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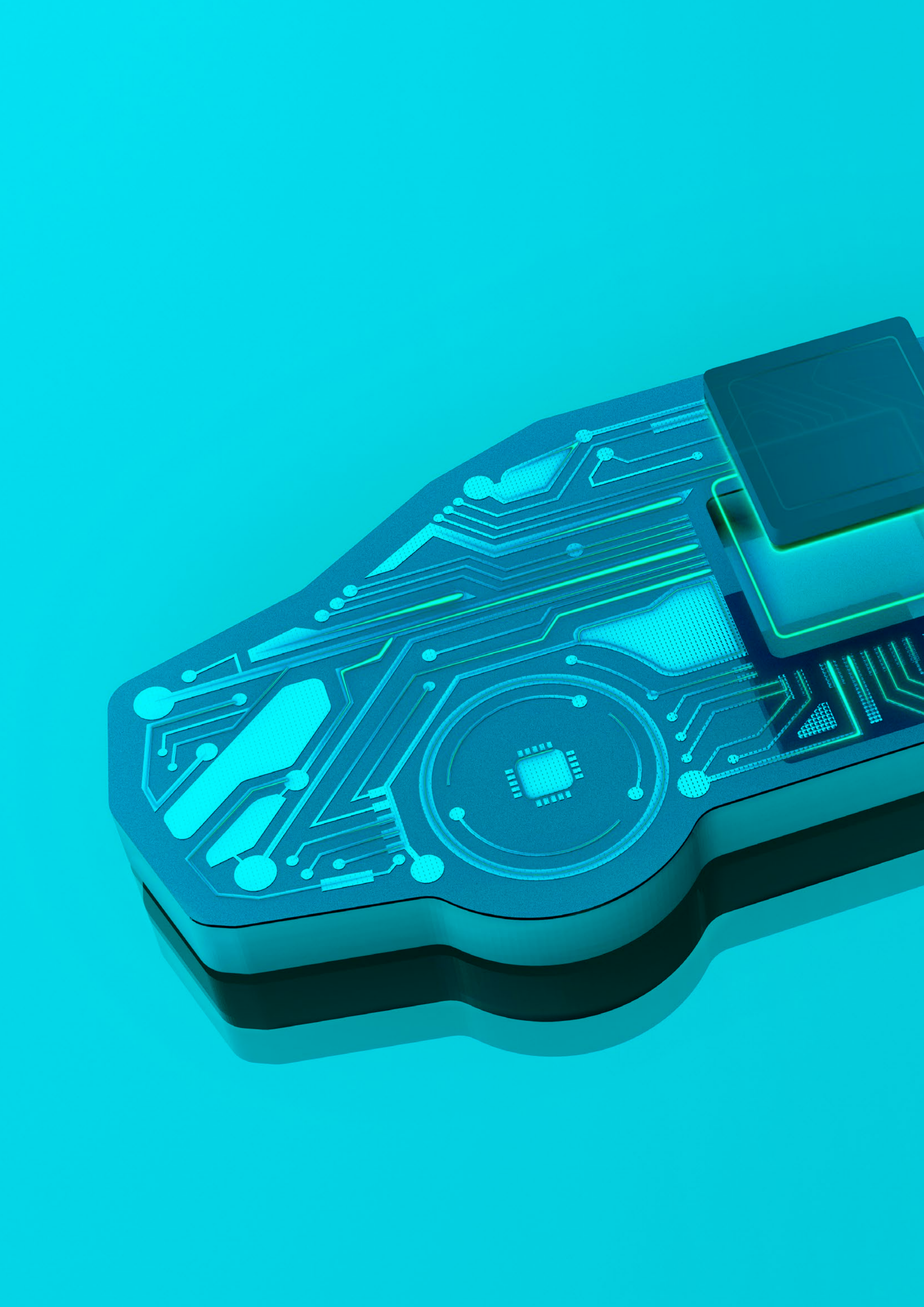
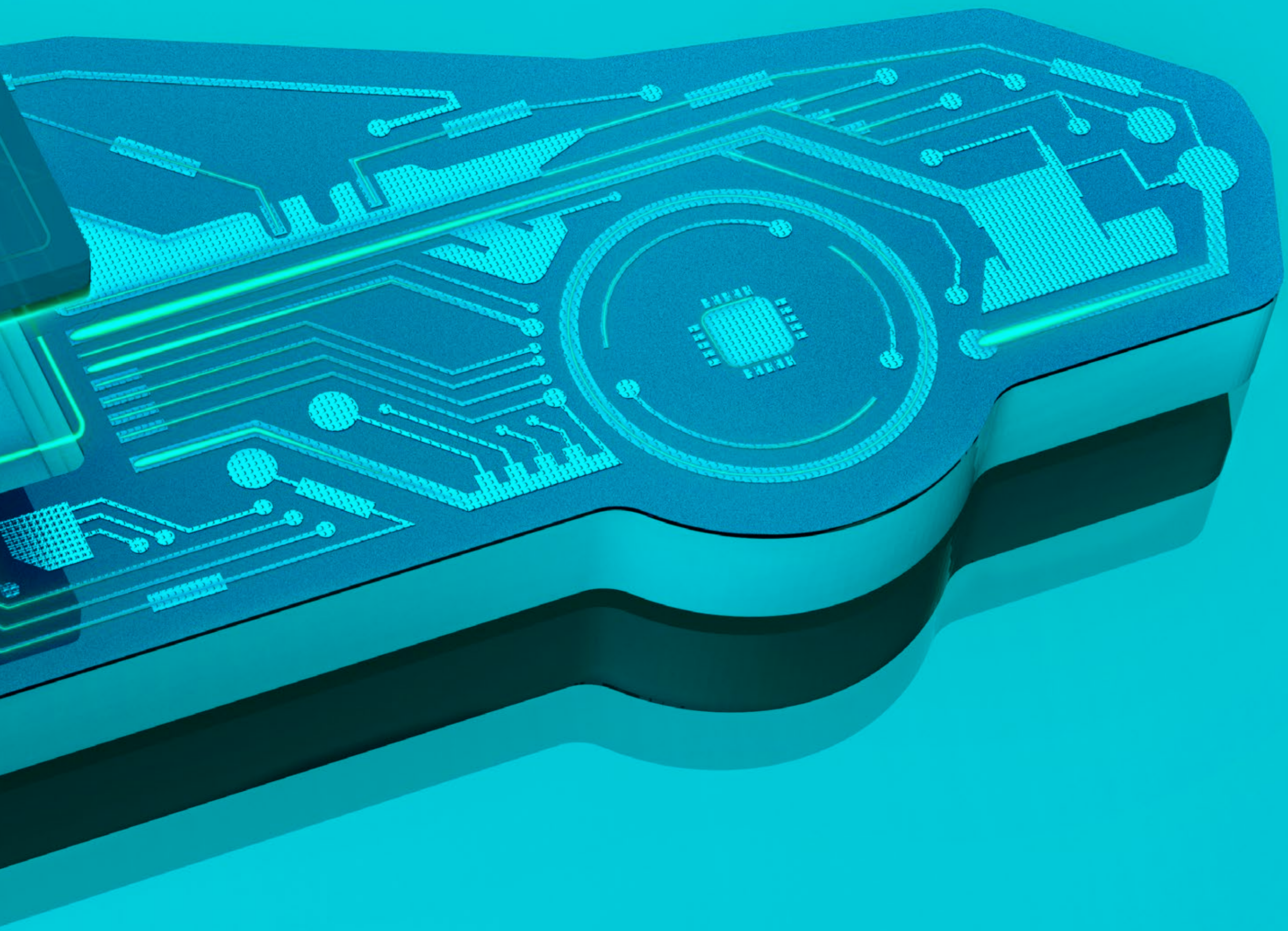
The Chip Crisis in the Automotive Industry

Challenges – Measures – Action Areas

HyValue





This study originated in the context of the research project "HyValue–Hybridisation in the Value Chain" and extends the results obtained during the main stage of the project. The interdisciplinary joint project HyValue was funded by the German Federal Ministry of Education and Research (BMBF) and the European Social Fund (ESF) within the framework of the research programme "Zukunft der Arbeit" (02L17B060 to 02L17B064) and was overseen by Projektträger Karlsruhe (PTKA) (project duration: April 2019 until October 2022). The authors are solely responsible for the content of this publication.

Summary

The chip crisis caught many companies in the automotive industry off guard. At the start of the COVID 19 pandemic in 2020, OEM management anticipated a prolonged slump in demand for vehicles, revised their production plans and communicated this information to suppliers. To avoid inventory costs, suppliers in turn cancelled much of their orders for chips from semiconductor companies. However, when demand for automobiles rebounded unexpectedly quickly after the initial lockdowns were lifted, semiconductor manufacturers had shifted capacity previously reserved for the automotive industry to meet the rapidly growing demand for chips used in office and consumer electronics. As chips have been incorporated into more and more components of modern vehicles over the years – from window regulators to engine controls – the sudden shortage had huge implications for the automotive industry. If just one chip was missing, vehicles could not be completed and delivered. Many companies were forced to cut back on production because of the chip shortage. Shifts were cancelled, model series were put on hold, entire plants were temporarily closed and employees in Germany were repeatedly put on short-time work (Kurzarbeit).

At first glance, the root cause of this disruptive event in semiconductor supply chains appears to be a classic bullwhip effect, in which fluctuations in demand have quickly built up into enormous dissonances. However, applying the conceptual and methodological arsenal of industrial sociology, this study shows that the phenomenon of the chip crisis is not exhaustively explained by this effect, and that the problem will not be solved in the long run by resorting to measures within the methodological spectrum of supply chain management alone. Rather, the chip crisis has revealed a more fundamental development dynamic that is rooted in deeper structural changes in the core products of the automotive industry and the role of semiconductors in vehicles.

The electrification and softwareisation of vehicles, which are shaping the current transformation of the industry, are not only significantly increasing the quantitative demand for semiconductors, but are also changing the quality of semiconductor use in vehicles. Semiconductors are becoming strategic building blocks – both as power electronics in the electrification of the powertrain and as high-performance computers, data transmitters and sensors in the redesign of software and electronics architectures and the realisation of market-differentiating software functions. For the creation of "software-defined electric vehicles", semiconductors can therefore no longer be regarded by the established car manufacturers as just another intermediate product on their purchasing lists and their producers treated as suppliers of commodities; instead, semiconductors have become key components of the car of the future.

The chip crisis has brought these developments and the associated challenges for automotive companies to the fore. They are demanding a far-reaching redefinition of their semiconductor strategies and their cooperation practices with the companies in the semiconductor industry. The chip crisis marks this turning point for the use of semiconductors in the automotive industry. At the same time, the attention generated by the crisis creates opportunities for companies and policy makers not only to redesign the use of semiconductors, but also to improve the overall sustainability of their material flows in this area towards a circular economy.

Based on interviews with experts and the analysis of numerous documents, the study examines the impact of the chip crisis on companies in the automotive industry and the measures they have taken. The aim is to capture the current assessments, experiences and lessons learned by industry experts, as well as managers and employees in OEMs and suppliers, in order to identify relevant areas for action and research needs. From this, initial considerations can be derived as to how companies in the automotive industry can both better deal with such disruptive events in the value chain in the future and set up their semiconductor strategies in a future-proof manner against the background of the industry's transformation.

The study shows that there are no patent recipes or blueprints for a new formulation of semiconductor strategies and their implementation that can simply be rolled out. Rather, it is important for companies in the automotive industry to find an appropriate way forward in line with the redesign of their business models and work processes, based on their specific starting conditions and contexts. The study identifies six action areas that need to be prioritised in automotive companies

Action area 1:
Creating transparency on semiconductor requirements – establishing consistent information systems

Action area 2:
Actively manage semiconductor risk – establish NextGen risk management for supply chain disruptions

Action area 3:
Semiconductors as core components – developing holistic chip strategies for vehicles

Action area 4:
Create collaborative value creation architectures – build partnerships with chipmakers

Action area 5:
Strengthening semiconductor competence in the automotive industry – qualifying managers, employees, students, and apprentices

Action area 6:
Creating a circular economy – implementing recycling strategies for semiconductors

The study presents these six action areas. It also explores how the role of semiconductors in the vehicle is currently changing, thus creating important preconditions for a deeper understanding of the dynamics of change revealed by the chip crisis and the associated challenges. It thus provides analytical guidance and action-oriented knowledge for managers, employees and works council representatives, while laying foundations for further research into the changing use of semiconductors in the automotive industry as part of the wider transformation of the sector.

