as trucks, too. Furthermore, as indicated in section 8.1.2.5, the production of vehicle parts plays a large role and is not considered in detail in the thesis.

The analysis of several sensitivities illustrates the high dependency of the German economy on foreign trade, especially vehicle exports. The variation of single indicators in the scenario definitions result in GDP development pathways that are close to their respective basic configuration. The deviation in GDP between variants of scenarios A-1 and A-2 is at a maximum of 4.75% in 2045. The minimum deviation, implicated by the sensitivities, reaches 3.70% in 2045. The deviation between variants of scenarios B-1 and B-2 reaches its highest point in 2050 at 1.54%, where the minimum deviation is at 1.20%.

8.3.2 Critical assessment of the modelling approach

The quantitative results help to gain a better understanding of the scale of possible economic effects and their distribution across industries, which are implicated by the scenarios. However, the quantitative assessment has to be understood as an approximation of effects rather than a concrete projection due to the simplified economic dynamics in a simulation model and the many uncertainties in the estimation of the development of global automotive markets.

As already mentioned in the description of the macroeconomic simulation model ISI-Macro in section 3.2.3, the used model has some weaknesses. The model takes on a demand perspective by neglecting limiting production factors. Demand-led models tend to provide more positive results compared to supply-led models (Mercure et al. 2019). The positive deviation between scenarios A-1 and A-2 should thus be understood as an economic potential that has to be fulfilled. Especially the required labor demand has to be met in order to realize such economic potential. In a world facing labor shortages, as described in section 5.5.2, the supply of the required workforce can present a limiting factor to economic success. Also, the aim of the model-based assessment of macroeconomic effects was to compare the potential influence of different industrial strategies of the German automotive industry on economic indicators until 2050. The deviation between two industrial strategies was assessed within two different market framework environments. In this setting, where only the shares of the domestic industry are varied between the compared scenarios, counter financing of investments in vehicles could be neglected. In other scenario settings and depending on the economic perspective, the modelling approach might need to be adapted. Furthermore, it is left to future research to assess price effects.

A general issue in using input-output analysis approaches is the assumption of homogenous goods in the IOT. While products in the automotive industry, for instance, vary in terms of their composition of intermediate goods, the industry "Manufacture of motor vehicles, trailers and semi-trailers" (NACE 29) considers an average input structure for all produced goods. Within the thesis, this issue is partly accounted for by assigning new components for autonomous driving directly to the IT and computer industries. These industries have a different input structure compared to the average automotive good and are expected to better fit the components' intermediates, according to the final demand approach as suggested by in Miller and Blair (2009). Within the model ISI-Macro, the input-structure is held constant at the initial structure for each year until 2050, which presents another shortcoming of the modeling approach. Prospective changes in the input-structure, for instance the developing electrification of the powertrain which implies increasing shares of intermediate inputs from industries such as electronics, are not considered. These parallel developments in the automotive industry have already been left out in the formulation of the scenarios. The detailed results on the industry group level probably underestimate the share of industries providing the components for the electrified powertrain. In addition to that, increasing digitization will probably affect other industries and their inputs, too. Future research could refine the analysis by developing dynamic input-structures that account for parallel trends in the automotive industry such as the electrification or circular economy measures as well as changes in the overall structure of the economy.

In the derivation of the quantitative impulses, a simplified perspective on the German economy is chosen that sets the production of German firms in Germany equal to the total production in Germany. The potential installation of production sites by foreign firms in Germany has not been assessed. The effect on the German economy in terms of the studied indicators GDP, GVA, labor demand is in large parts independent from the national roots of a firms. While for instance an increasing role of contract manufacturing has been considered a threat to German OEMs, it does not necessarily have negative effects on the German economy, if the production sites are located in Germany. The same argument can be made concerning subsidiaries of international ICT firms, which would also generate labor demand and value added in Germany. Other factors, such as working conditions, including the establishments of labor unions could, however, still make a difference.

In general, the implications of individual firms' decisions for other firms have not been studied in detail. Regional cluster effects can reinforce certain development tendencies in both, the positive and negative direction. If an OEM or large supplier shifts its production site or builds up a new one, upstream suppliers tend to follow. From a German perspective, this might intensify the effects of individual firm decisions in both directions (a new OEM production site might draw the build of suppliers in the region, the decision to move a production site abroad in turn might lead to suppliers following).

Furthermore, in the design of the quantitative impulses, the level of production volumes and service offerings is set independently from the individual firm and business perspective. However, a linear up- or downscaling of production volumes is not necessarily possible, for example in case of a rather unsuccessful automotive industry in Germany that might reduce the number of shifts or even closes production sites, which could lead to a drop rather than a steady decline in production capacities.

The influence of the power distribution in value chains and the distribution of margins is also not depicted in the macroeconomic assessment and is hard to estimate on basis of the current state in development of autonomous vehicles. This issue can relate to a potential shift in the type of relationship between actors from the automotive and ICT sectors as described in section 6.1. For instance, robotaxi services are currently carried out in pilot projects and might develop into an important transport mode in autonomous mobility systems. Currently, pilot projects are often carried out as joint projects by a few firms with complementary competencies. The sales platform, the vehicle and the autonomous driving technology are partly provided by different firms that collaborate for the individual projects. Cooperation for knowledge combination on a level playing field appears to be an important mode in the development phase. The type of relationship that characterizes the future provision of robotaxi services on a large scale can determine the split of revenues from the service among the providers. If ICT firms as platform providers become the new lead firms in the provision of future mobility and they implement an integrative relationship towards their suppliers, automotive manufacturers might degrade to being such suppliers. That could have large effects on their margins. In the simulation, however, the role of margins is not assessed explicitly, but margins are calculated endogenously in the model, according to the IOT.

Several issues regarding the diffusion of autonomous driving and the implementation of autonomous vehicle technology are also not considered in detail in the derivation of automation levels. As mentioned in the introduction of section 8.1.2, this would require the application of an integrated transport system model, which is beyond the scope of the thesis. One central assumption, which is made in the estimation of exports, is the equal diffusion of autonomous driving technology in different global markets. The assumption is based on the past development of passenger vehicle markets that has shown rather similar developments, despite smaller differences such as demand for certain vehicle sizes. With autonomous vehicles that could possibly change. Regulations on autonomous driving and on the design or security standards of autonomous vehicle technology may differ between markets (see section 5.3.2). Also, the acceptance for the technology in general as well as different forms of the implementation of autonomous driving could vary (see section 5.4.5). In increasingly fragmented markets, where for instance a non-autonomous vehicle model cannot be combined with autonomous technology, standardized production principles could come under pressure.

While the automotive vehicle market for individual transportation has so far been quiet clearly distinguished from the public transport market, these borders become increasingly blurry when autonomous mobility services are introduced. The role of public transport firms and their implications for the German economy has not been considered in detail throughout the thesis. Autonomous shuttles are shortly discussed in sections 5.1.3 and 5.4.2. The analysis suggests that automotive firms are not active in the development or provision of autonomous shuttles, but it is rather startups or firms from the field of production and logistics automation that focus on that type of vehicles. Shifts towards non-cars but other vehicle types could negatively affect the German automotive industry, if they become a primary mode of transportation (Knie et al. 2019). The entailed impact on the German economy as a whole has not been assessed in the macroeconomic simulation, where the focus was on the German automotive and new ICT industry.

9 Summary and conclusions

9.1 Summary of the results

In the thesis, the current and future roles of the automotive industry in the development and provision of autonomous driving were assessed from an innovation system perspective. The focus was on the interplay between the broader automotive and ICT sectoral systems in the innovation system of autonomous driving. Based on the findings, scenarios for the German industry in the context of the global autonomous driving market were derived. In a final step, the economic implications from the key characteristics of four scenarios were simulated until 2050, using the macroeconomic simulation model ISI-Macro.

In the first part, an integrated innovation system approach was developed, which allows for an in-depth analysis of autonomous driving development by combining perspectives from sectoral systems of innovation (SSI), national systems of innovation (NSI) and technological innovation systems (TIS). Each of the viewpoints has its strengths in explaining transformation in sectors, the national context or with regard to technologies. The integrated innovation system analysis starts with an assessment of the two participating sectoral systems' (automotive and ICT) key characteristics, their products, services and strategies, as well as their production networks and value chains (research question 1). With the latter, the roles of international markets and production locations were introduced. The background knowledge on the sectors' functioning as well as the identification of Germany, USA, and China as key players in the automotive and ICT sphere builds the base for the functional innovation system analysis of autonomous driving along the TIS functions. Within the functional analysis, the selection of the indicators was oriented towards their ability to distinguish between the participation and the roles of the considered sectors and regions (research question 2). The analysis of the current state of autonomous driving development was complemented with an analysis of the interactions between the sectors in order to derive implications on the potential reconfiguration of value chains. The evolving persistent relationships between the automotive and ICT sectors are considered to shape the implementation of autonomous driving and thus the role of the sectors along the future value chain. The integrated innovation systems analysis of the current status and potential future development of autonomous driving provides insights to patterns and structures of the evolving system and allows the derivation of key aspects in the transformation of value chains (research question 3).