Contents

1.

The Chip Crisis in the Automotive Industry – A Symptom of Structural Change?

When the infectious disease COVID-19 began to spread across the globe in early 2020, the automotive industry in Germany was looking back on a decade of steady growth. After the economic and financial crisis from 2007 to 2009, new records had been set for sales, turnover and profits again and again, despite the "diesel gate" in 2015. According to the Federal Statistical Office, the turnover of companies in the automotive industry rose from € 262.5 billion in 2009 to € 436.2 billion in 2019, and the number of employees had also increased almost continuously during this period. This was mainly due to the growth of the Chinese market. While sales figures in the Western markets were largely stagnant, demand for German-made cars in China had exploded across all segments (Puls/Fritsch 2020, 33).[1]

In the face of the first lockdowns in China in February 2020, analyst firms such as IHS Markit and Oliver Wyman predicted a rapid decline in car sales, indicating an abrupt end to this growth dynamics (Wayland 2020; Oliver Wyman 2020). The management of carmakers immediately took steps to reduce vehicle production. As a result of their customers' revised production plans, suppliers of software and electronic components cancelled ongoing orders with manufacturers of microcontrollers and semiconductors for the automotive industry. However, when demand for cars picked up unexpectedly quickly after a brief slump, semiconductor manufacturers had already shifted production capacity previously reserved for the automotive industry to meet the surge in demand for chips for consumer electronics, notebooks and other gadgets such as home fitness equipment at the start of the pandemic. Suddenly there was not enough capacity in the semiconductor fabrication plants, known as fabs, to meet the rapidly growing demand for chips in the automotive industry.

As semiconductors have been incorporated over the years into a wide range of components and systems in modern vehicles – from windscreen wipers and window regulators to engine control modules and infotainment systems – these dissonances in the automotive value chain have huge implications for the industry. If only a single chip is missing, vehicles cannot be completed and delivered. The shortage of semiconductors has forced many OEMs to adapt and cut production despite high demand for vehicles (Frieske/Stieler 2022). At times, vehicles were delivered without chips for non-safety-critical functions such as seat adjustments or certain infotainment system functions (Walsh 2021). Car production plants had to cancel shifts, model series were put on hold and many plants were temporarily closed. In Germany, many employees were repeatedly put on short-time work (Kurzarbeit). Schuh et al. (2022) estimate that in 2021 OEMs were forced to cancel the production of up to 10 million vehicles worldwide due to the shortage of semiconductors. These measures had other side-effects, for example, causing used car prices to explode in the US due to the reduced supply of new cars (Boudette 2021).

After OEMs and suppliers had initially blamed each other for the difficult situation, task forces were immediately formed in the procurement departments. They worked flat out to create transparency about chip demand and feverishly searched the market for additional chips, while trying to allocate the available chips in the best possible way to keep production going. The top management of the OEMs personally contacted the operators of the semiconductor fabs, trying to secure any capacity that might become available. Consultancy firms rushed to develop crisis management strategies, drawing up catalogues of short-, medium- and long-term measures to be taken by companies in the automotive industry. Politicians around the world also reacted, promising large subsidies for investment by the semiconductor industry in new production facilities. However, given the very long lead times required to increase semiconductor manufacturing capacity, it appears that automotive companies will have to accept sales losses due to the semiconductor shortage for the time being.

Experts quickly engaged in an intensive discussion about what lessons could be learned from the situation for the future design of value-added processes in the automotive industry and how their organisational resilience could be strengthened (Katasaliaki et al. 2022). Initially, the chip crisis was interpreted by some experts as evidence of the failure of lean production principles. Companies in the automotive industry were advised, among other things, to increase their overall inventory levels in the future in order to rebuild larger buffers against fluctuations in supply and demand and to reduce dependencies on timely deliveries (Goodman/Chokshi 2021; McLain 2021). Other experts countered that the companies that were initially less affected by the crisis were those whose transparency in production flows and supply chains was due to a high degree of maturity in applying lean production methods. This maturity had enabled them to learn from past supply shortages and to identify and selectively increase their inventories of critical goods (Kim 2021). However, with a few exceptions (e.g. Frieske/Stieler 2022), discussions to date have rarely been based on empirical analyses of the actual experiences of companies in the automotive industry in dealing with the chip crisis.

Against this background, as an extension of the project "HyValue – Hybridisation in the Value Chain", we investigated the impact of the chip crisis on companies in the automotive industry. The aim of our research was to record and reflect on the experiences and lessons learned by industry experts, managers and employees of OEMs and suppliers. Building on this, we sought to identify relevant areas for action to enable automotive companies to better deal with such disruptive events in the value chain in the future, and to outline future research needs. At the same time, we wanted to explore the extent to which the findings from the HyValue project (Heidling/Ziegler 2022) on the development of a prototype of a cross-company collaboration platform for vehicle development projects (Heimberger et al. 2022) and the development of a concept for collaborative service work (Ziegler/Heidling 2023) can contribute to crisis management and resolution.

In the interviews with experts from companies and associations, however, it quickly became clear that the phenomenon of the chip crisis was not limited to a temporary disruption in the automotive value chain that could be dealt with solely by measures within the methodological spectrum of supply chain management. Rather, the chip crisis revealed a more fundamental development dynamic that had been smouldering for a long time and was rooted in deeper structural changes in the industry's core products. The electrification and softwareisation of vehicles, which has clearly gained momentum in the industry in recent years (Boes/Ziegler 2021; Pfeiffer/Author's Collective 2023), is not only having a significant impact on the quantitative demand for semiconductors in vehicles, but is also changing the qualitative use of semiconductors: instead of being just another component on the bill of materials, as was previously often the case, semiconductors are advancing alongside batteries and software to become strategic components in software-defined electric vehicles. The chip crisis has brought these developments and the challenges they pose into sharp focus. They require a far-reaching redefinition of automotive companies' semiconductor strategies and their collaboration practices with semiconductor companies.

Structure and Empirical Basis of the Study

The key findings of this study are presented below. The second section begins with a brief historical reconstruction of the development of the use of semiconductors in vehicles. The third section looks at how the role of semiconductors in vehicles is currently changing. The focus is on the electrification of the powertrain and the introduction of software-defined vehicles. This background is essential for a deeper understanding of the dynamics of change revealed by the chip crisis and the challenges it poses to automotive companies. On this basis, the fourth section takes a closer look at the developments that triggered the chip crisis and provides insights into the immediate measures taken by automotive companies to cope with the situation. This sets the scene for the fifth section, which outlines the key areas for action for automotive companies in terms of reshaping their semiconductor strategies and the challenges this will pose. The concluding outlook summarises the main findings of the study and identifies the need for further research.

The study is based on two empirical pillars. The first pillar consists of qualitative expert interviews with 15 representatives of OEMs, system suppliers and tier-2 suppliers in the German automotive industry, the semiconductor industry as well as associations and research institutions, which were conducted in the period from June to December 2022 in addition to the previous empirical work in the HyValue project (Heidling/Ziegler 2022). Furthermore, interim results were discussed and evaluated in workshops with industry experts and a national and international research community on global value chain development. These discussions provided valuable input.

The second empirical pillar of the study is a comprehensive document analysis. The documents examined include media coverage of the chip crisis in the form of articles and reports in daily newspapers and the trade press, as well as annual reports, press releases, strategy and background papers from companies in the semiconductor and automotive industries, and expert reports from associations and consultancies. On the other hand, relevant public interviews and discussions with experts and company representatives in the context of podcasts, blog posts and presentations at trade events were also included. With a few exceptions, all the documents analysed are publicly available on the Internet and are listed as sources in the bibliography. In the evaluation process, these two empirical pillars were condensed into the present extract of an industry case study.

We would like to thank all the experts who patiently answered our questions during the interviews and provided information and contacts to other interviewees. We would also like to express our special thanks to the Federal Ministry of Education and Research and the European Social Fund for funding the study in the context of the HyValue project, as well as to the Projektträger Karlsruhe for their excellent monitoring of the project. At the ISF Munich, we would like to thank our colleagues for many instructive remarks and critical comments, Frank Seiß for the sound proofreading of the present version and Torsten Royère for designing and fine-tuning the layout of the study.

2.

Semiconductors in Vehicles: A Historical Sketch

When the semiconductor industry took shape in the 1950s[2], the automotive industry was already one of the established industrial sectors, and as one of the leading industries, shaped the economic development of the post-war period (Jürgens et al. 1989; Canzler/Knie 2018). The term Fordism is representative of this and has become widely used in the social science debate to describe the specific pattern of economic and social development in the post-war period (Boyer/Durand 1993; Kuhlmann 2004, 17).

Up until the 1950s, the spectrum of technologies used by the automotive industry in the production of vehicles ranged from mechanics, metalworking and thermodynamics to hydraulics and electrics, while electronics hardly played a role at all at that time. Electronic components were installed in vehicles only in isolated cases. For example, the first car radios produced by the company Blaupunkt in the 1930s used electronic tubes. However, because car radios with tubes were very energy-intensive, expensive and maintenance-intensive, OEMs initially offered them only as optional equipment in premium cars. With the advent of semiconductor technology, electron tubes could be replaced by smaller, more robust and energy-efficient transistors. Combined with the invention of the alternator[3], car radios became affordable and were increasingly fitted as standard in vehicles from the second half of the 1950s (Morris 2014, 329).

In the 1960s, the establishment of the semiconductor industry and the ongoing development of its products and manufacturing processes (such as the invention of planar technology and photolithographic processes) created opportunities for new applications of semiconductors in the automotive industry. Beyond the realm of consumer electronics in the car, the first application-specific circuits were developed to monitor, control and regulate ignition, fuel injection or the alternator[4]. These circuits were not yet implemented as programmable microcontrollers. Instead, various semiconductor components were soldered onto circuit boards according to the system designers' circuit diagrams, and their arrangement performed the desired function.

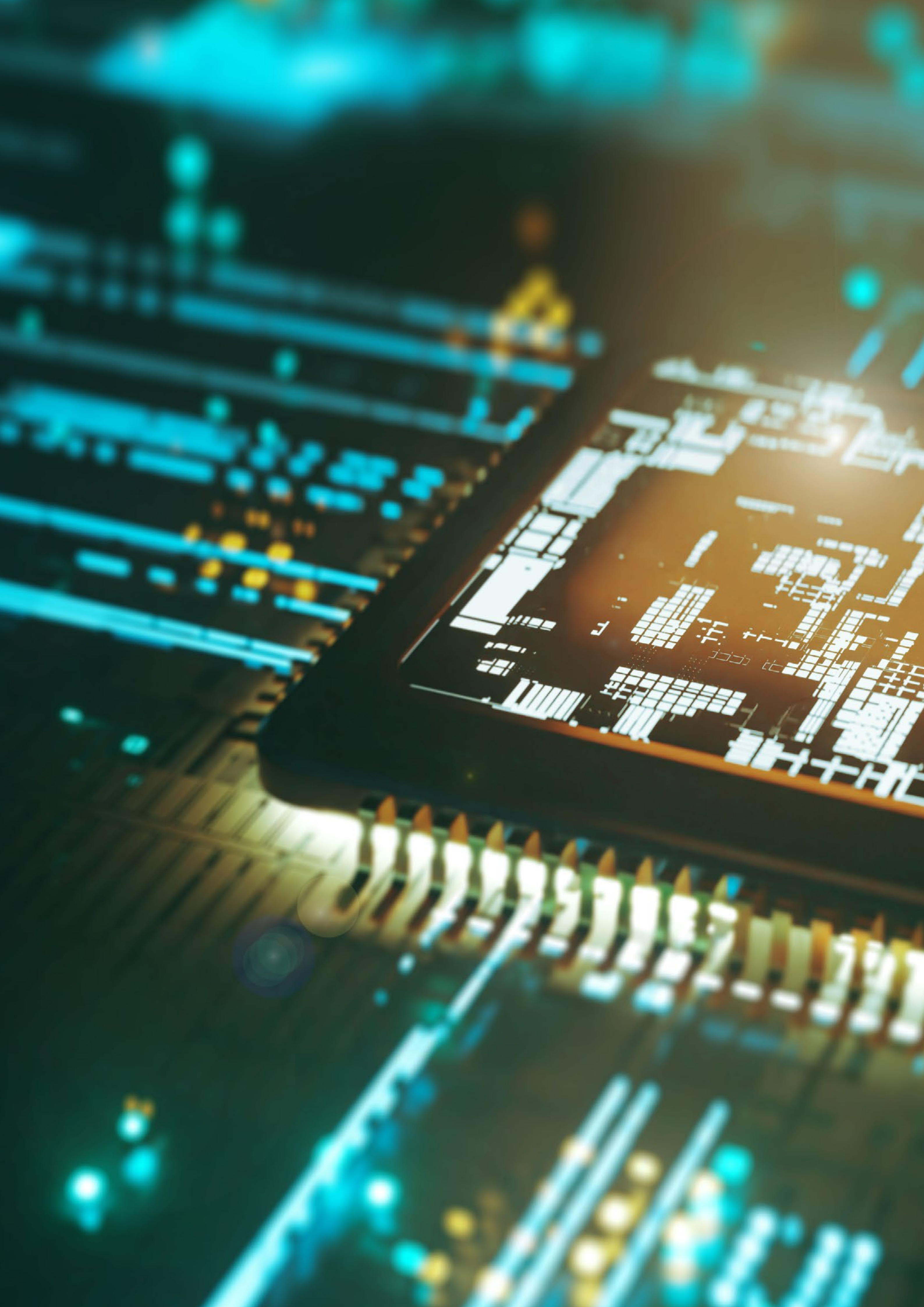
The invention and commercialisation of the microprocessor by Intel a decade later laid the foundation for the development of programmable vehicle controllers and increased their use. As a result, the use of semiconductors in vehicles gradually expanded from the mid-1970s (Bereisa 1983). Many mechanical, hydraulic and electromechanical control modules were now replaced by so-called electronic control units (ECU) connected to sensors and actuators.[5] These "substitution innovations" (Bierich 1987, 1f) opened up more precise control possibilities and became largely indispensable, for example, to comply with exhaust regulations or to optimise fuel consumption in the midst of the 1973 oil price crisis (Shih 2022). ECUs were also less prone to wear and tear than mechanical control modules, for example, and could be applied to vehicles from different manufacturers with less effort, so that over time they could be produced at a lower overall cost. To be used in vehicles, semiconductor components originally designed for consumer electronics had to be adapted to the special requirements of automotive applications. They had to be able to withstand temperature fluctuations, humidity and vibration, as well as meet high standards of electromagnetic compatibility, reliability, availability and functional safety over long product life cycles (Schäuffele/Zurawka 2016).[6]

Initially, individual ECUs were used for specific functions in the vehicle. Software programs were written to perform the functions, e.g. in the case of the airbag control unit, processing data from acceleration and impact sensors in milliseconds to make a deployment decision. As Broy et al. (2007, 356) describe, this software, often written in machine language or C, initially operated strictly locally. It remained functionally and technically isolated, adapted to the limited computing power and memory of the ECU, and was bundled with the hardware by ECU suppliers as part of the overall product, similar to the model applied to mainframes in the early days of the IT industry.[7] Continual improvements in the performance of microelectronics made it possible to use single ECUs for multiple functions and to exchange data between different ECUs via bus systems such as LIN, CAN, FlexRay or MOST. This has made it possible to implement functions that are distributed across several ECUs. Such system developments include, for example, vehicle dynamics systems such as ABS, ASR or ESC (Bingmann 1993; Vdovic et al. 2019).[8]

As more and more analogue controls were replaced by ECUs and ECUs were added for new vehicle functions (Jürgens/Meißner 2005, 77ff), the software and electronics architecture in vehicles took on the form that can basically still be found in the vehicles of established manufacturers today. In technical jargon, the term E/E architecture has become established. It consists of an ever-increasing number of distributed ECUs that are interconnected via various bus systems. One of our interviewees sums up the development as follows:

> *"Semiconductor control has become more and more complex (...). This means that if you have to adapt to the environment, sensors are added, (...) other semiconductors are also needed, for example to regulate electrical voltage, flow and the like (...) So the number of semiconductors has therefore simply increased enormously on average over the years."* Project Manager, System Supplier

For example, at Volvo Cars in 2020, the software and electronics architectures of the vehicle models with their different equipment variants were assembled from a set of more than 120 ECUs (Charette 2021).[9] McKinsey consultants Burkacky et al. (2018) refer to this architecture as the "add a feature, add a box" model, which has led to an ever-increasing complexity of the overall system.



The Value Chain for Software and Electronic Components of Vehicles

Another characteristic of the E/E architecture structure is that it has been designed and implemented as a static system. Both the semiconductor hardware and all the software components must be ready by the start of production of new vehicles and are installed in the production process of the vehicles. Once the vehicles have been delivered, and even during the production period of the respective model series, no changes should be made to the system.

In connection with the evolution of the E/E architecture, an organisational division of labour between OEMs and suppliers in the development of software and electronic components for new vehicles or model variants has become established:

1. the OEMs focus mainly on the overall system design of the E/E architecture and its functional scope, the definition of specifications for the ECUs, their verification and validation, and the vehicle integration, calibration and testing of the overall system. In addition, some OEMs reserve the right to develop and design the infotainment systems at the user interface.[10]

2. the system suppliers develop and produce the ECUs based on the specifications and sell it to the OEMs. They do so on the basis of their ECU platforms, which are adapted in accordance with the specifications. In addition, they often subcontract individual components and modules to Tier-2 suppliers.

Accordingly, the software used to perform the ECU functions is usually developed by the suppliers, who also select the microcontrollers and semiconductors to be used. Both components are sold to OEMs as a bundled product. The core of the innovation work for the development of the ECU platforms and the realisation of new vehicle functions, e.g. driver assistance systems, has thus so far been mainly in the hands of the suppliers (Kalkowski/Mickler 2015, 97).[11]

This division of labour is reflected in the value chain structure for automotive software and electronics. For example, former Volkswagen CEO Herbert Diess stated in 2021 that only 10% of the software in the group's vehicles was developed by the OEM, while 90% came from suppliers (Matthes/Menzel 2021). Consequently, the development of vehicle electronics and software is characterised by cross-company projects, often involving several suppliers (Heidling 2014; Hab/Wagner 2017). Based on this division of labour, an organisational and process structure has emerged which in turn has reinforced the design pattern of the software and electronics architecture. This represented the technological "state of the art" (Knie 1991, 35) until the 2010s and was considered a "highly successful division of labour" (Broy et al. 2007, 357).[12]

The V-model has become established in the German automotive industry as a process model for structuring ECU development projects (Schäuffele/Zurawka 2016; Schmidtner/Timinger 2022). According to this model, at the beginning of the development process for new vehicle models, system developers at the OEM design the E/E architecture based on the preliminary work on previous models and define the functional and non-functional requirements for the subsystems to be developed. Based on this, specifications for the subsystems are drawn up, which are then passed on to the system suppliers in the form of a product requirements document. At the system supplier, functional developers analyse the requirements, break them down into sub-functions if necessary, and produce a scope statement. The various functions are then modelled using model-based design environments (e.g. Matlab/Simulink). These modelled sub-functions are then coded. The software of the sub-functions is then tested and integrated. The tested work products are handed over to the relevant OEM departments where they are verified and validated using techniques such as a hardware-in-the-loop system. The result of a cycle through the V-model is the "product", which can reach a certain degree of maturity (functional sample, prototype, pre-production sample, etc.) of the planned end product (Zurawka/Schäuffele 2016, 26).[13] Finally, the overall integration of the developed systems into the vehicle takes place at the OEM.

To improve the integration process of heterogeneous control units, an industry development partnership with AUTOSAR was initiated in 2003. The partnership aims to establish a hardware-independent, standardised software architecture for ECUs. This reference architecture is intended to ensure that ECUs from different manufacturers are compatible with each other and can be verified and validated uniformly in terms of reliability and functional safety (Jakobs/Tröger 2017).[14] As a result of this division of labour, in many areas it is the Tier 1 or sometimes Tier 2 suppliers who source the semiconductors needed for the vehicle systems and control the interface with the semiconductor companies, which are usually classified as Tier 2 or Tier 3 suppliers. At the same time, the historical division of labour has had the side-effect that OEMs have so far taken only a peripheral interest in the semiconductors that go into the ECUs of their vehicles and where they come from. From the point of view of the semiconductor industry, this division of labour is seen in the following way:

> *"The car manufacturer itself is rarely in direct contact with a chip manufacturer. These are in fact the Tier 1s (...) the OEMs define the requirements, which are then cascaded down the chain to the respective manufacturer at some point."*
> Semiconductor Industry Expert

In turn, suppliers have often seen no need to share information with OEMs about the microcontrollers and semiconductors they use. Venture capitalist Olaf Sakkers (2020) therefore also describes the E/E architectures in the vehicles of established OEMs as a composition of "intra-vehicle fiefdoms", which are controlled and defended by the respective system suppliers. In this context, our interviewees point out that the Tier 1 suppliers can in part also refer to the contractual situation when defending their spheres of influence:

> *"The Tier 1 has contracts not only with a single OEM, but also with other OEMs. So that's why some Tier 1s don't want to have joint meetings with a single OEM and Tier 2, 3, 4 suppliers together. It is also contractually and politically difficult. Some even don't participate in such multi-party calls at all because they say 'we are your supplier and the rest is none of your business'."*
> Industry Expert

Decentralised decision-making on the use of semiconductors and their close coupling with software at Tier 1 and Tier 2 suppliers has also contributed to the fact that few standard semiconductors have been used between different ECUs in vehicles and that microcontrollers can be very heterogeneous in some cases. As one interviewee described it, a "patchwork" has become established, which increases the overall vulnerability of the production process: If just one of the semiconductors needed for the ECU is missing, vehicles cannot be completed and delivered.

This brief historical reconstruction shows that the current use of semiconductors in vehicles, as well as the development of E/E architectures, are less the result of strategic decisions taken by companies in the automotive industry in full awareness of all options and consequences. Rather, they are the result of complex "closure and consolidation processes" (Knie 1991, 306), as sociological research has shown for other technologies such as the diesel engine. Over the years, more and more semiconductor-based control units have been integrated into vehicles on an ad hoc basis, and their use has expanded, building on the previous generation. Organisational structures and spheres of influence formed around this structure, which in turn stabilised it. A fundamental re-conceptualisation of the E/E architecture and thus of the use of semiconductors did not take place until well into the 2010s. As will be shown in section 3, this sedimented design approach is now increasingly reaching its limits due to the qualitative increase in the importance of semiconductors, software and the Internet for the functioning of vehicles, and is being fundamentally challenged by new competitors.

The Automotive Industry as a Market for the Semiconductor Industry

The automotive industry has become a steadily growing market for the semiconductor industry as the number of control units installed in vehicles has increased.[15] According to estimates by the consultancy Deloitte (cited in Charette 2021), the cost of electronic components and systems as a proportion of total vehicle costs has already risen from 1% in 1960 to up to 40% in 2017.[16]

Overall, however, the share of products supplied by the semiconductor industry to the automotive industry is still small compared to other target industries such as consumer electronics or the server market. In 2018, it amounted to 11.5% worldwide ($53.9 billion) of a total market volume of $469 billion (SIA 2019, 10; ZVEI 2019, 25). It is rumoured that the chip demand of the tech company Apple alone exceeds the market volume of the entire chip demand of the global automotive industry (Shiao et al. 2021). For European semiconductor companies, the automotive industry is the largest customer with a share of 35%, similar to the Japanese semiconductor industry.[17] However, the European semiconductor industry's share of the global semiconductor market has been declining steadily over the past 20 years and currently stands at 9%. Compared to other segments of the semiconductor market, the automotive industry has several unique characteristics.

First, the leading automotive semiconductor manufacturers are not the semiconductor industry's top-selling companies such as Intel, Samsung, TSMC or Qualcomm. Instead, they are companies such as Europe's Infineon, NXP Semiconductors, STMicroelectronics and the semiconductor division of Bosch, Renesas and ROHM from Japan, or Onsemi, Texas Instruments, Micron and Analog Devices from the US. These companies typically both design and manufacture their chips. In recent years, however, an increasing number of designs have been handed over to contract manufacturers (foundries), which then produce the semiconductors from wafers according to the designs. Infineon and NXP are the largest semiconductor manufacturers in the automotive industry, each with a market share of almost 12%. However, a clear market leader has not yet emerged (Frieske et al. 2022, 81).[18] Even among the foundries that produce for the automotive sector, the heavyweights of the industry, such as TSMC and Samsung, do not dominate the market on their own. GlobalFoundries, which was spun off from AMD in 2008 and has adapted some of its manufacturing processes to the specific requirements of the automotive industry, also plays an important role (Stroh 2017).