The explicit consideration of how sectors and regions participate in the autonomous driving innovation system showed many differences along sectoral and national borders. This finding points out the high relevance of contextual factors in the functioning of innovation systems and confirms that their consideration is relevant for an in-depth understanding of innovation systems. The key characteristics of the automotive and ICT sectors, specifically the embedded sectoral know-how of the two sectors, already indicates the partly complementary engagement of the different actors (research questions 1 and 2). Traditionally, the automotive sector is vehicle- or, more broadly, product-oriented but has been introducing new and service-oriented business models. This is reflected in the participation of the automotive sector in the development of autonomous vehicle technology components and the provision of full autonomous vehicle systems. The ICT sector is more orientated towards the development of platforms and surrounding services. New autonomous driving firms, backed by both actors from the automotive sector and the ICT sector, focus on the development of autonomous driving technology. The overlap between the two sectors is thus not so much in the provision of the autonomous vehicle as a whole, but in some autonomous vehicle technology components. The interactions between the sectoral systems are found to be diverse (cooperation, competition, integration, spill-over) and to change over time. The three analyzed countries Germany, USA and China participate actively in the development of autonomous driving. Partly different foci are found (research question 2). The automotive country Germany ranks high with regard to assisted and autonomous driving technology patents over the past 15 years. The USA and China have increased their patenting activity recently, especially the USA with regard to patents targeting the full concept of autonomous vehicles. The USA and China lead in new firm foundations and the implementation of pilot robotaxi services, where mostly domestic firms engage. However, the implementation of testing and pilot projects appears feasible in all analyzed countries.

Through the integrated innovation system analysis, five central factors were identified that influence the potential reconfiguration of value chains and the division of tasks between the automotive and the ICT sectors (research question 3). First, the degree of servitization in the autonomous mobility market determines the degree to which established, product-oriented business models of the automotive sector may have to be adapted. Second, varying acceptance among customers and different forms of autonomous driving implementation can induce a fragmentation of global markets. Third, the technological development speed and achievements in the further testing of autonomous vehicles will determine feasible degrees of automation, which will in turn influence the modes of implementation. Fourth, the persistent relationships between industrial players will determine the roles that firms play in the future value chain. Lastly, the relationship within value chains is also dependent on the success of individual firms, which determines their power in actively forming the future value chain. This success is dependent on the ability to attract capital and human workforce.

The development of autonomous driving requires competencies from both sectors and while players aim at expanding their knowledge in new fields, inter-sectoral dependencies and cooperation persist. Currently, the complete servitization of the mobility market seems unlikely, which might lead to the coexistence of lead firms from the automotive and ICT sectors. Overall, the automotive and ICT sectors' interactions on the interface of autonomous driving have led to what could be described as light coupling.

In the second part of the thesis, the insights on the current state of the innovation system and its implications for value chain reconfiguration were used in order to build scenarios for the participation of the German industry in the global autonomous driving market (research question 4). The scenarios were built in an adapted scenario-building process, which did not primarily use expert workshops as a source. Instead, scenario factors and their development alternatives were derived from the findings of the integrated innovation system analysis and validated trough an iterative process of reflection and adaptation, backed up by focused discussions with experts. The process yielded the definition of two dimensions of scenario sets, each including two sub-scenarios that were then combined.

One set contains scenarios on the development of market framework conditions. These scenarios are named "Autonomous driving uptake" (scenario A) and "Moderate automation of mobility" (scenario B). Scenario A is characterized by a faster diffusion of autonomous driving in Germany and internationally, the coexistence of privately owned autonomous vehicles and autonomous mobility services, and continued growth in international trade. Scenario B is characterized by a slower diffusion of autonomous driving in Germany and internationally, the dominance of privately owned autonomous vehicles, and less open markets. The other set of scenarios examines the positioning of the German industry. The scenarios are named "Successful digital modernization" (scenario 1) and "Bumpy adaptation to autonomous mobility" (scenario 2). In scenario 1, the German industry actively participates in the development of autonomous driving, partly engages in the provision of autonomous mobility services and successfully sells vehicles and new components for all automation levels in the domestic and international markets. Scenario 2 is characterized by a focus of the industry on lower automation levels and corresponding sales, no engagement in mobility services and no provision of new components by German suppliers. The cross combination of scenarios from the two sets yields four scenarios that combine trajectories of autonomous driving market development and strategies of the German automotive industry (research question 4).

The four scenarios were analyzed in a macroeconomic simulation regarding their impact on the German economy until 2050 (research question 5). The focus of the analysis was on how different modes of engagement of the German automotive industry in a given global market development may influence the economic situation in Germany. Therefore, a comparison of A-1 to A-2 and B-1 to B-2 was conducted. The key characteristics of the scenarios were translated into quantitative impulses by drawing from and combining different estimations in the literature. Impulses were defined for the domestic vehicle sales and export potentials, surcharges for automation technologies, and the size of the mobility service market. These were combined with estimated market shares of German firms in vehicle and mobility service markets and assumptions on the role of domestic versus imported intermediaries. In order to reflect the input-structures of the different demanded components and services, and thus indirectly affected industries in the German economy, the impulses were attributed to several industries, such as vehicle manufacturing, electronics and IT and programming. The simulation was carried out using the macroeconomic simulation model ISI-Macro, which builds on dynamic input-output tables and allows for the assessment of direct, indirect and induced effects on the German economy.

The results show the high dependency of the German economy on foreign trade, especially vehicle exports. Several sensitivities are considered, which confirm this dependency. The variations of single indicators in the definition of sensitivities result in GDP development pathways that are close to their respective basic configuration. The deviation between scenarios A-1 and A-2 is higher than the deviation between B-1 and B-2. Looking at the basic configuration and sensitivity calculations for the deviation between A-1 and A-2, the maximum in terms of GDP is reached in 2045, at 4.75% (research question 5). In the same year, the minimum deviation in an A-1/A-2 sensitivity with no growth in international trade yields 3.70%. The deviation between variants of scenarios B-1 and B-2 reaches its highest point in 2050 at 1.54%, where the minimum deviation of a sensitivity simulation is at 1.20%. The production of vehicles itself represents about 23% (49 billion €) of the total difference in GVA between A-1 and A-2 and about 25% (14 billion €) of the total difference in GVA between B-1 and B-2 in 2050. The results of the simulation show that the different industrial strategies imply a much larger deviation in terms of GDP, GVA and labor demand in a world that develops actively towards autonomous driving and that is characterized by persistent international trade. Furthermore, the consideration of direct, indirect, and induced effects displays the widespread impact that developments in the automotive industry have on various sectors in the German economy.

9.2 Methodological reflection

The goal of the thesis was to assess the potential role of the German automotive industry in the provision of future autonomous mobility and to quantify the potential economic effects associated with different industrial strategies. In order to answer the research questions defined in the introduction, the work intends to fill two central research gaps: First, the missing sound conceptual basis, which accounts for the interactions between sectors in the field of autonomous driving and the implications these interactions can have on the respective sectoral systems and their value chains, and second, the need to transfer the conceptual basis into a prospective approach of future scenario development and assessment (see section 3.1).

The integrated innovation system approach, developed in the thesis, represents such a conceptual basis that accounts for the interplay between the automotive and ICT sectors in the development of autonomous driving. The explicit consideration of the interactions between the sectors allows for a translation of findings on current activities towards potential reconfigurations of value chains.

Approaching the topic of value chain transformation from an innovation system point of view allows for a systemic consideration of influencing factors and helps to structure the analysis. However, the application of a flexible framework to the broad research subject of the transformation of internationally large sectors in different countries and with regard to a possibly disrupting technology has some shortcomings. For one, there are countless activities in the field of autonomous driving in the two sectors and in many countries. There was the need to narrow down the analysis to the central automotive and ICT markets and suppliers Germany, USA, and China, and to focus on key players and central achievements in the development of autonomous driving. State-of-the-art empirical methods, such as the evaluation of patent applications or trademark registrations, were combined. The combination of methods represents a balance between covering the whole picture of developments and taking into account the activities of individual firms. The usage of innovation indicators in innovation systems analysis falls short on methods that substantiate causalities between observed developments and their drivers. The assessment of individual firms could be enlarged with the explicit consideration of additional firms and more extensive case studies. The analysis could be also deepened by considering single technological sub-components in more detail. With regard to the quickly changing technological state of knowledge and industrial landscape, the analysis of the status quo would need to be a dynamic and iterative monitoring process. The scope of analysis could have been more comprehensive in order to identify more entanglements, such as related parallel technological development processes, other connected sectors and countries. These problems, however, are intrinsic to each innovation system analysis, which has to delineate systems with regard to granularity, time, and involved activities. Despite these inherent problems, the analysis nevertheless shows a systemic picture of current status and potential future development of autonomous driving based on data up to 2022.