Second, most of the chips used in the automotive industry have so far been manufactured with nodes in excess of 20 nanometres:

> *"Some of the technology that car manufacturers are using is still at 400, 600 nanometres. When I compare that with new Intel chips, for example, I still think of the moon landing. So these are ancient chips, some of which are used there, some of which are no longer lucrative for the manufacturers."* Industry Expert

The most powerful chips on the market, on the other hand, have nodes with nanometre sizes in the single-digit range – and the trend is down.[19] As a result, semiconductor manufacturers often have to use older manufacturing techniques to produce chips for the automotive industry (Scholz 2022). As one interviewee described, this use is particularly pronounced in commercial vehicles such as trucks and vans:

> *"On the commercial vehicle side, we have very long product lives, sometimes 15, 20 years. The development cycles are longer. On the electronics side, we have now seen in the crisis that some microcontrollers at Infineon and Texas Instruments are simply no longer relevant, because they say: end of life, mini-quantities."* Manager, OEM

Third, the automotive industry uses fewer standard semiconductors than other target industries:

> *"The share of specialised semiconductors in the automotive industry is significantly higher than in the consumer industry, for example (...) because each vehicle can be very different, (...) because a supplier makes its design in a special way, and the semiconductors have to interact accordingly (...) which is then only used for one model series. These issues make automotive semiconductors very complex."* Semiconductor Industry Expert

Due to the high number of variants, unit volumes are also significantly lower than in other target industries of the chip industry. As a result, the economies of scale and the margins that can be achieved are lower. This is one of the reasons why the automotive industry has not been a very attractive target market for major chipmakers:

> "Of course, we always try to buy as much as we can directly from the chipmakers, but Samsung, for example, doesn't even talk to us because our quantities are so small compared to consumer electronics, they don't care." Buyer, System Supplier

Fourth, automotive companies often expect semiconductor companies to deliver their chips to the factories at fixed prices and at the times required by just-in-time and just-in-sequence production strategies. While automotive companies sometimes place orders with lead times of 12 weeks, semiconductor manufacturers can require lead times of up to 24 months. In contrast, the semiconductor industry's collaboration with consumer electronics customers typically involves longer-term development partnerships and, in some cases, multi-year supply agreements (Schuh et al. 2022). While companies in the automotive industry have thus been able to save on inventory costs, it has been primarily the chip manufacturers who have had to bear the uncertainties and risks of investing in designs and production capacities for the automotive industry.

Fifth, chipmakers need to develop specific competencies to supply the automotive industry as well as other more regulated target markets such as healthcare or energy. For example, to be used in safety-critical applications in vehicles, microcontrollers and semiconductors must go through automotive certification processes. As one interviewee described, chipmakers need to build up the expertise to meet these requirements:

> *"It is like this, in the automotive industry there is an added complexity. You have to be automotive certified, you have to be able to do automotive. It's not like other industries where you can just change suppliers or something like that. The number of vendors that can do automotive is just limited. In most cases there are only a handful of companies that can supply a particular product or meet the requirements. (...) It takes many years, in fact, to get a consumer semiconductor manufacturer to supply and produce automotive semiconductors. So we're not talking about a few years, we're talking about at least five to ten years to get somebody there."*
> Semiconductor Industry Expert

Due to these characteristics of the automotive industry as a target sector for chipmakers, the world's leading OEMs have also experienced during the crisis, as described by one interviewee, that they are not necessarily at the top of the priority list of some semiconductor companies:

> *"The CEO of the OEM wanted to go to semiconductor manufacturer X in person and is told, 'Yes, we'll have to see if we have a timeslot available'. If an Apple executive were to go to a semiconductor manufacturer, the statement wouldn't be, we'll have to see."*
> Manager, OEM

Furthermore, the automotive industry, as a target market for the semiconductor industry, is currently undergoing a number of profound changes. These changes and their impact on semiconductor demand, as well as on the co-operation between the two industries, are the focus of the following section.

3.

From Intermediate Goods to Strategic Components: The Changing Role of Semiconductors in Vehicles

Two developments in particular are currently driving demand for semiconductors in the automotive industry: the electrification of the powertrain, and the transformation of vehicle software and electronics architecture and the realisation of new software-based applications. In recent years, as one interviewee describes, these developments have gained enormous momentum and, in particular because of their concurrence and interaction, pose new challenges for established companies:

> *"Electric vehicles and autonomous driving or other higher functions, these developments have really happened cumulatively. (...) For the car industry, this increase in functions, which has only happened in the last few years, has been faster than usual. The car industry is normally prepared for a way in which things are introduced bit by bit, it takes time, the cycles are very long. So it really does take years to introduce certain features. But in the last few years, so many features have developed so quickly that it was simply difficult to predict, even for the automotive industry."*
> Industry Expert

The associated changes of these developments for semiconductor demand are presented in the following sections.

Power Semiconductor Devices: Key Components of the Electric Powertrain

A key driver of the growing demand for semiconductors in the automotive industry is the electrification of the powertrain. Over the last twenty years, the competitiveness of the electric powertrain compared to the internal combustion engine (ICE) powertrain has gradually increased. This is due to a number of interrelated developments. These include the continuous work on technological innovations, in particular the adaptation and further development of lithium-ion technology for the construction of the battery cells used in the vehicles (Eberhard 2006); the expansion and further development of the charging infrastructure; increasing economies of scale through the scaling up of electric vehicle production; the continuous tightening of legal requirements for emission reduction[20]; as well as government subsidies for the purchase of zero-emission vehicles through purchase premiums and other economic policy instruments (Sanguesa et al. 2021). As a result, the average cost of an electric vehicle is increasingly converging with the average cost of internal combustion engine vehicles (Liu et al. 2021; Ewing 2023), although in the last decade the expansion of oil production, particularly in the US, based on new extraction methods such as superfracking, has counteracted this convergence.

The electrification of the powertrain is changing the demand for semiconductors in the vehicle. While many components used in ICE vehicles, such as injection systems, pistons, exhaust pipes or emission control systems, are no longer needed (Bauer et al. 2020), the demand for semiconductors in the vehicle is increasing. This is particularly true for power electronics, which control and convert electrical energy in vehicles (Emadi 2017). In addition to the low-voltage electrical system, which is also required in ICE vehicles, power electronics in electric vehicles regulate the interaction between the battery and the electric motor in the high-voltage electrical system. For example, the power electronics control the charging process of the battery, convert the direct current (DC) of the battery into alternating voltage (AC) for the electric motors, and control the electric motor.[21] At the same time, it enables energy to be recovered through regenerative braking (Lindemann 2019). The power semiconductors used for this (e.g. inverters, DC/DC converters) must be able to handle high voltages (400 to 800 volts in the vehicle electrical system).[22] A new generation of power semiconductors based on silicon carbide (SiC) and gallium nitride (GaN) wafers has been under development for several years. The use of SiC as a material is expected to enable longer ranges and faster charging in battery-powered vehicles, in part due to its higher semiconductor efficiency compared to other substrates (Ding et al. 2017).[23]

To control the battery and power electronics components, microcontrollers such as battery management units or cell monitoring units are used, which also incorporate silicon semiconductors. In combination with software, e.g. for battery management systems, engine control and temperature management, the use of semiconductors will become a differentiating factor for the powertrain in vehicles, as one interviewee points out:

"Power electronics is currently a core competence (...) because in terms of drive efficiency, i.e., range, which is logically related to consumption, performance, this is currently a very dynamic environment and is seen as a game changer if you master the competence." System Supplier Executive

By further developing the software and the semiconductors, powertrain performance can be increased to achieve the greatest possible range at the lowest possible cost.

Overall, analysts and consultants calculate that more than twice as many semiconductors are used in battery electric vehicles than in ICE vehicles. According to management consultancy Kearney, the cost of all semiconductors used in an ICE powertrain in an average vehicle is $90, while the cost of semiconductors needed for battery electric vehicles averages $580, which is 544.4% higher (Shiao et al. 2021). According to management consultancy Roland Berger's Automotive Electronics Component Model, the cost of electronics (semiconductors + software) in an ICE vehicle averaged $3,145 in 2019. By contrast, the cost of electronics in a battery electric vehicle with autonomous driving features is forecast to increase by 124% to an average of $7,030 by 2025. This would increase their share of total vehicle costs from 16% to 35% (Meissner et al. 2020, 7).

Increasingly, however, manufacturers of semiconductors for power electronics and its control are moving beyond the supply of semiconductor hardware to become involved in the development of software. For example, NXP has entered into a partnership with Continental's subsidiary Elektrobit to jointly develop a battery management system solution that includes semiconductor hardware and software (Schäfer 2022).

Until recently, it has been difficult for established companies in the automotive industry to predict demand for electric vehicles and adjust production capacity accordingly – especially as demand for vehicles with conventional powertrains continues to be met in parallel. In the midst of the Corona pandemic, this situation changed. In August 2022, CARB adopted a new regulation to allow only zero-emission vehicles on Californian roads from 2035, and in October 2022 it was announced that EU member states and the European Parliament had also agreed on legislation to allow only zero-emission vehicles from 2035

(Wittich et al. 2022). In China, the world's largest car market, no such date has yet been set. However, in September 2020, the Chinese government announced a target to make the entire economy carbon-neutral by 2060, and is massively promoting the sale of electric vehicles through purchase incentives (Meng Fang/Zhou 2022), which has contributed to China's emergence as one of the world's leading electric vehicle markets.

These political decisions created a new framework for established manufacturers, some of which had already announced their intention to develop all-electric models in the future (Blumer/Tabuchi 2021). Volkswagen and Audi, for example, have announced plans to develop all-electric vehicles from 2026 and to sell all-electric vehicles in the EU from 2033 (Gomoll 2022; Fasse 2021). While until recently many OEMs considered battery electric powertrains as a viable option among other alternative powertrain technologies such as hydrogen and e-fuels, they have now announced similar targets. Taking these developments into account, the demand for power semiconductors in the automotive industry is expected to continue to grow, at least for the time being.

The Transformation of Vehicle Software: Semiconductors as Enablers of Software-Defined Vehicles

A further development that is contributing to the expansion of the use of semiconductors in vehicles is the continuing increase in the importance of vehicle software. Today, it is a legal requirement for vehicles to be equipped with a wide range of software-based safety features, such as emergency braking assistance. In premium vehicles in particular, software-based functions ranging from infotainment to advanced driving assistance systems (ADAS) and autonomous driving are increasingly becoming a decisive factor in end customers' purchasing decisions (Weiß et al. 2018).[24] And the quality of the software that controls the power electronics, battery systems and charging infrastructure also plays a crucial role in the performance of the electric powertrain. At the beginning of the 2000s, industry experts estimated that software development accounted for 80% of all innovation activities in the automotive industry (Leen/Heffernan 2002, 88), with the result that an average premium vehicle in the past decade contained up to one hundred million lines of code (Broy et al. 2011). In order to fulfil its functions, this vehicle software relies on semiconductors on which it is stored and executed, which constantly generate data about their environment and transmit these data streams in milliseconds between computing instances, sensors and actuators. But the established software and electronic architectures in cars are increasingly reaching their limits in current innovation processes.

On the one hand, despite the establishment of standardised reference architectures for ECU development such as AUTOSAR, the ever-increasing number of decentralised ECUs has increased the complexity of vehicle development processes and become a permanent source of problems and cost drivers (Zerfowski/Crepin 2019, 37; Antinyan 2020). When the ECU is integrated into the overall system, the interaction of ECUs from different suppliers must be tested and calibrated at great expense. As a result, errors in the software can sometimes only be detected at a late stage in the development process. Corrective work is then not only costly, but can also jeopardise the start of production.[25] Increasingly, software problems are also appearing in vehicles after they have been delivered. According to the US National Highway Traffic Safety Administration (NHTSA), the number of recalls in the US due to software problems has tripled between 2009 and 2019. Fixing these problems in the workshop is not only costly. There is also a safety risk if vehicles with software errors remain on the road until a software update is available and patched (Lilly 2020).

On the other hand, established software and electronics architectures are not designed to meet the requirements of complex and data-intensive applications such as infotainment, driver assistance systems or even autonomous driving functions. The enormous performance demands placed on semiconductors by such applications require the use of state-of-the-art system-on-chips (SoCs) and are no longer feasible with the microcontrollers used in the automotive industry to date.[26] In addition, to support the intention of many OEMs to install and monetise additional software functions after delivery of the vehicle, it will be necessary not to decide on the use of semiconductor hardware primarily on the basis of cost optimisation. Instead, as with smartphones and PCs, additional resources will need to be embedded in the vehicle and potential expansion stages will need to be considered at the vehicle design stage. The use of semiconductors is thus, as industry expert Henner Lehne puts it, "increasingly moving from a pure parts issue to a tech issue" (cited in Stroh 2021).

In view of these requirements, ongoing developments in several key technologies are opening up opportunities to develop vehicle software differently, to use it in new ways and to overcome the limitations of established software and electronics architectures. For example, the increase in data transfer rates in the vehicle through technologies such as automotive Ethernet and CAN FD, and the further development of virtualisation technologies for automotive applications, enable vehicle components, semiconductor hardware and vehicle software to be more decoupled from each other. A smaller number of high-performance chips can then be used for a much larger range of functions in the vehicle.[27] In addition, a variety of new applications, such as the collection and analysis of fleet driving data or remote access to vehicle software for updating, configuring, upgrading and controlling (e.g. unlocking the doors via smartphone), are becoming possible by connecting vehicles to IT infrastructures in public or private clouds via the Internet and by improving wireless data transmission technologies (5G).

In combination, the pressure to innovate generated by changing market requirements on the one hand and new technological possibilities on the other is challenging the "techno-economic paradigm" for the design of software and electronic architectures in vehicles that has been established in the automotive industry for decades, as well as the corresponding "organisational practices" (Perez 2002, 14) and, not least, the use of semiconductors.

Centralising the Software and Electronics Architecture: Towards the Software-Defined Vehicle

For decades, the evolutionary development of software and electronics architecture and the static nature of the system once vehicles were delivered were rarely questioned. This changed in the first half of the 2010s. In Tesla's Model S, which was launched in 2012, the potential of the technological possibilities of the then emerging "Internet of Things" (Ziegler 2020, 27-44) was to be adapted and used for the development of the vehicle software in order to realise a dynamic software and electronics architecture in the vehicle. This happened at a time when established OEMs were focusing on connecting their infotainment systems to the Internet and trying to make this area of vehicle software updateable (Taub 2016; Coppola/Morisio 2017, 3f). At Tesla, the goal was to develop a system in which the entire vehicle software could be continuously changed via an Internet connection. At the same time, the system had to meet the highest functional safety requirements for the safety-relevant functions in the vehicle.

To achieve this, Tesla had to break with the established division of labour in the automotive industry and, as an OEM, no longer outsource the majority of its vehicle software development work to suppliers. Instead, the company set up its own vehicle software development organisation, which included many automotive software specialists recruited from system suppliers. The "Vehicle Software Organisation" was given the task of developing not only infotainment, but also application software for functions such as engine control, thermal management, battery management, door locking, windows and driver assistance, including the firmware firmly embedded in the ECUs (from the boot loader to the real-time operating system (RTOS)). Instead of buying them from automotive suppliers, Tesla bought most of the SoCs and microcontrollers used in its cars directly from chipmakers, such as infotainment chips from Intel and later AMD, digital signal processors (DSPs) for continuous processing of audio and video signals from Texas Instruments, for example, and other chips from Freescale (now NXP) or Melexis.[28] In parallel, a continuous tool chain was established for development, test automation, validation, calibration and deployment of new vehicle software via OTA updates

While working on this architecture and toolchain, Tesla's developers went through an extensive learning process. As a start-up, the company had the advantage over established OEMs of being able to start with a small fleet of vehicles and gradually scale up the learning experience. Rather than installing a dedicated ECU for each function, the decision was made to integrate high-performance computers for specific zones into the vehicle and connect them to each other and to sensors, actuators and smaller microcontrollers via powerful data links. The vehicle's computers were equipped with a hardware abstraction layer and perform larger functional scopes in their respective zones, such as autopilot (driver assistance systems and autonomous driving functions), infotainment and instrument cluster, body and chassis (electric powertrain). A terminal gateway connects the components in the vehicle to back-end IT infrastructures via the Internet. As a result, the number of ECUs installed in the Model S and subsequent models has been significantly reduced.[29]

Compared to the established software and electronics architectures, the variant of a "zonal architecture" (Meissner et al. 2020, 12; Kouthon 2022) implemented at Tesla involves a number of changes and opens up new possibilities. Under the heading of "software-defined vehicle", similar variants have not only been replicated at other electric startups such as NIO and Lucid Motors. In the second half of the 2010s, this architecture also guided the efforts of more and more OEMs and system suppliers looking to re-engineer their established E/E architectures.

Changes in the Software Development Process

Historically, the software used in vehicles has been developed, tested, validated and calibrated in line with the product development process and installed during vehicle production. The structure of the software development process remained very much aligned to the overall vehicle development process and its schedule. Accordingly, the entire software and electronics architecture was primarily designed as a static system (Jakobs/Tröger 2017, 1479). Changes to both the vehicle software and the semiconductor hardware should only be introduced for new model series. If software problems occurred in vehicles on the road, they could only be diagnosed in the workshop by connecting to the ODB port and using the UDS diagnostic communication protocol (Kessler 2017).[30] For vehicles in the field, there were therefore very limited opportunities to implement changing information requirements during their lifecycle or to evaluate data parameters other than those created during the development process for fault diagnosis.

In the context of the realisation of software-defined vehicles, the existing software development process in the automotive industry is changing. The increasing decoupling of software from semiconductor hardware, the modularisation of application software (Ziegler 2022, 11), and the Internet-based connection to a back-end make it possible to transform the static architecture into a dynamic one. Not only in the infotainment area, but also in all other areas of the car, the software and electronics architecture is being designed in such a way that the vehicle software can be further developed over the life cycle of the car and modified remotely via software updates.[31] This mechanism can be used to continuously fix bugs in the software, adjust software configurations or make improvements to the existing software (e.g. user interface optimisation, technical debt reduction and code refactoring), as well as adding new functionality.[32] At the same time, instead of running and maintaining several different software versions in parallel, it becomes possible to run one current version of the vehicle software on the entire fleet (if the semiconductor hardware allows this), which differs only in the configurations (e.g. country-specific).

In connection with the dynamisation of vehicle software, the dimensions of uncertainty in its development are increasing along with the design possibilities. Instead of viewing vehicle software primarily as a complicated system with so-called "known unknowns" and treating it accordingly in the process models underlying the development process, vehicle software is now increasingly taking on the character of an emergent complex system with many so-called "unknown unknowns" (Kurtz/Snowden 2003). Due to the growing complexity of the work object, the established V-model is reaching its limits (Ziegler et al. 2020, 43ff; Böhle et al. 2016). Especially for novel applications such as the development of autonomous driving functions, an approach in which all properties of the software to be developed are specified in the initial phase and then sequentially developed and validated according to plan does not lead to good results. Instead, it has become common practice in these contexts to translate assumptions about the system's behaviour and functionality into software increments at an early stage, to test them repeatedly through experiments, and to base further development on the feedback from the tests. In addition to changes in the use of technology, it is therefore also essential to redesign automotive software development processes to take advantage of centralised software and electronic architectures (Pfeffer et al. 2019).

In the process, procedures and practices of agile software development and DevOps (Johnson et al. 2018; Dumitrescu et al. 2021; Kim et al. 2022) are adapted to the automotive context and a corresponding tool chain for the continuous development of vehicle software is established. This includes, for example, the establishment of a distributed version control system at the OEM for the entire vehicle software and the development of an automated test and validation environment in which new software increments can be continuously tested, validated (especially with regard to functional safety requirements) and deployed.[33] Similar to continuous integration and continuous deployment (CI/CD) practices in tech companies, such automation steps in the development process can significantly simplify and shorten the code-build-deploy loop (Daum 2022).[34] While many established OEMs are now able to remotely update software in the infotainment area and some other subsystems, BMW, for example, is also able to provide updates for all software in its vehicles on all ECUs and has reportedly been doing so since 2019 (BMW 2022a; Bielawski et al. 2020, 2).

At the same time, the use of high-performance computers that can perform many different functions simultaneously reduces the complexity of the overall architecture and integration effort. In addition to lower testing costs, the total number of ECUs can be reduced and fewer cables need to be installed. In the case of electric vehicles, both weight reduction and increased energy efficiency of semiconductors always have a direct impact on range.[35]

Reducing the number of ECUs also means that OEMs have significantly fewer supply chains to manage.

Overall, the introduction of a centralised software and electronics architecture creates the basis for much greater decoupling of vehicle software development from the development process of vehicle components and electronics hardware. Vehicle software development can proceed at its own pace. But it also no longer ends with the start of production, but can be maintained over the entire lifecycle of the vehicle. The Internet capability of the vehicle also creates new requirements for risk management and ensuring cybersecurity. In 2016, employees of the Chinese tech company Tencent were able to access the Model S's gateway and CAN bus via WLAN, allowing them to remotely control the vehicle (Nie et al. 2017). To address this vulnerability, engineers at Tesla developed a cryptographic method that checks a digital security code before each software update applied to vehicles.[36]

To capitalise on the potential offered by centralised software and electronics architectures, many established OEMs seek to expand their value-added software development activities. While industry giants such as Volkswagen (Cariad) and Toyota (Arene) are setting up their own tech units to develop centralised software and electronics architectures, system suppliers such as Bosch, Continental, ZF and Aptiv are reorganising their automotive electronics and vehicle software divisions, entering into new partnerships and expanding their portfolios through acquisitions in order to offer their customers holistic solutions for the design of "software-defined vehicles".

Implementing New Applications and Transforming the Customer Relationship

Centralising the software and electronics architecture also enables car manufacturers to implement a range of new applications in and around the vehicle. By connecting to back-end IT infrastructures, data from the vehicle can be collected and analysed in data lakes (Geurkink 2022). This data can be used, for example, to improve the development processes of vehicle components. It can also become the basis for new applications such as predictive maintenance, data-based fleet management and personalised car insurance, or for integrating the offerings of the global "information space" (Boes/Kämpf 2007) – from music, karaoke and video apps to games and navigation – into the infotainment of vehicles on a personalised basis. The connection of a back-end IT infrastructure to the vehicle thus creates the opportunity for OEMs and third parties to maintain a permanent, digitally mediated relationship with end customers and to monetise software-based functions independently over the product life cycle of the vehicles (Boes/Ziegler 2021, 36; Geurkink 2022). For example, software updates can be used to activate seat heating or extra engine power, and lighting and bodywork can be used to personalise the vehicle's appearance.[37] In order to implement all these possibilities, it is important to have scalable chip resources in the vehicle, which may only be needed at a later point in the vehicle's life cycle.

The use of advanced SoCs in vehicles also makes it possible to implement functions that require high memory and processing capacities. In addition to infotainment, these include advanced automated driving (e.g. distance, lane and parking assistants) and autonomous driving – whether in specific Operational Design Domains (ODD) such as on motorways or in so-called robotaxis, which are currently being operated without safety drivers in geographically limited areas by companies such as Waymo (San Francisco/Phoenix), GM Cruise (San Francisco) or Baidu (Wuhan, Chongqing, Shenzhen). By using SoCs with parallel processing capabilities (GPUs), powerful machine learning algorithms can be efficiently deployed in the vehicle. These algorithms process huge amounts of sensor data such as camera, radar, ultrasonic, lidar and geospatial data in near real time to drive the vehicle. The development and training of these algorithms in turn requires a continuous two-way transfer of vehicle data between the vehicle and the cloud infrastructure, where the machine learning algorithms are developed outside the vehicle, trained with simulation data, revised, and tested for functional safety before a new version is deployed as an OTA upgrade to the autonomous driving software on the SoC (Chang et al. 2022).[38]

This fundamental reorientation of the software and electronics architecture in vehicles and the connection of vehicles to the Internet is further changing the role of semiconductors in vehicles. In combination with software, they are becoming strategic building blocks in the car. At the same time, there are increasing signs that this is changing the value chain in which they are produced and find their way into OEM vehicles.

From Tier 3 to Tier 0.5: The Ambitions of the Producers of High-Performance Chips in the Automotive Industry

The efforts of OEMs and system suppliers to redefine software and electronics architectures in vehicles coincide with major efforts by leading chipmakers to expand their automotive activities. Building on their core competencies, they are pursuing the development of energy-efficient, high-performance chips for the automotive industry and are seeking to position themselves as partners to OEMs on the path to the software-defined electric vehicle. In addition to power electronics, they aim to provide the chips needed for infotainment, driver assistance and autonomous driving. In many cases, however, they are not just supplying the chips, but also providing the appropriate software development and runtime environments for developing applications for their chips. Some have even moved into providing integrated solutions, e.g. for advanced driver assistance systems, thereby significantly expanding their software development capabilities.