The analysis in the thesis uses as its point of departure the linkage between the participation of actors and systems in the innovation process of a product or service and the future role in the supplier markets and value chains, which has been identified in the literature. In light of the manifold factors influencing the development and implementation of autonomous driving, such as technological breakthroughs, individual firm decisions, shifts in demand, or external shocks, many uncertainties prevail with regard to the development of future value chains. The analysis does not allow for predictions of the future but, drawing from the current state of knowledge, derives potential implications for the division of roles between the automotive and ICT sectors and the countries Germany, USA and China.

In order to assess the implications of uncertainty in the conclusion of the analysis, scenarios are used. In an adapted scenario-building process, the insights from the integrated innovation system analysis in the first part of the thesis are transferred into scenarios and evaluated quantitatively in a macroeconomic simulation. The two steps address the identified second research gap, which calls for the transfer of findings into a prospective approach of prospective scenario development and assessment.

The use of a large set of factors and their alternative developments in the scenarios accounts for the complexity of industrial dynamics in the field of autonomous driving. In addition, the strong influence of market conditions on the outcomes is accounted for by introducing two sets of scenarios and by combining those into four scenarios. The independent combination of scenarios from both sets presents a trade-off: It allows for a direct comparison of different forms of industrial engagement in Germany in a given market environment but ignores the potential interdependencies that may exist between the activities of an industry and the development of the market framework. Sensitivities were introduced in order to partly address this shortcoming in the conceptual approach.

Furthermore, in the formulation of the final four scenarios, complexity had to be reduced in order to keep the scenarios accessible. Especially in the context of the quantification of impulses and the macroeconomic simulations, only the key characteristics of the scenarios could be taken into account. The neglect of the potential fragmentation of international markets presents such a limitation.

The modelling results show effects on GDP, GVA and labor demand in different industries in Germany until 2050. The macroeconomic simulation and quantification of impulses builds on many assumption, which may be debatable, especially considering the long time horizon until 2050 (see section 8.3.2). The application of the macroeconomic impact assessment model ISI-Macro involves model-specific restrictions such as fixed input structures, homogenous goods, and the limited consideration of price effects and reciprocal financing. Nevertheless, the modelling approach allows for an explicit consideration of the introduction of the new autonomous driving technology through the formulation of respective impulses. Furthermore, directly and indirectly affected industrial branches in Germany are accounted for in high sectoral resolution. Finally, the simulation considers the implications of the industry being a major determinant of German income flows and thus provides a systemic analysis of the impact on the German economy.

9.3 Conclusions and outlook

The ongoing development and implementation of autonomous driving can change the established structures of the automotive industry, including its value chains, the mobility system and the current principles of mobility markets. The aim of the thesis was to assess these changes by introducing an integrated innovation system analysis approach and to estimate the potential effects of different strategies of the German automotive industry on the German overall economy.

The analysis shows that the German automotive industry is actively engaging in the development of autonomous driving by focusing on both, assisted and autonomous vehicle technologies. Industrial players expand their knowledge in new fields, participate in cross-sectoral development cooperations and form new supplier relations. However, the German automotive industry is confronted with strong competition from the USA and China, specifically from large ICT-players or their supported subsidiaries that focus on developing autonomous driving technology and aim at transforming the private transport market into a platform-based autonomous mobility system. While the coexistence of transport modes and thus partly complementary lead firms from the automotive and ICT sectors in the supply of the future mobility market seems likely, the loss of market shares of the German automotive industry can entail severe negative effects on economic activity and employment in Germany. The continued production of vehicles and components by OEMs and suppliers in Germany, especially for exports, is an important factor for German economic prosperity.

The understanding of and the interplay between the ICT sectoral system and the automotive sectoral system was placed in the focus of the analysis. While large parts of the analysis focus on the activities of the industrial systems, they are considered in a broader context, including factors such as institutions, infrastructure, and society. The thesis contributes to the existing literature in several ways.

First, the integrated innovation system approach explicitly accounts for sectoral, national and technological specifics. A sectoral innovation system analysis of the automotive and ICT sector is prepended to the functional innovation system analysis of autonomous driving. The identification of key characteristics and structures of the sectors helps to assess the patterns of participation with regard to the development of autonomous driving. By choosing indicators, both qualitative and quantitative, accordingly, a differentiation between sectoral activities and geographical locations was possible throughout the functional analysis. From both the sectoral and the national perspective differences in the patterns of participation are identified, which once more underlines the relevance of contextual factors to the dynamics and design of innovation systems.

Second, it is assessed how the analysis of sectoral interaction can be embedded into an innovation system analysis. One the one hand, indicators that allow for a sectoral differentiation with regard to the participation in the autonomous driving innovation system were used in order to deepen the understanding of the interaction between the sectors. On the other hand, a supplementary function was introduced that describes the interactions between the automotive and ICT system. The introduction of such a function at the end of the analysis allowed to join the gathered specific information on sectoral interaction throughout the other functions.

Third, the question of value chain transformation is approached from an innovation system perspective. The systemic viewpoint allows for and also makes sure that autonomous driving is studied in a comprehensive manner, including factors that go beyond the technological development and the industrial subsystem. While there is no direct transferability of the exact procedure, especially the chosen indicators, to other research subjects, the analysis shows the ability of an integrated innovation system analysis to account for sectoral and national contexts. The strength of the innovation system perspective is found to be in its structuring and holistic characteristics, while being broadly adaptable to the specific research question. The systemic perspective has the potential to enrich the analysis of industrial and value chain dynamics through the explicit consideration of influential factors outside industries.

Fourth, the analysis is conducted from a comprehensive viewpoint and combines information from many different sources and research streams. A central conclusion is that the automotive and ICT sectors' activities can be considered complementary along sectoral borders for many of the technological subfields. The complementary competencies entail sectoral and geographical cross-border partnerships. After a phase of high investments and many new foundations, the field seems to have entered a phase of consolidation that is also expressed in the forming of partnerships and mergers. The size of the autonomous driving service market is found to be a key determinant with regard to the depth of the transformation of the automotive value chain. While mainly ICT players offer the platforms for autonomous driving services, the market of privately owned (autonomous) vehicles is expected to prevail and so are principles of the product-oriented value chains of the automotive industry.

Fifth, an adapted scenario-building process was carried out that builds on the insights from the integrated innovation system analysis. The formulation of the prospective scenarios is thus based on a systematic and in-depth analysis of the phenomena of autonomous driving and its industrial implications. The final scenarios are a combination of sub-scenarios on two levels: market framework scenarios and industry positioning scenarios. The design of the scenarios thus allows to study how different modes of engagement of the German automotive industry in a given global market development may influence the economic situation in Germany.

Finally, the macroeconomic simulation with ISI-Macro provides novel insights into the potential effects that different configurations of scenarios can have on the German economy until 2050, by considering direct, indirect, induced effects on 72 industries. The automotive industry is a large contributor to economic prosperity in Germany and the effects of its transformation can go beyond the industry itself. Other industries providing electronic components, IT and programming solutions or mobility services may play an increasing role in the provision of autonomous mobility.

The thesis combines principles of innovation system analysis with prospective scenario-building and macroeconomic modelling. The insights can be refined and complemented in several ways. For instance, the analysis of the current state of the innovation system of autonomous driving can be advanced by assessing the causal effects of industrial strategies on technological advances or economic success. Furthermore, the interaction of the industrial actors from the automotive and ICT sectoral systems was in the center of the analysis, since they are considered to drive the transformation of value chains. It is left to further research to explicitly assess the interactions of other systems' components. The analysis of the interplay between research institutions, research teams, university chairs and individual researchers, for instance, might provide important insights into how the delineation of academic fields and faculties in the automotive and ICT sectors evolves. With regard to the economic assessment of the scenarios, a more comprehensive translation of the scenarios, for instance by using a transport model, could refine the estimation of macroeconomic effects. The key challenge for innovation studies that cope with prospective developments is the incorporation of an uncertain future. While scientific findings are always preliminary, every step towards a better understanding of the specifics and dynamics in the innovation system and its processes can lead to more realistic estimates of possible future states. In this sense, the dissertation contributes by providing novel insights into the innovation system of autonomous driving and relevant contextual factors, and by displaying the economic implications of potential development pathways.

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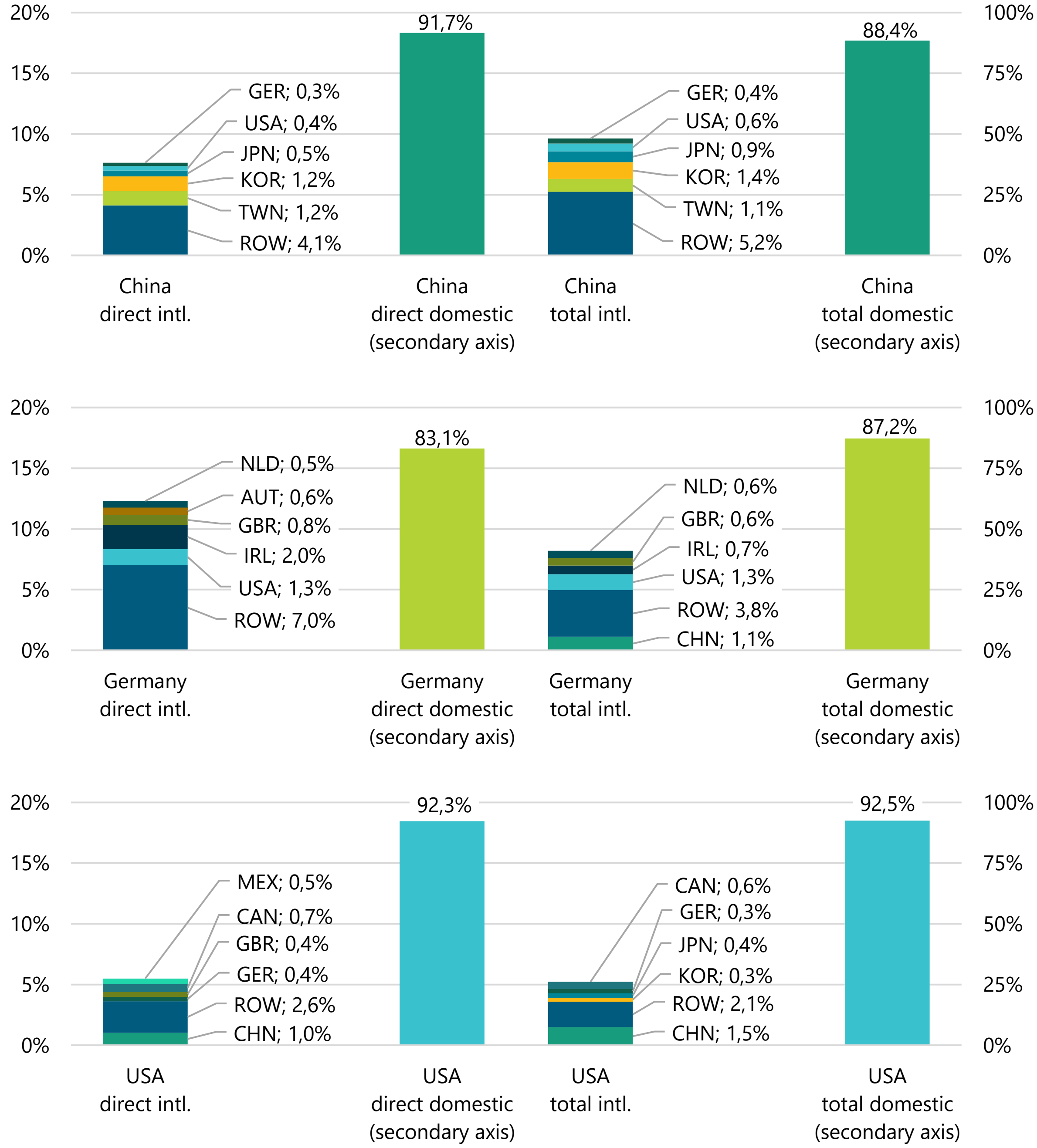
Annex

Figure A 1: Regional origin of intermediates into the computer programming, [...] and information service industries

Share of direct and total intermediates delivered to computer programming, [...] and information service industries of China, Germany and USA, by regional origins, largest supplying nations, 2014



Source: Own calculations based on WIOD database (Timmer et al. 2015)

Table A 1: Activities of selected firms in the field of autonomous driving (Status 02/2022) (I/ VII)

Company	Headquarter	sector / type	1. Technologies in focus 2. Company slogan / vision / aim autonomous driving 3. Autonomous driving services	Technologies					Slogans	Mobility services orientation		Source
				Fully autonomous Vehicle systems	Components	Digital environment	Information / Communication solutions	Accompanying solutions	vehicle oriented, mobility system, other aspects	On-road autonomous service provider	Accompanying solutions / technologies	
Aisin	*Japan*	*Automotive*	Recognition: Recognition sensor, driver monitoring system, peripheral monitoring, cloud, infrastructure cooperations, high-precision maps; Judgement: automated (valet) parking, cruise control, lane keep; Execution: drive control		x	x						*Aisin (2022)*
			“Accelerating our development of automated driving technology with brake and vehicle dynamics control technology to achieve zero traffic accidents”						vehicle oriented			*Aisin (2022)*
			-									-
Amazon	*USA*	*ICT*	AWS IoT FleetWise, Autonomous Vehicle Data Lake on AWS, DXC and AWS Robotic Drive Cloud, Capgemini Driving Automation System Validation			x	x	x				*Amazon Web Services, Inc. (2022)*
			“Autonomous Mobility: accelerate autonomous vehicle development with purpose-built AWS and partner services and solutions”						vehicle oriented			*Amazon Web Services, Inc. (2022)*
			Acquisition of robotaxi developer Zoox with test operation US West Coast; automation of own fleet with Plus / Iveco							x		*tagesschau.de (2021)*
Aptiv	*Ireland*	*Automotive*	Advanced Driver-Assistance Systems (ADAS) as part of Smart Vehicle Architecture	x								*Aptiv (2022b)*
			“Autonomous Mobility - Enabling a self-driving future”						mobility system			*Aptiv (2022a)*
			Joint Venture "Motional" with Hyundai Motor Group, Robotaxi Service in collaboration with Lyft								x	*Motional (2020)*
Argo AI	*USA*	*Autonomous vehicles*	Lidar, software and hardware for self-driving systems	x								*Argo AI (2021)*
			"We’re building self-driving technology you can trust."						vehicle oriented			*Argo AI (2021)*
			Autonomous Ridehailing with Ford and Lyft as well as Volkswagen and MOIA								x	*Ford (2021a), Argo AI (2021)*
Audi	*Germany*	*Automotive*	Integration, safe system architecture with VW’s Cariad and others, (C-)V2X technologies, societal questions of autonomous driving	x								*Audi AG (2022a), Eddy (2021)*
			-						-			-
			-									-

Table A 1: Activities of selected firms in the field of autonomous driving (Status 02/2022) (II/ VII)

Autoliv	*Sweden*	*Automotive*	Sensors for safety technologies in autonomous vehicles, spin-off: Veoneer		x							*Autoliv (2021)*
			-						-			-
			-									-
Baidu	*China*	*ICT*	Activities within Apollo enterprise: Valet parking, V2X, Cloud, Smart Traffic Signals			x	x					*Apollo (2022)*
			-						-			-
			Robotaxi-Service "Apollo", started in 5 cities, target 100 cities in 2030, vehicles from Baidu and FAW							x		*Kharpal (2021)*
BMW	*Germany*	*Automotive*	Integration and development of autonomous driving system, sensors, computing	x								*Pertschy (2021), BMW Group (2022)*
			"Intelligence that drives us."						other aspects			*BMW Group (2022)*
			-									-
Bosch	*Germany*	*Automotive*	Environment detection: image processing with AI (multifunction cameras), sensor technologies (Long-range lidar, inertial sensors); Real-time processing for driving strategies: Vehicle computing, electric steering systems, braking systems, networked and automated parking systems	x	x							*Bosch (2022)*
			“Automated mobility - Bosch is teaching the vehicle how to drive”						vehicle oriented			*Bosch (2022)*
			Robotaxi project with Daimler terminated									*Kunkel (2021)*
BYD	*China*	*ICT*	Joint Venture with Momenta: DiPi Intelligent Mobility Co	x								*Shirouzu (2021)*
			-						-			-
			-									-
Continental	*Germany*	*Automotive*	Environment model generation with cameras, radar sensors, lidar; Control units; V2X / M2XPro; supercomputer for AI; Road database based on sensor data; Integration in Crusing Chauffeur	x	x							*Continental (2022b), Continental (2022a)*
			“Seamless Mobility Experience - Sit Back. Relax. We’ll do the Driving”						vehicle oriented			*Continental (2022b)*
			CUbE (Continental Urban mobility Experience) vehicle platform for robotaxis, which are used as delivery robots during off-peak hours.								x	*Continental (2019)*
Cruise	*USA*	*Autonomous vehicles*	Autonomous driving system including hardware, AI, embedded systems, simulation, and infrastructure	x		x						*Cruise (2023a)*
			“Safety is our north star”						safety			Cruise (2023b)
			Pilot projects with robotaxis e.g. in San Francisco							x	x	*Tanenblatt (2022)*