In March 2017, for example, Intel, the world's largest semiconductor company by revenue, acquired the Israeli company Mobileye for $15.3 billion. Mobileye develops software for driver assistance systems and autonomous driving functions, and designs both the chips required for this with its EyeQ series and sensor technology such as the cameras themselves.[39] Nvidia, one of the leading chip designers of graphics processing units (GPUs), introduced the Nvidia DRIVE SoC specifically designed for driver assistance systems and autonomous driving at the 2015 Consumer Electronics Show (CES) in Las Vegas and has since continued to develop its GPU architecture and software tools for developing autonomous driving functions with Nvidia HYPERION. Qualcomm, the market leader in chip design for Android smartphones and wireless communications, has also been working intensively for several years to make the automotive industry an important growth market for its business. At CES 2023, Qualcomm unveiled Snapdragon RIDE Flex, the first SoC to combine infotainment with driver assistance and autonomous driving capabilities, aiming to provide nothing less than the "digital chassis" for the vehicles of the future. Qualcomm's $4.5 billion acquisition of the Arriver software division of Swedish systems supplier Veoneer, which beat out automotive supplier Magna, underlines the company's efforts to expand its software development capabilities for driver assistance and autonomous driving functions. It has reportedly been working with BMW, among others, to provide an integrated system for advanced driver assistance and autonomous driving functions (Bundeskartellamt 2022; BMW 2022b). Samsung, for its part, is not only increasing its sales of memory chips and cameras for the automotive industry, but in 2017 also launched the Exynos Auto V chip series for in-vehicle infotainment and telecommunications, which is now being used in Volkswagen and Audi vehicles, for example. TSMC, the world's largest foundry, has also seen a significant increase in orders for the automotive target market in recent years. Among other things, TSMC is rumoured to have been selected by Tesla to manufacture the next generation of Tesla's self-designed Hardware 4.0 chip for automated driving in 4-nanometre process (Lambert 2022). TSMC is also reported to be considering building its first European fab in Dresden and a fab in Japan to meet growing demand from the automotive industry (Li et al. 2022).

While the automotive industry has historically been more of a niche market for semiconductor leaders, they now see significant growth opportunities in the context of efforts to rethink software and electronics architecture. Even before the pandemic, McKinsey projected automotive software and electronics revenues growing from $238bn in 2020 to $469bn in 2030 (Burkacky et al. 2019). Semiconductor leaders are scrambling to secure a piece of this pie.

However, when it comes to working with automotive companies, the leading chipmakers are taking a different approach from the companies that have traditionally produced the majority of semiconductors and microcontrollers for the automotive industry. Instead of selling their products almost exclusively to suppliers, they are seeking direct relationships with OEMs. Instead of supplying their products at fixed prices over short time horizons, they expect car companies to enter into longer-term partnerships in which cooperation is on a more equal footing, risks are shared and potential profits from cooperation are shared, too. For example, according to reports in the Financial Times and Handelsblatt, and recently confirmed by Mercedes, Nvidia has agreed with Mercedes to receive a 50% share of revenues generated by the partnership for the development of autonomous driving functions (Nuttall 2020; Hohensee 2023). And Qualcomm is said to have received contractual assurances from BMW that it can continue to commercialise the results of the joint development partnership for autonomous driving functions (Hubik/Hofer 2022). The established structure of the value chain between the automotive and semiconductor industries is thus being shaken up. Irwin (2023a) interprets these developments to mean that chip manufacturers such as Mobileye, Nvidia and Qualcomm are seeking a new role in the automotive industry and proposes the term Tier 0.5 for them.

This fundamental transformation of the role of semiconductors in the car (and beyond) was already underway when the chip crisis was triggered in the wake of the COVID 19 pandemic. The following section traces the development of the chip crisis in the automotive industry and provides an overview of the immediate measures taken by companies to deal with it.

4.

The Chip Crisis in the Automotive Industry: Development Dynamic and Immediate Measures

"So, if you look at the multitude of issues that culminated, yes, Corona, so Corona per se, the fact that the workforce wasn't there, then lockdowns, the fact that the containers weren't in the right place either, the fact that the market itself didn't get off the ground at all, because of the long lead times – I don't think any of us, even those of us who are about to retire, have seen anything like this. There have always been crises, strong fluctuations in the demand in the commercial vehicle market, or quality issues, everyone has experienced that at one time or another, but something like this, I think – 'unseen'. There was no blueprint. I'm going to go out on a limb here: There was no blueprint there."
Senior Executive, System Supplier

The automotive industry slid into the chip crisis as a result of a classic "bullwhip effect" (Lee et al. 1997)[40], but one that is unusual in its cumulative effects. To be sure, there have been repeated disruptions in semiconductor supply chains in the past (Katasaliaki et al. 2022). However, these are all dwarfed by the current developments. The automotive industry was one of the sectors hardest hit by the general shortage of semiconductors. As the interviewee quoted at the beginning of this section describes, even managers and employees with many years of professional experience in the industry had never experienced a similar situation in their careers. The first step in this section is to take a closer look at the background that has led to these huge dissonances in the automotive supply chains. The second step is to present an example of the range of measures taken by the automotive companies to minimise the immediate impact of the semiconductor shortage on their business.

A Perfect Storm: The Development of the Chip Crisis in the Automotive Industry

In the early 2020s, the COVID-19 virus began to spread rapidly around the globe. Governments in many countries imposed contact restrictions and curfews lasting several weeks in order to contain the virus among their populations. Companies in the automotive industry were also forced to temporarily close their plants during the first "lockdowns" in March 2020 (Eckl-Dorna 2020). In the face of these developments, macroeconomic risk indices spiked and analyst houses, central banks and policymakers predicted a severe economic recession in their forecasts (De Santis/Van der Veken 2020; BMWK 2020). As a consequence, when production could be ramped up again in April 2020, OEMs pre-emptively adjusted their production plans in anticipation of a difficult economic situation and falling sales figures in order to avoid an overproduction of vehicles. The new planning data was passed on to the suppliers, who in turn adjusted their production plans on this basis, including cancelling many orders for microcontrollers and semiconductors from their suppliers in order to control their inventory costs.

At the same time, demand for PCs, laptops, smartphones and other home devices such as game consoles and fitness equipment, which contain a variety of semiconductors, exploded as a result of the pandemic's contact restrictions measures and the large-scale purchase of remote working equipment. Against this backdrop, chipmakers such as TSMC, Samsung and GlobalFoundries quickly retooled the capacity in their manufacturing plants freed up by the cancellation of orders from the automotive industry. When demand for automobiles picked up unexpectedly quickly after the initial lockdowns were lifted and stimulated by economic policies in many developed countries (Lechowski et al. 2023), there was no more capacity available in the semiconductor industry to meet the automotive industry's demand for semiconductors. Combined with the increasing demand for semiconductors due to electrification and softwareisation, these developments compounded to create a situation known in supply chain management as "supply chain disruption" (Tomlin/Wang 2011). The cumulative effect of these factors as triggers for the crisis-like developments in the automotive industry is also underlined by our interviewees:

> *„Capacities (...) were just at their peak and (...) and generally led to a shortage in the entire spectrum of semiconductors. (...) and then these trends – Covid, electric vehicles and autonomous driving – then you have four topics, (...) which have all accumulated, then you have the scenario (...) of the perfect storm, so to speak."* Semiconductor Industry Expert

Although the automotive industry was hit particularly hard by this "perfect storm", many other industries were not immune. Goldman Sachs analysts put the number of industries affected by the semiconductor shortage at 169 (Howley 2021).

For the automotive industry, the situation was exacerbated by a series of events that further impacted the capacity of the global chip industry for this target market. For example, individual manufacturing sites of the Japanese manufacturers AKM (October 2020) and Renesas (March 2021) had to temporarily shut down some of their manufacturing facilities due to fires and were slow to resume production.[41] In Texas, an ice storm caused widespread power outages and curtailed production at the local manufacturing plants of chipmakers such as Infineon, Samsung and NXP (Frieske/Stieler 2022, 3). Furthermore, in Taiwan, one of the world's top chip exporting countries, a prolonged drought in 2021 not only exposed the resource intensity and externalities of semiconductor production (Zhong /Chang Chien 2021), but also forced manufacturers to reduce production due to the rampant water shortages. This also disappointed the hopes of many companies in the automotive industry, which had speculated that the Taiwanese semiconductor industry would be able to ramp up production in the short term and meet a large part of their chip demand in the face of the difficult supply situation (Ruwitch 2021). Renewed lockdowns in Malaysia in June 2021, a key location for chip testing and package assembly, also had a negative impact on global semiconductor supply (Lee 2021). Overlaying these developments were ongoing geopolitical disputes, particularly between the US and China, which saw the US move to impose sanctions on Chinese tech companies and chipmakers such as Huawei, ZTE and SMIC from 2019 onwards, cutting them off from chip supplies and production equipment (Bloomberg 2022; Miller 2022, 311ff). As a result, many Chinese companies therefore began to buy up markets and stockpile chips, fearing that they would also be affected by such measures in the future. And the war in Ukraine, which broke out in February 2022, created further disruption to the automotive value chain.

The Hour of the Task Forces: Measures Against the Chip Crisis in the Automotive Industry

The chip crisis affected all car manufacturers and electronic components suppliers. The extent and timing of the impact of the semiconductor shortage varied among OEMs. Toyota, for example, was initially largely unaffected by the semiconductor shortage because, as a lesson learned from the 2011 Fukushima disaster, it had extended its just-in-time strategy for designing its semiconductor supply chains to include a "just-in-case strategy" and had built up four-months' worth of safety stocks for certain chips (Nathan et al. 2021). However, when these stocks were depleted, Toyota was also hit by the crisis – although somewhat less severely than some other manufacturers because of the time it had gained (Davis 2022). Looking at the manufacturers with the largest sales figures, the trade press, citing figures from the analyst firm LMC Automotive, reported that Ford, for example, was estimated to sell 1.25 million fewer vehicles in 2021 than demand would have allowed. Volkswagen's production was 1.15 million vehicles lower than planned. GM and Toyota missed their targets by 1.1 million each and Stellantis by 1 million units (Knauer 2022). In the case of the system suppliers, the impact of the crisis was, of course, not reflected in a drop in car deliveries. Instead, they issued profit warnings, cut dividends and revised sales targets downwards.

However, the shockwaves that were sent through the value chains also affected those automotive suppliers whose products do not contain semiconductors. In Germany, for example, medium-sized companies such as the plastics specialist Heinze from Herford (Gelowicz 2021), Bolta-Werke from Diepersdorf (Schindhelm 2021) or the PWK Group (Ringel 2021), a manufacturer of special parts from Krefeld, filed for insolvency. According to the companies, production stoppages at OEMs and system suppliers as a result of the semiconductor shortage had led to an abrupt drop in orders for these Tier 2 suppliers, which they were no longer able to compensate for. In order to generate sufficient returns, Tier 2 suppliers who produce so-called commodity parts are particularly dependent on high volumes to achieve the necessary economies of scale in production.

The variance in the extent and timing of the impact is also due to the fact that the companies in the automotive industry have different ways of responding to the consequences of the chip crisis in the short term. One of the most important parameters is only partly under their control: depending on where they are positioned in the value chain, companies have different options. While OEMs have the widest range of measures at their disposal, the scope for action of system suppliers is already more limited, since they have to fulfil their current contracts and always have to take into account the dependencies on the OEMs first in their coping strategies (see the contributions in: Deiß/Döhl 1992). Tier X suppliers, on the other hand, have the least room for manoeuvre and are under particular pressure because they have very little room for manoeuvre in their margins and cannot maintain capital-intensive margins of flexibility on suspicion, but are always dependent on timely relevant information for their business. As a result, the measures taken to overcome the chip crisis by OEMs, system suppliers and Tier 2s vary considerably.

As far as OEMs were concerned, the spectrum of measures taken tended to two poles. On the one hand, measures were focused on procuring additional chips in the short term on the spot market, under the motto "build cars, whatever the cost", as one of our interviewees put it. On the other hand, production adjustments were made in various ways, with the aim of achieving the highest possible yields from the cars still to be produced on the basis of the available chips.