Table A 1: Activities of selected firms in the field of autonomous driving (Status 02/2022) (III/ VII)

Denso	*Japan*	*Automotive*	Environment detection systems (sensors, radar, lidar, cameras); vision support systems; information security systems; cockpit information systems; quantum computing for Mobility IoT		x	x	x					*Denso (2022b)*
			-						-			-
			MaaS Architecture that is IoT cloud-based and replicated real-life urban environments in virtual space (digital twin); robotaxis in cooperation with Aurora and Toyota								x	*Denso (2022a), Ohnsman (2021)*
DiDi	*China*	*Mobility Services*	DiDi Autonomous Driving unit: HD map and positioning, environment perception, route planning, simulation platform, infrastructure; Smart transportation systems; DiDi cloud; AI Labs	x		x	x	x				*DiDi (2022a), (2022b)*
			"To Become a Global Leader in the Revolution in Transportation and Automotive Technology"						mobility system			*DiDi (2022b)*
			Pilot projects in Beijing, Shanghai, Suzhou, California; automotive partner Volvo							x	x	*DiDi (2022b)*
Ford	*USA*	*Automotive*	Development of autonomous driving with partner Argo AI									
			"We're bringing a history of automotive experience into the future of autonomous mobility."						mobility system			*Ford (2022a)*
			Pilot project autonomous ridehailing service in cooperation with Argo AI and Lyft from 2022; Test project autonomous delivery service in cooperation with DP World London Gateway.								x	*Ford (2021a), Ford (2021b)*
Hitachi	*Japan*	*Automotive*	Radar; Camera; Control units; gateways; map position unit; OTA software updates		x							*Hitachi Astemo (2022)*
			-						-			-
			-									-
Huawei	*China*	*ICT*	Mobile Data Center (MDC): CPU; SSD control chips; software; AI		x							*Yige (2022)*
			-						-			-
			-									-
Innoviz	*Israel*	*Autonomous vehicles*	Lidar, accompanying "Perception Software".		x							*Innoviz (2022)*
			"Autonomous driving is safer driving"						safety			*Innoviz (2022)*
			-									-

Table A 1: Activities of selected firms in the field of autonomous driving (Status 02/2022) (IV/ VII)

Intel	*USA*	*ICT*	Intelligent Transport Systems (ITS): processors, AI portfolio, 5G technologies, storage technologies, networking technologies; Acquisition of Mobileye (autonomous driving technologies)		x	x						*Intel (2022b)*
			"Autonomous Cars You Can Trust“						trust			*Intel (2022a)*
			Cooperation with Waymo, acquisition of Moovit (MaaS solutions company) and Mobileye (autonomous driving firm)							x	x	*Intel (9/18/2017), Intel (5/4/2020)*
Jtekt	*Japan*	*Automotive*	Sensors, Steer-by-Wire systems		x							*JTEKT (2020), JTEKT (2021)*
			-						-			-
			-									-
LG	*South-Korea*	*ICT*	Automotive Vision Systems: cameras and processing; telematics: C-V2X, smart antenna, cybersecurity; display, infotainment solutions, IVI; SVL Simulator: simulation platform, cloud simulation, digital twin generation		x		x	x				*LG VS Company (2022), LG (2022)*
			“Innovation partner for Future Mobility - We are accumulating integration of consumer electronics technologies, such as hardware, software, and HMI, into vehicle component solutions.”						mobility system			*LG VS Company (2022)*
			AVFMS (Fleet Management System for Autonomous Vehicle) platform extendable for sharing services of autonomous vehicles								x	*LG CNS (2022)*
Mercedes-Benz (Daimler)	*Germany*	*Automotive*	Autonomous systems development: First internationally valid system approval for conditionally automated driving; cooperation with e.g. Nvidia: software with over-the-air updates; together with Bosch: driving systems for SAE Level 4/5; Luminar: lidar; own operating system MB.OS	x								*Mercedes-Benz Group (2020, 2021, 2022b), Mercedes-Benz Group and Bosch (2022)*
			“From the intelligent to the autonomous car. Intelligent Drive – today and tomorrow”						vehicle oriented			Mercedes-Benz Group (2022a)
			Athlon (Mercedes-Benz Group): Mobility solutions								x	*Athlon (2022)*
Mobileye	*Israel*	*Autonomous vehicles*	Coverage of full value chain of autonomous driving: ADAS (esp. camera), Responsibility-Sensitive-Safety (RSS), Mapping (REM), Mobileye Drive, Sensing, System-on-Chip, acquired by Intel	x		x						*Mobileye (2022b)*
			-						-			-
			Robotaxis in munich in cooperation with Sixt and Moovit, based on Nio vehicle; integration of Mobileye technologies in Schaeffler self-driving Shuttles								x	*Mobileye (2021)*

Table A 1: Activities of selected firms in the field of autonomous driving (Status 02/2022) (V/ VII)

NSK	*Japan*	*Automotive*	Integrated mechatronic systems, steering systems		x							*NSK (2022)*
			"Bearing solutions for adaptive cruise and collision avoidance."						vehicle ori-ented			*NSK (2022)*
			-									
Panasonic	*Japan*	*ICT*	Cameras, sensors, ADAS, control units; IVI, next-generation cockpit system		x							*Panasonic (2022)*
			-						-			-
			-									-
Qualcomm	*USA*	*ICT*	"Snapdragon digital chassis": Ride Platform: ADAS, vision SoC; Cockpit Platforms: compute, computer vision, AI, multi-sensor processing; Car-to-Cloud services; Auto Connectivity Platform: 4G/5G, C-V2X, Wi-Fi; posi-tioning solutions		x		x					*Qualcomm (2022)*
			"Accelerating the digital transfor-mation of automotive."						other aspects			*Qualcomm (2022)*
			-									-
Samsung	*South-Korea orea*	*ICT*	Processors e.g. for IVI systems, 5G-enabled memory chips, optical sen-sors		x							*Samsung (2022)*
			"The future of mobility"						mobility sys-tems			*Samsung (2022)*
			-									-
Scania	*Sweden*	*Automotive*	Development of "Autonomous Transport Solutions" system: han-dling logistics, task assignment, infor-mation sharing; NXT self-driving ur-ban concept car	x								*Scania Group (2022)*
			"The shift to autonomous transport has begun."						vehicle ori-ented			*Scania Group (2022)*
			Autonomous buses on regular routes in cooperation with Nobina outside Stockholm								x	*Nobina (2022)*
Schaeffler	*Germany*	*Automotive*	Digital accelerator, brake and steer-ing system consisting of hardware and software components (drive-by-wire); rolling chassis (modular, scala-ble vehicle platform for driverless mo-bility solutions)		x							*Schaeffler (2021)*
			-						-			-
			Self-driving, highly flexible and cus-tomizable vehicle platform will be available from 2023, cooperation with Mobileye								x	*Schaeffler (9/6/2021)*

Table A 1: Activities of selected firms in the field of autonomous driving (Status 02/2022) (VI/ VII)

Siemens	*Germany*	*ICT*	Siemens: Autonomous vehicle development solutions and tools; Siemens Advanta: Business model development for future autonomous vehicle systems; Venture Simulytic: simulation platform for safety analysis; Siemens Mobility: intelligent infrastructure installation, city digital twin, cloud-based mobility management			x		x				*Siemens (2022), Siemens Advanta (2022), Siemens Mobility (2022b)*
			Siemens Mobility: "Autonomous shuttles optimally support public transport - not only for the first and last mile"						mobility systems			*Siemens Mobility (2022b)*
			Development of autonomous mobility systems with cities, public transport companies and research institutes; Sitraffic mooV; e.g. Hamburg, Munich, Singapur							x	x	*Siemens Mobility (2022b), Siemens Mobility (2022a)*
SONY	*Japan*	*ICT*	SONY Vision-S Concept Car: Oval sensing, driving assistance, advanced camera monitoring system, in-cabin monitoring; imaging and sensing technology	~	x							*Sony (2022b), Sony (2022a)*
			-						-			-
			-									-
Tesla	*USA*	*Automotive*	Autopilot system: AI, image processing systems, Chips, neural networks	x								*Tesla (2022)*
			-						-			-
			-									-
Toyota	*Japan*	*Automotive*	Two automation concepts: Toyota Guardian: Ai system that blends vehicle control between driver and vehicle for increased safety; Toyota Chauffeur project: cars completely self-driving by AI system, similar to SAE level 4-5	x								*Toyota (2022), Reuters (2022)*
			"Technology has once again expanded what is possible for mobility."						mobility systems			*Toyota (2022)*
			Building MaaS platform for business purposes: "e-Palette" development cooperation with other external partners; Robotaxis in corporation with Aurora and Denso							x	x	*Ohnsman (2021), Toyota (2020)*
Uber	*USA*	*Mobility Services*	Sale of autonomous driving unit to start-up Aurora, acquistion of Aurora shares					x				*Metz and Conger (2020)*
			-						-			-
			Driverless food deliveries with Motional (JV Aptiv/Hyundai)							x		*Agustin (2021)*
Valeo	*France*	*Automotive*	Lidar scanners; cameras, radar, sensors; cleaning systems for optical sensors; telematics control devices		x							*Valeo (2022a)*
			"Creating technology for tomorrow's car"						vehicle oriented			*Valeo (2022b)*
			-									-

Table A 1: Activities of selected firms in the field of autonomous driving (Status 02/2022) (VII/VII)

Veoneer	*Sweden*	*Automotive*	Software, hardware and systems for Advanced-Driving Assistance Systems (Radar, Lidar, Vision Systems, …), Collaborative and Automated Driving, spin-off from Autoliv	x						Veoneer (2022)
			"Our purpose is to create trust in mobility"				trust			Veoneer (2022)
			-							-
Volvo	*Sweden*	*Automotive*	Creation of unsupervised autonomous vehicle solution with subsidiary Zenseact (software technologies, compute infrastructure on-board / off-board in cloud, ecosystem of data driven development tools), cooperation with others as e.g. Luminar, Nvidia; own operating system VolvoCars.OS	x						*Stroh (2021), Volvo Car Corporation (2/8/2022, 6/30/2021), Zenseact (2022)*
			"The next step in advancing safety - Autonomous Drive"				safety			*Volvo Car Corporation (2022)*
			Cooperation with DiDi (shared mobility technology platform) for robotaxis in China						x	*Volvo Car Corporation (4/19/2021)*
Volkswagen Group	*Germany*	*Automotive*	Development of autonomous vehicles with self-driving system in collaboration with Ford, Argo AI; VW's CARIAD group bundles software, own operating system VW.OS	x						*Volkswagen AG (2022a)*
			-				-			-
			MOIA ridehailing: autonomous mobility services planned from 2025 on VW's ID.BUZZ platform					x	x	*Becker (2021), Volkswagen AG (2022b)*
Waymo	*USA*	*Autonomous vehicles*	Waymo Driver: mapping, system of sensors (Lidar, Camera, Radar), machine learning, computing	x		x				*Waymo (2022b)*
			"We're building the World's Most Experienced Driver TM."				vehicle oriented			*Waymo (2022a)*
			Waymo One: Ongoing pilot projects with robotaxis in San Francisco and operation of robotaxis in Phoenix; Waymo Via: long haul trucking and last mile delivery					x	x	*Waymo (2022c), Waymo (2022d)*
ZF	*Germany*	*Automotive*	Central computer and zone control units, driver assistance systems, middleware (central software platform), AI, automated valet parking		x					*ZF (2022a), Neemann (2022)*
			"Next Generation Mobility. Now."				mobility system			*ZF (2022c)*
			Autonomous transport systems for public transport, e.g. RABus						x	*ZF (2022b)*

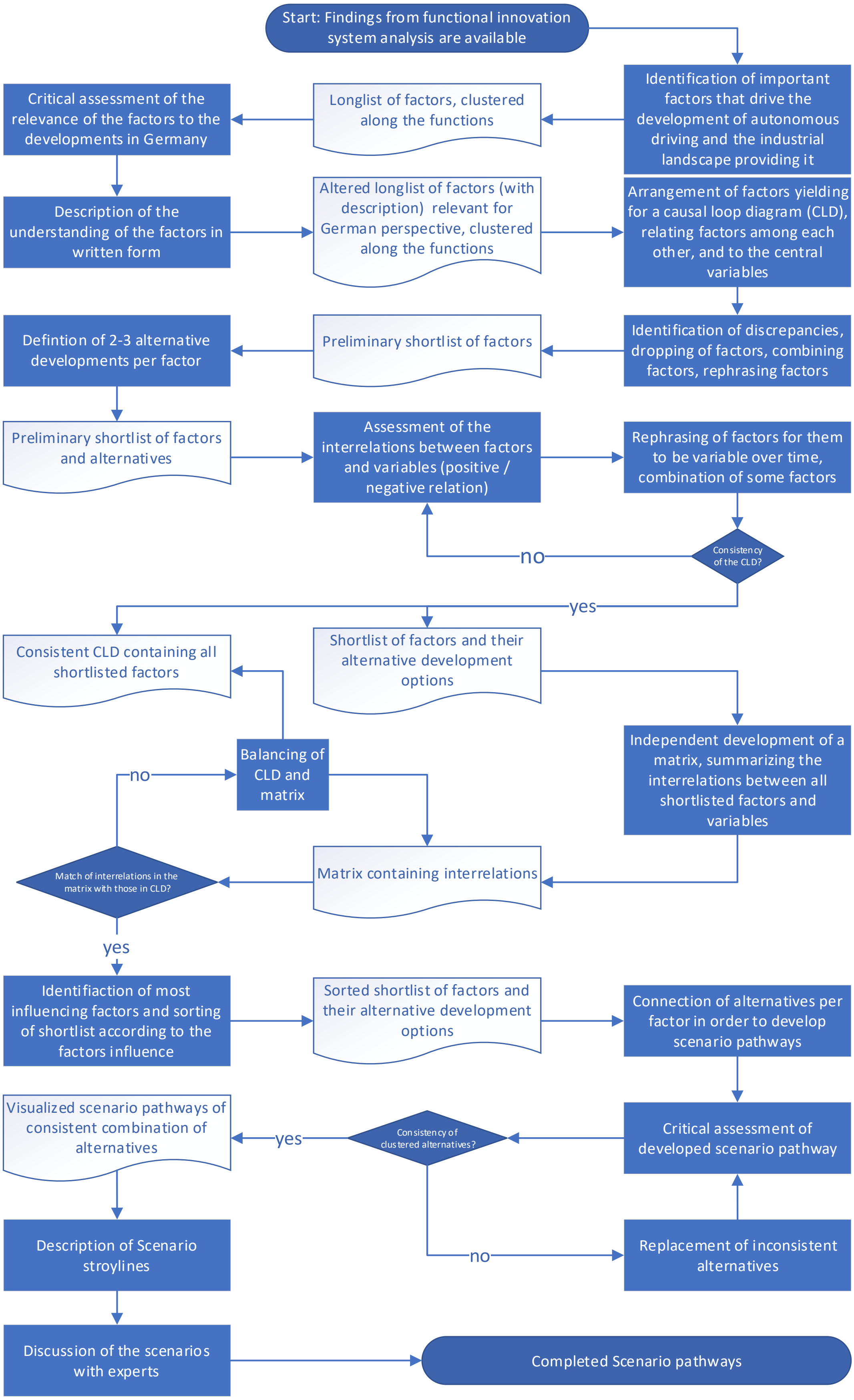
Source: Own representation, published in Grimm and Walz (2024)

Table A 2: Discussion of scenario factors and scenario pathways - Experts and their expertise

Name	Date	Area of expertise
Dr. Jonathan Köhler	14.07.2023	Innovation in transport; modelling of socio-technological transitions in transport
Dr. Michael Krail		Integrated impact assessment of long-term policies and strategies in the field of transport, climate and technology; analysis of impacts of autonomous driving; focus on the field of socioeconomic systems and the implication of dynamics on transport, climate and technology
Dr. Konstantin Krauß	25.07.2023	Supply structures and business models for mobility platforms and shared mobility services; techno-economic analysis of technologies and policies for decarbonizing passenger transport
Dr. Luisa Sievers		Economic impact assessment of long-term strategies in the field of transport, climate and technology; input-output modelling; System Dynamics modelling; structural change in the mobility sector
Dr. Djerdj Horvat	31.07.2023	Innovation and Knowledge Management; digital transformation and value chain dynamics; analysis and (model-) simulation in System Dynamics approach
Dr. Christian Lerch		Analysis of the relevance and the consequences of industrial trends and of new technologies for production and value creation in manufacturing; analysis, measurement and evaluation of the causes of servitization of Manufacturing Industries as well as its contribution to industrial and economic change