The first set of measures was activated as soon as the semiconductor supply shortage became apparent in the second half of 2020. Task forces were formed in OEM procurement departments to deal with the chip crisis. One of our interviewees describes this as follows:

"In autumn 2020, we established the task force and embedded it completely into the organisation, also with the board and so on. That was the first measure. Developing transparency, setting up the matching teams with the suppliers and managing them as best as possible." Manager, OEM

These task forces were usually made up of cross-functional members. In addition to representatives from purchasing, experts from production and development were also nominated. One of the tasks of the task forces was to create group-wide transparency about the availability and exact demand for semiconductors (types, quantities). Many OEMs found themselves in a situation where, due to the division of labour in chip procurement described in section 2, they did not have a precise overview of which semiconductors were installed in the ECUs of their vehicles and where they came from. In many cases, the OEM task forces were therefore faced with the challenge of first developing an appropriate information system. The first task was to identify all the actors involved in the production of the semiconductors used along the supply chain and to determine their capacities, and the second was to record the volume and specification of the chips required for the individual model series and model variants of the vehicles within their own companies. These information systems formed the basis for the search for additional chips, which was carried out in cooperation with the suppliers:

"The OEM now has its own departments that deal solely with semiconductors (...) There, the OEM tries to solve the problems and find solutions at the working level, going up to the board level with two party calls, three party calls, depending on who you want to bring on board, in weekly, monthly consultations and for the respective Tier 2s there are sponsors, who then also have a more direct connection." Industry Expert

The organisation involves close coordination between OEMs and suppliers at different stages of the value chain and an intensification of cooperation. However, in some cases, as described by one interviewee, OEMs have also approached semiconductor manufacturers directly to reserve production capacity that might become available:

"Tier 1 stops delivering, then of course the issue is escalated up to the board level and at some point the board says, this can't be, I can't imagine this, we are going to talk to Tier 1. Tier 1 says, well, semiconductor manufacturer X can't deliver, and the board says, I'm not going to put up with that, I'm going to call them and ask why you can't deliver. Then semiconductor manufacturer X says, well, I don't know, semiconductor manufacturer Y can't deliver. Then he says, okay, picks up the phone, calls them."
Executive, OEM

The second set of measures in the OEMs focused on adapting production. As one interviewee points out, the development of information systems has also created the conditions to better implement a reallocation of chips to production:

> *"And this database forms the basis for these capacities, delivery quantities and requirements. So what are the requirements, what are the current runs, how many cars do you want to build, compared to the capacity of the suppliers, what they have promised us. That is the basis: we have so and so much shortage here and here, so then the priorities are also set, (...) do we prefer expensive cars, electric cars, certain platforms, and then both the allocation is made and we look at where we have to go deeper, where we also have to look at technical alternatives, how we can make progress there."*
> Project Manager, OEM

First, production adjustment measures include producing in stockpiles and delaying vehicle deliveries. In an effort to keep production going for as long as possible, some OEMs started producing vehicles even though some components were missing. Vehicles were then temporarily stored in car parks with the aim of retrofitting them as soon as the missing chips became available. Customers were asked to be prepared for longer waiting times, sometimes with counter-measures such as price reductions. According to press reports, this measure played an important role, for example, in the coping strategies of commercial vehicle manufacturers such as the VW subsidiary Traton and Daimler Trucks (dpa 2021).

Second, vehicles were delivered without certain non-safety-critical equipment options. Mercedes, for example, reportedly decided to remove certain options from the S-Class. For some time, cars were delivered without the latest navigation software which projects route information onto the windscreen, because the necessary chips were not available (Köster 2021). For the Porsche SUV. Macan, a seat system with 18 adjustable positions was removed as an equipment option in the US (Blanco 2021). BMW delivered vehicles with infotainment systems without touchscreen functionality (ibid.). General Motors did not equip the engines of some truck and SUV model series with an automatic start/stop function and gave its customers a price reduction in return (Hall 2021). Some manufacturers issued only one key to customers instead of several or, like Toyota, replaced electronic keys with mechanical ones (Kim 2022). Peugeot also reverted to analogue technology, replacing digital speedometers on its 308 models with an analogue version (Ewing/Boudette 2021).

Third, OEMs allocated the remaining chip capacity to the production of higher-priced premium models in order to achieve higher margins through their completion and sale. For example, the VW group prioritised the completion of Porsche and Audi models (Buchenau 2022). At Mercedes, production of the E-Class at the Sindelfingen plant was temporarily suspended in order to use the available chips for the production of the S-Class, EQS and Maybach series. As our interviewees describe, OEMs have also sometimes tried to re-allocate available chips within the supplier structure:

"I need five chips for the control unit, I have four, one is not coming, but I know that I also need the chips for the other control unit, so I'll take the chips from the supplier and take them to the other one so that at least he can continue building." Project Manager, OEM

As a result of these measures, premium manufacturers in particular were able to increase their profit margins to record levels in 2021, even though overall sales fell and many employees in Germany had to go on short-time work (Bay 2021). Another factor contributing to this result was that the high demand for vehicles at dealerships and the tight supply meant that in many cases it was possible to sell without discounts.

Fourth, as a last resort, production was curtailed. Measures ranged from the cancellation of individual shifts to the temporary shutdown of production lines for individual model series and the closure of entire plants. In Germany, for example, Audi temporarily halted production of the A4 and A5 models at its Ingolstadt and Neckarsulm plants, while Ford completely closed its Saarlouis plant and Opel its Eisenach plant for several months (for an overview see Frieske et al. (2022, 80)).

For many OEMs, these measures overlapped. Some of the task forces still meet regularly to analyse the supply situation and plan production in the short term according to the available chips.

Beyond production adjustments, some OEMs have also expanded their options over time by managing to use available alternatives for non-existent chips and adapting software accordingly. One interviewee described this approach and its challenges as follows:

"Semiconductor manufacturer X doesn't have the chip, so we go to semiconductor manufacturer Y and see if they have a similar chip. Are they in a similar temperature range, are they in a similar performance range, do they have similar Pin compatibility, are they automotive-approved or do I need a new homologation [approval by a testing authority, author's note], these are the questions that come up. And the closer the chip is to the one I actually use, the easier it is to adapt it. But I also go so far as to say, OK, I'll take an industrial product that's relatively similar, but I still have to get it approved for use in cars. Then I go in with risk approvals, say I'm going to build the things first, install them in the car, put the cars more or less on the train, and then the approval comes, OK, it works, or it doesn't, the risk is taken and then they say, I'd rather build and not let the belts stand still and do the approval later, in the worst case I might have to tear out the chip again and build in a new one." Project Manager, OEM

Tesla, for example, told its shareholders that it had been able to mitigate the impact of the chip crisis by switching to alternative microcontrollers available for a number of microcontrollers that could not be delivered (Tesla 2021). Within a few weeks, Tesla's engineering organisation is said to have adapted and validated the relevant software for 19 new chip variants. In addition to the fact that Tesla's zonal software and electronics architecture means that it relies on a smaller number of semiconductors with fewer variants overall, this extended scope for action due to high proportion of software development at Tesla helped the company to double its vehicle production in 2021 despite the chip crisis (Ewing 2022). But BMW, for example, was also able to use its software expertise to develop measures to overcome the chip crisis. In one case, BMW switched to a newly available terminal chip for connecting to wi-fi and interfacing between Android Auto and CarPlay functionality. However, the software for the new supplier's chip was not yet certified. BMW took the risk of installing the chip without the software while the development organisation worked flat out to adapt and certify the software. As soon as the software was certified, BMW was able to install it via an over-the-air update and activate the functionality even after the vehicles had already been delivered (La Rocco 2022).

The scope for action and flexibility of the system suppliers remains limited compared to the OEMs. This is mainly due to the fact that they cannot unilaterally adjust in production. In the event of supply disruptions, Tier 1s can be held directly responsible for the OEM's production stoppages. As Tier 1s are contractually obliged to guarantee uninterrupted supply to OEMs, they may be subject to direct penalties if they fail to deliver the promised components. As a result, maintaining supply has become a top priority for system suppliers, as one interviewee notes:

> *"If we don't get any semiconductors, (...) if we shut down the OEM, (...) that's panic to the power of ten, because we would have to pay a lot of money and we've been lighting more than one candle in the last year, hoping that please, please the others will shut down the OEM, because then it's just a matter of a lot of money."*
> Member Works Council, System Supplier

The OEMs, in turn, are often contractually obliged to pay if they cannot take delivery of the agreed quantities.
Task forces were also set up immediately at the system suppliers. These were anchored with the management. The task forces were charged with maintaining the supply of electronic components as far as possible. To do this, they began meticulously tracking the semiconductors used and, according to one interviewee, received supplier updates for several hundred parts several times a week:

"We had a big potpourri of parts that were in short supply at the height of the crisis. Basically everything was tight, from the print-specific microcontroller to a standard resistor. Some of them were also tight and had to be dealt with by task forces. And at the moment the situation is such that it is narrowing down more and more to a few families of parts that are chronically scarce and will remain chronically scarce." Manager, System Supplier

The aim was to use this "micro-management" of suppliers to identify parts in short supply as early as possible. As soon as it became apparent that a part was going to be in short supply, it was put into "allocation" and the parts still available were allocated to the products for the different customers according to an audited distribution key. In parallel, the system suppliers also tried to find alternative sources of semiconductors and eliminate the shortages.

A special case among the system suppliers was Bosch, which had already built up its own semiconductor manufacturing division in the past. While Bosch, as one of the world's leading system suppliers of automotive electronics, was hit hard by the semiconductors shortage and, together with Renesas, was famously scolded by Elon Musk on Twitter for this (Lambert 2021), the group's chip division now announced high investments in the expansion of its development, production and testing capacities.

In June 2021, a new production facility was opened in Dresden, for which the foundation-owned company has made the largest single investment in its history: €1 billion. By 2026, Bosch plans to invest a further € 3 billion in the expansion of its semiconductor business, which addresses other target markets besides the automotive industry (Robert Bosch GmbH 2022).

In the short term, crisis management in the semiconductor supply chain and the re-allocation of production became key competencies in overcoming the chip crisis and minimising its damage. For many companies, however, the crisis was a complementary starting point for fundamentally changing the course of their semiconductor strategies in the medium and long term and for accelerating the changes that had already been initiated. The following section describes the key areas of action on this path.

5.

Lessons Learned: Six Action Areas for Companies in the Automotive Industry

The analysis so far has shown that the chip crisis was indeed triggered by escalating dissonances in the value chain. However, its significance should not be reduced to this. Measures aimed solely at minimising the damage and smoothing out the current fluctuations are therefore inadequate. In the medium and long term, what is needed is a holistic redefinition of the strategies for dealing with semiconductors in automotive companies, which includes a comprehensive further development of supply chain management for semiconductors and cooperation with the semiconductor industry as well as a new concept for the use of semiconductors and their integration into the companies' electrification and software strategies. There are no patent recipes or blueprints for how to successfully redefine and implement semiconductor strategies. Rather, it is up to the companies in the automotive industry to work out a suitable path in line with the design of their business models and work processes, based on their particular starting conditions and contexts of action. On the basis of our explorative analysis, we were able to identify six action areas that need to be worked on in automotive companies.

Overview of the Action Areas for Companies in the Automotive Industry

1. Creating Transparency on Semiconductor Requirements – Establishing Consistent Information Systems

2. Actively Manage Semiconductor Risk – Establish NextGen Risk Management for Supply Chain Disruptions

3. Semiconductors as Core Components – Developing Holistic Chip Strategies for Vehicles

4. Create Collaborative Value Creation Architectures – Build Partnerships with Chipmakers

5. Strengthening Semiconductor Competence in the Automotive industry

6. Creating a Circular Economy – Implementing Recycling Strategies for Semiconductors

Action Area 1:

CREATING TRANSPARENCY ON SEMICONDUCTOR REQUIREMENTS – ESTABLISHING CONSISTENT INFORMATION SYSTEMS

"A big lesson learned, I think for the whole industry (...) a lot of us thought that you order a microcontroller and then you get it (...). But to consciously look at the value chain that we have, from wafer production to the front ends, to the back ends and, let's say, the downstream shipping, where parts sometimes travel around the globe several times to become finished goods, that we have lead times that typically range from 20 weeks and currently from 50 weeks to almost two years, these are changes that nobody had on their radar, and they're not going to go away per se because we're just significantly increasing the overall electronics content of the vehicle. " Executive, System Supplier

In many companies in the automotive industry, there is a lack of transparency about which semiconductors are used in vehicles, which companies manufacture them and how they end up in the final product.

A key action area is therefore to continue the work begun in many task forces to develop consistent, easy-to-use information systems across the entire value chain and to anchor them in the organisations.