Source: Own representation

Figure A 2: Procedure of scenario development



Source: Own representation

Figure A 3: Cross-influence between factors and parameters

	Trade climate	Premium German OEM	Other challenges	Contract manufacturing	Engagement Software	Engagement Services	Engagement Hardware	GER focus Level 2 / 3	ICT landscape in Germany	Readiness technology	GER advances (full concept)	Production / distribution a...	Admission auto. vehicles	Diffusion auto. vehicles	Market shares private / sh...	Monopolistic ICT platform	Financial investment cap...	Availability of human res...	Acceptance auto. vehicles	Acceptance auto. shared m...	Cost of autonomous driving	Regulation auto. mobility	Market share "GERMANY"	Market volume	Production / services in G...	Profits in Germany	Origin intermediates	**SUM**
Trade climate		0	0	0	0	0	0	0	0	1	0	2	0	1	0	0	0	0	0	0	0	0	1	1	1	0	-2	**9**
Premium German OEM	0		0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	0	0	2	0	**5**
Other challenges	0	0		0	-2	-2	-2	0	0	0	-2	0	0	0	0	0	-2	-2	0	0	0	0	-1	0	0	0	-2	**15**
Contract manufacturing	0	0	0		0	0	0	0	0	0	0	2	0	1	0	2	0	0	0	0	0	0	-2	0	0	0	0	**7**
Engagement Software	0	0	0	0		0	0	0	1	0	2	0	0	0	0	0	-1	-1	0	0	0	0	2	0		0	0	**7**
Engagement Services	0	0	0	0	0		0	-1	1	0	0	0	0	0	0	0	-1	-1	0	0	0	0	2	0		0	0	**6**
Engagement Hardware	0	0	0	0	0	0		1	0	0	2	1	0	0	0	0	-1	-1	0	0	0	0	2	0		0	0	**8**
GER focus Level 2 / 3	0	0	0	0	0	-1	1		0	0	-2	1	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	**8**
ICT landscape in Germany	0	0	0	0	0	0	0	0		0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	1	**5**
Readiness technology	0	0	0	1	0	0	0	0	0		0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	**5**
GER advances (full concept)	0	0	0	0	0	0	0	-2	0	1		0	0	1	0	0	0	0	0	0	0	0	2	0	1	0	1	**8**
Production / distribution ability	0	0	0	0	0	0	0	0	0	0	0		0	2	0	0	0	0	0	0	-1	0	0	2	0	0	0	**5**
Admission auto. vehicles	0	0	0	0	0	0	0	0	0	0	0	1		2	0	1	0	0	2	0	0	1	0	0	0	0	0	**7**
Diffusion auto. vehicles	0	0	0	0	0	0	0	0	0	0	0	0	1		0	0	0	0	2	0	1	0	0	2	0	0	0	**6**
Market shares private / shared	0	0	0	0	0	-1	0	0	-1	0	0	0	0	0		-1	0	0	0	0	0	-1	0	2	0	0	0	**6**
Monopolistic ICT platform	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0		0	0	0	0	-1	2	-2	0	0	-1	0	**9**
Financial investment capacities	0	0	0	0	2	2	2	0	0	2	0	2	0	0	0	0		0	0	0	0	0	1	1	0	0	0	**12**
Availability of human resources	0	0	0	0	2	2	2	0	1	2	2	2	0	0	0	0	0		0	0	0	0	1	1	1	0	1	**17**
Acceptance auto. vehicles	0	0	0	0	0	0	0	-1	0	0	0	0	0	2	0	0	0	0		1	0	0	0	2	0	0	0	**6**
Acceptance auto. shared mobility	0	0	0	0	0	1	0	0	1	0	0	0	0	1	-2	0	0	0	0		1	0	0	2	0	0	0	**8**
Cost of autonomous driving	0	1	0	0	0	0	0	1	0	0	0	0	0	-2	0	1	0	0	-2	-2		0	0	-2	0	0	0	**11**
Regulation auto. mobility	0	0	0	0	0	-1	0	1	0	-1	0	0	0	-1	0	0	0	0	-1	-1	0		0	-2	0	0	0	**8**
Market share "GERMANY"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0		0	2	0	0	**3**
Market volume	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	-1	2	0		2	0	0	**8**
Production / services in Germany	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		2	2	**4**
Profits in Germany	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0		0	**2**
Origin intermediates	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0		**3**
SUM	**0**	**1**	**0**	**3**	**6**	**10**	**7**	**8**	**5**	**7**	**11**	**11**	**1**	**16**	**2**	**5**	**7**	**6**	**9**	**5**	**5**	**6**	**23**	**19**	**11**	**5**	**9**	

Legend

2	**strong positive influence**
1	**weak positive influence**
0	**no direct influende**
-1	**weak negative influence**
-2	**strong negative influence**
2	**strong influence positive / negative on sub-factors**

Source: Own representation

Table A 3: New vehicle registrations in Germany, scenario A and B, 2025 – 2050

	2025	2030	2035	2040	2045	2050
Number of vehicle registrations	3,102,457	3,074,272	3,046,086	3,017,900	2,989,715	2,961,529

Source: Own representation based on Krail et al. (2019), supplementary data

Table A 4: Vehicle prices and automation surcharges, scenario A, 2025-2050, €2019

Vehicle segment	Prices / surcharges	2025	2030	2035	2040	2045	2050
small	classic components / vehicle hardware	20,693	20,693	20,693	20,693	20,693	20,693
middle	classic components / vehicle hardware	37,282	37,282	37,282	37,282	37,282	37,282
premium	classic components / vehicle hardware	81,786	81,786	81,786	81,786	81,786	81,786
small	surplus L1	1,081	1,025	969	913	856	800
	surplus L2	2,893	2,714	2,536	2,357	2,179	2,000
	surplus L3	-	3,455	3,341	3,227	3,114	3,000
	surplus L4	-	-	3,500	3,333	3,167	3,000
	surplus L5	-	-	-	-	5,000	5,000
middle	surplus L1	2,675	2,300	1,925	1,550	1,175	800
	surplus L2	3,000	2,607	2,166	1,725	1,284	2,000
	surplus L3	3,893	3,714	3,536	3,357	3,179	3,000
	surplus L4	-	3,952	3,714	3,476	3,238	3,000
	surplus L5	-	-	-	8,636	6,818	5,000
premium	surplus L1	943	914	886	857	829	800
	surplus L2	2,500	2,400	2,300	2,200	2,100	2,000
	surplus L3	4,042	3,000	3,000	3,000	3,000	3,000
	surplus L4	5,000	4,250	3,500	3,333	3,167	3,000
	surplus L5	-	-	12,000	9,667	7,333	5,000

Source: Own representation based on adjusted numbers from Wittich (2022) and Krail et al. (2019)

Table A 5: Vehicle prices and automation surcharges, scenario B, 2025-2050, €$_{2019}$

Vehicle segment	Prices / surcharges	2025	2030	2035	2040	2045	2050
small	classic components / vehicle hardware	20,693	20,693	20,693	20,693	20,693	20,693
middle	classic components / vehicle hardware	37,282	37,282	37,282	37,282	37,282	37,282
premium	classic components / vehicle hardware	81,786	81,786	81,786	81,786	81,786	81,786
small	surplus L1	1,081	1,025	969	913	856	800
	surplus L2	2,946	2,857	2,768	2,679	2,589	2,500
	surplus L3	-	3,477	3,420	3,364	3,307	3,250
	surplus L4	-	-	3,500	3,417	3,333	3,250
	surplus L5	-	-	-	-	5,000	5,000
middle	surplus L1	2,675	2,300	1,925	1,550	1,175	800
	surplus L2	5,250	4,993	4,758	4,524	4,289	3,500
	surplus L3	3,946	3,857	3,768	3,679	3,589	3,500
	surplus L4	-	3,976	3,857	3,738	3,619	3,500
	surplus L5	-	-	-	8,818	7,909	7,000
premium	surplus L1	943	914	886	857	829	800
	surplus L2	5,938	5,700	5,463	5,225	4,988	4,750
	surplus L3	4,771	4,250	4,250	4,250	4,250	4,250
	surplus L4	5,000	4,833	4,667	4,444	4,222	4,000
	surplus L5	-	-	12,000	10,833	9,667	8,500

Source: Own representation based on adjusted numbers from Wittich (2022) and Krail et al. (2019)

Table A 6: Assignment of German OEM model series and KBA-segments to the used vehicle segments (small, medium, premium) (I/II)

Vehicle segment (aggregated)	Vehicle segment (according to Kraftfahr-Bundesamt)	Model series	Quantity 2019
small	Mini	VW UP	28,982
	Kleinwagen	AUDI A1, S1	18,503
	Kleinwagen	BMW I3	9,382
	Kleinwagen	VW POLO	61,286
	Kompaktklasse	AUDI A3, S3, RS3	42,609
	Kompaktklasse	BMW 1ER	31,901
	Kompaktklasse	BMW 2ER	33,037
	Kompaktklasse	MERCEDES A-KLASSE	44,189
	Kompaktklasse	VW BEETLE	102
	Kompaktklasse	VW GOLF	204,550
	SUV	AUDI Q2	20,203
	SUV	BMW X1	36,109
	SUV	MERCEDES GLA	16,953
	SUV	VW T-ROC	58,898
	Geländewagen	AUDI Q3	24,460
middle	Mittelklasse	AUDI A4, S4, RS4	50,740
	Mittelklasse	AUDI A5, S5, RS5	16,444
	Mittelklasse	BMW ALPINA B3	36
	Mittelklasse	BMW ALPINA B4	69
	Mittelklasse	BMW 3ER	43,327
	Mittelklasse	BMW 4ER	9,424
	Mittelklasse	MERCEDES C-KLASSE	64,403
	Mittelklasse	MERCEDES CLA-KLASSE	17,525
	Mittelklasse	VW ARTEON	6,775
	Mittelklasse	VW PASSAT	59,322
	Obere Mittelklasse	AUDI A6, S6, RS6	44,037
	Obere Mittelklasse	BMW 5ER	35,949
	Obere Mittelklasse	MERCEDES E-KLASSE	43,265
	SUV	BMW X2	13,174
	SUV	MERCEDES GLB	138
	SUV	VW T-CROSS	23,718
	Geländewagen	AUDI Q5	22,210
	Geländewagen	BMW X3	28,688
	Geländewagen	BMW X4	6,988
	Geländewagen	VW TIGUAN	87,771
	Mini-Vans	MERCEDES B-KLASSE	33,709
	Großraum-Vans	MERCEDES V-KLASSE	20,540
	Großraum-Vans	VW SHARAN	9,393
	Großraum-Vans	VW TOURAN	39,847

Table A 6: Assignment of German OEM model series and KBA-segments to the used vehicle segments (small, medium, premium) (II/II)

Vehicle segment (aggregated)	Vehicle segment (according to Kraftfahr-Bundesamt)	Model series	Quantity 2019
premium	Oberklasse	AUDI A7, S7, RS7	3,454
	Oberklasse	AUDI A8, S8	2,533
	Oberklasse	BMW 6ER	1,509
	Oberklasse	BMW 7ER	4,151
	Oberklasse	BMW 8ER	2,639
	Oberklasse	MERCEDES CLS	3,890
	Oberklasse	MERCEDES S-KLASSE	4,450
	Oberklasse	PORSCHE PANAMERA	3,585
	Oberklasse	PORSCHE TAYCAN	31
	SUV	AUDI E-TRON	3,578
	SUV	MERCEDES GLK, GLC	38,369
	Geländewagen	AUDI Q7	5,709
	Geländewagen	AUDI Q8	6,407
	Geländewagen	BMW X5	13,906
	Geländewagen	BMW X6	1,211
	Geländewagen	BMW X7	1,787
	Geländewagen	MERCEDES G-KLASSE	5,362
	Geländewagen	MERCEDES GL-KLASSE, GLS	780
	Geländewagen	MERCEDES ML-KLASSE, GLE	10,203
	Geländewagen	PORSCHE CAYENNE	7,036
	Geländewagen	PORSCHE MACAN	9,084
	Geländewagen	VW TOUAREG	12,615
	Sportwagen	AUDI R8	668
	Sportwagen	AUDI TT	5,081
	Sportwagen	BMW I8	350
	Sportwagen	BMW Z4	4,714
	Sportwagen	MERCEDES AMG GT	3,221
	Sportwagen	MERCEDES E-KLASSE COUPE	6,418
	Sportwagen	MERCEDES SL	294
	Sportwagen	MERCEDES SLK, SLC	2,362
	Sportwagen	PORSCHE BOXSTER	1,763
	Sportwagen	PORSCHE CAYMAN	1,025
	Sportwagen	PORSCHE 911	7,884
	Sportwagen	PORSCHE CAYMAN	1,025
	Sportwagen	PORSCHE 911	7,884

Source: Own representation based on Kraftfahr-Bundesamt (2020b)

Table A 7: Passenger vehicle exports from Germany by quantity and value

	2019	2020	2021	2022
Quantity of passenger vehicles exported to Europe	2,150,241	1,619,451	1,328,207	1,448,724
Quantity of passenger vehicles exported total	3,484,756	2,645,466	2,371,420	2,599,299
European share (quantity of vehicles)	**62%**	**61%**	**56%**	**56%**
Value of passenger vehicle exports to Europe [thousand $€_{2019}$]	72,392,563	60,710,794	65,706,313	79,192,385
Value of passenger vehicle exports total [thousand $€_{2019}$]	128,109,789	106,986,315	118,206,542	148,311,850
European share (value of vehicles)	**57%**	**57%**	**56%**	**53%**

Source: Verband der Automobilindustrie (2023a), Statistisches Bundesamt (2023a)

Table A 8: Top-10 carsharing suppliers by vehicle fleet size

OEM-backed carsharing have a gray background

Carsharing provider	**Fleet size [number of vehicles]**	**Share of all carsharing vehicles**
SHARE NOW (car2go & DriveNow)	7,400	33%
Flinkster	4,500	20%
Stadtmobil	2,600	12%
Cambio	1,700	8%
MILES	1,500	7%
WEShare	1,500	7%
teilAuto	1,200	5%
Book N Drive	1 063	5%
Stattauto München	450	2%
Ford Carsharing	320	1%

Source: Own representation based on Statista (2020)

Table A 9: Assignment of industries to aggregate industry groups (I/II)

Industry	Industry group
Agriculture_01	Agriculture, Mining
Forestry_02	Agriculture, Mining
Fishery_03	Agriculture, Mining
Coal_04	Agriculture, Mining
OilGas_05	Agriculture, Mining
Mining_06	Agriculture, Mining
Food_07	Manufacturing Industries (others)
Textiles_08	Manufacturing Industries (others)
Wood_09	Manufacturing Industries (others)
Paper_10	Manufacturing Industries (others)
PrintMedia_11	Manufacturing Industries (others)
Coke_12	Manufacturing Industries (others)
Chemicals_13	Manufacturing Industries (others)
Pharmaceuticals_14	Manufacturing Industries (others)
Rubber_15	Manufacturing Industries (others)
Glass_16	Manufacturing Industries (others)
Ceramics_17	Manufacturing Industries (others)
FerrousMetals_18	Manufacturing Industries (others)
NonferrousMetals_19	Manufacturing Industries (others)
MetalCasting_20	Manufacturing Industries (others)
MetalProducts_21	Manufacturing Industries (others)
Computers_22	Computers
ElectricalEq_23	Manufacturing Industries (others)
Machines_24	Manufacturing Industries (others)
Vehicles_25	Vehicles
TransportEq_26	Manufacturing Industries (others)
Furniture_27	Manufacturing Industries (others)
MachineRepair_28	Manufacturing Industries (others)
Electricity_29	Energy and Water supply
Gas_30	Energy and Water supply
Water_31	Energy and Water supply
SewerageWaste_32	Energy and Water supply
Construction_33	Construction
CivilEng_34	Construction
SpecConstruction_35	Construction
VehicleWholesale_36	Vehicle Wholesale

Table A 9: Assignment of industries to aggregate industry groups (II/II)

Wholesale_37	Trade and Transport services
Retail_38	Trade and Transport services
LandTransport_39	Trade and Transport services
WaterTransport_40	Trade and Transport services
AirTransport_41	Trade and Transport services
Warehousing_42	Trade and Transport services
Post_43	Trade and Transport services
AccomodationGastro_44	Other services
Publishing_45	Other services
AVMedia_46	Other services
Telecom_47	Other services
ITProgramming_48	IT, Programming
Financial_49	Finance, Real Estate, Research and Tech Services
Insurance_50	Finance, Real Estate, Research and Tech Services
AuxFinancial_51	Finance, Real Estate, Research and Tech Services
RealEstate_52	Finance, Real Estate, Research and Tech Services
Legal_53	Finance, Real Estate, Research and Tech Services
ArchitectureEng_54	Finance, Real Estate, Research and Tech Services
RandD_55	Finance, Real Estate, Research and Tech Services
Advertising_56	Finance, Real Estate, Research and Tech Services
OtherTechServices_57	Finance, Real Estate, Research and Tech Services
RentalLeasing_58	Rental, Leasing
EmploymentServices_59	Other services
TravelServices_60	Other services
SecurityOfficeServices_61	Other services
PublicAdmin_62	Public services
SocialSecurity_63	Public services
Education_64	Public services
Health_65	Public services
ResidentialCare_66	Public services
CreativeLibraryMuseums_67	Public services
Sport_68	Public services
MembershipOrgs_69	Public services
TechRepair_70	Public services
PersonalServices_71	Public services
HouseholdServices_72	Public services

Source: Own representation