Important parameters to be captured are the quantities required and the technical specifications of the semiconductors. Although the task forces have made great progress in this action area during the crisis, major challenges remain.

In many companies, for example, the IT landscapes are not yet integrated, so that, for example, the transfer of semiconductor data between different tools or the information systems of different business units still requires a lot of manual effort. In the cross-company context, there are also data protection issues, as one interviewee highlights:

"Because, of course, this is highly sensitive data. You always have the problem of data protection. That means that you get the data you process from Tier 1, that is of course data about Tier 2, the data does not belong to you, it still belongs to Tier 1, but you have it in your database. That is also a very big data protection issue, what data, how can I process it, who can access it, how can I play it out. These are big data protection issues where the Tier 1 also has to agree, yes, you are allowed to store it, but you are only allowed to use it in such and such a way." Manager, OEM

There is also the question of how the costs of providing, maintaining and updating these information systems are to be met in the long term:

"Of course, filling the database is also a problem. At the moment we are at 60 per cent, but of course, some people will refuse. (...) Many simply don't want to enter their data (...) Entering data is an effort. Who pays me for it?" Manager, OEM

Given the resources required to create and maintain these information systems, silo solutions by individual companies do not appear to be very effective. From an overarching point of view, it seems much more promising to create a framework for the development of a common information system in which the cross-company exchange of semiconductor information can be facilitated and cooperation between the companies in the automotive industry along the value chain can be intensified. Important starting points for this would be the findings of the HyValue project on the establishment of a cross-company collaboration platform (Heidling/Ziegler 2022), the development of cooperative operator models for platforms (Porschen-Hueck/Rachlitz 2022) and the automotive network Catena-X, in which the digitalisation of supply chains is promoted and technologies for sovereign data exchange are being developed.

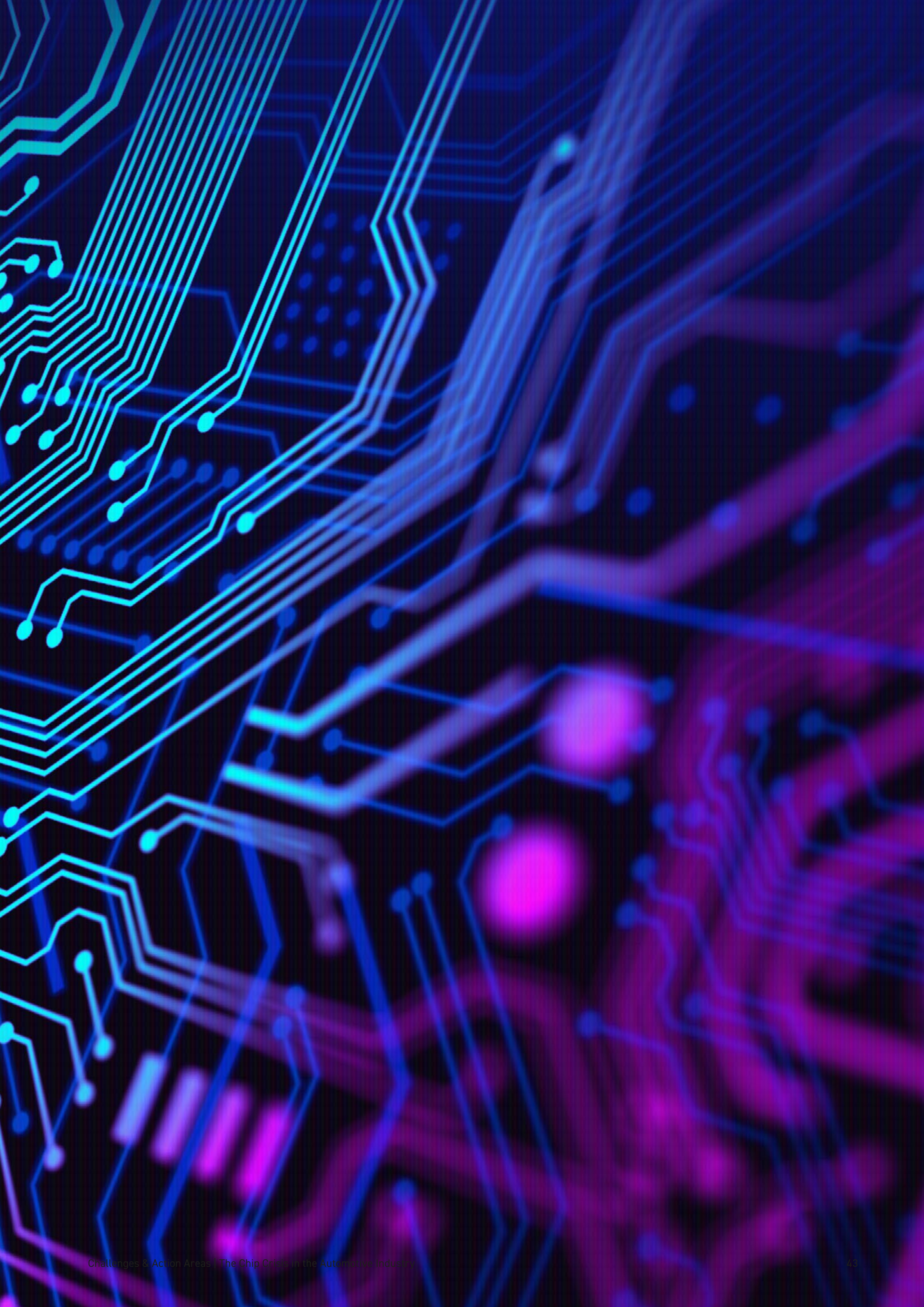
Action Area 2:

ACTIVELY MANAGE SEMICONDUCTOR RISK – ESTABLISH NEXTGEN RISK MANAGEMENT FOR SUPPLY CHAIN DISRUPTIONS

With the increase in extreme weather conditions, geopolitical tensions and the ongoing differentiation and dynamisation of competition, the likelihood of disruptive events such as the chip crisis in the globalised value creation processes of the automotive industry is increasing (Kiebler et al. 2020, 5). Building on the establishment of end-to-end information systems for the use of semiconductors, it is therefore necessary to develop a comprehensive risk management of the next generation – a data-driven risk management (Porsche Consulting 2022, 12). On the one hand, this means that disruptive events and their potential effects must be recognized immediately, for example by continuously monitoring the throughput times at chipmakers so that any disruptions can be communicated in a targeted manner. This provides an important basis for initiating countermeasures as quickly as possible and minimising damage. On the other hand, the aim is to develop measures to minimise risks in advance. Such preventive measures can range from the establishment of permanent dialogue channels along the supply chain to the development of alternative suppliers, to the identification and stockpiling of individual strategic semiconductor components and the reduction of the variance of the semiconductors used, to the formation of cross-functional teams in order to increase the scope for flexibility in the management of supply chains and their adaptability. One of our interviewees describes how his company has brought together the electronics purchasing, logistics and quality functions to lay the foundations for holistic and proactive supplier management:

> *"Electronics [will] retain a special role in the long term. That's why we've integrated logistics and quality into purchasing, for example, because we said that from a business point of view this has to be handled from a single source. This is not standard for us (...) we only have this integration of our own supply chain department into a commodity in electronics and also the integration of a supplier quality department into electronics."* Executive, System Supplier

It is also important to establish communication channels with Tier 2 suppliers who do not use semiconductors in their products. In the event of disruptions in the chip supply chain, these SMEs can be involved in the communication at an earlier stage and take appropriate action for their business, thereby contributing to the overall resilience of the automotive value chain.



Action Area 3:

SEMICONDUCTORS AS CORE COMPONENTS – DEVELOPING HOLISTIC CHIP STRATEGIES FOR VEHICLES

"Hardly any of the OEMs have thought through the car in terms of electronics. That means we still have unbelievably different modules, platforms, so simply the electronics layout is not standardised. (...) First of all, nobody did anything wrong, it's just the way the car industry worked (...) Tesla had an easier time because they had thought through the electronics of the car, so its complexity was better to manage." Industry Expert

Semiconductors have risen to become core elements of software-defined electric vehicles. They play a key role in controlling electrical power, centralising software and electronics architectures, and enabling data-intensive applications such as infotainment, driver assistance and autonomous driving functions in the vehicle. As a result, they are increasingly becoming a differentiating factor in the market.

In view of this qualitative increase in the importance of semiconductors, existing strategies for the use of semiconductors in automotive companies are no longer sufficient. Instead of delegating this task to the silo perspective of individual departments and component managers and focusing primarily on cost optimisation calculations, a key action area for companies in the automotive industry is the development and implementation of a holistic strategy for the use of semiconductors in vehicles, in line with the electrification of the powertrain and the redesign of their software strategy.

Key elements range from reorienting the use of semiconductors towards high-performance SoCs in centralised software and electronics architectures and reducing the number of ECUs used, to standardising the chips[42] used, for example by involving materials management more closely in the development processes, to updating existing vehicle and model types with new chip generations, and developing in-house chip design expertise.

In the context of the chip crisis, it has become clear that a number of OEMs and system suppliers, similar to tech corporations such as Apple, AWS, Google or Microsoft, are pursuing the long-term goal of significantly expanding their influence on the design of the chips they use and strengthening their competencies and investments in these areas. As one interviewee put it:

“It is true that we, i.e. the OEMs and Tier 1s, are getting more and more involved in the development of microprocessors because the software is playing an increasingly important role, which means that from the supplier development side and from the fast pace of the model cycles, we now have to contribute in a completely different way than when you used to order your resistors and the standard microcontrollers in the sense of ‘one fits all’. We just don’t have that anymore.” Project Manager, System Supplier

Action Area 4:

CREATE COLLABORATIVE VALUE CREATION ARCHITECTURES – BUILD PARTNERSHIPS WITH CHIPMAKERS

"We have learnt that this model, where you have a budget plan in the autumn and then you go out and negotiate your annual price for the next year, no longer works. We now have to plan much more long-term with the chipmakers, we also have to know from our customers – this is also a re-education effect that starts with the OEM – for a longer period of time: What products and what vehicle classes do you want to build, so that we can secure our capacities with the semiconductor manufacturers for the next two or three years, because we have these long lead times. And that thought process is what we are working on." Manager, System Supplier

Relationships between the companies in the automotive and semiconductor industries have been essentially transactional in nature (Schuh et al. 2022). Typically, automotive companies placed their orders at short notice in order to minimise financial risk. This was coupled with the expectation that semiconductor manufacturers would deliver the required quantities at the right time and at fixed prices.

The chip crisis has reinforced the view that this form of cooperation no longer makes sense, can have serious consequences and is no longer readily accepted by the chipmakers. A key action area is therefore to establish long-term oriented, partnership-based relationships with the companies in the semiconductor industry and to improve long-term planning along the entire value chain.

An important measure in this area is to establish a close exchange on technology and product roadmaps on an equal footing and to agree on longer-term agreements on purchase volumes, as one interviewee points out:

"It would be necessary for the semiconductor people to say to the automotive people, you really have to speed up your function roadmaps, (...) so how many of these functions will be desired at some point, in what form, that has to be determined. And of course the cooperation in the chain from Tier 1 down to the semiconductor manufacturers has to happen quickly, so that the semiconductor manufacturers can then derive from this. And it is precisely these chains that need to be improved. So that the top-down planning then works better. And of course, it must also be possible to influence it from the bottom-up, because if the OEM wants something that cannot be realised, that is of course also a problem."
Semiconductor Industry Expert

These measures help to create the basis for strengthening trust as a mode of cross-company cooperation and for promoting the potential of collaborative cooperation, such as the flexible development of joint solutions in the case of unforeseen events, inter-organisational learning, but also co-innovation and the development of joint products (Ziegler/Heidling 2023). Some of our interviewees argue that system suppliers, as the link between OEMs and chipmakers, can play a crucial role in building these partnership-based value-creation relationships:

"We increasingly have differentiators that start with semiconductors. That is why it is important (...) that we as Tier 1s and also our competitors in the market make even greater efforts to cooperate in terms of technology, in terms of eco-systems, in terms of how we secure access to the technologies and also how we integrate ourselves in the design and further development, keyword connection and smooth transition between the hardware, if it is microcontrollers, and the software, both of which then come together more and more in the end product." Executive, System Supplier

On this basis, further measures are conceivable, such as sharing the risks of investing in the construction of new semiconductor production facilities or developing business models based on partnerships, in which revenues generated from cooperation are shared.

Action Area 5:

STRENGTHENING SEMICONDUCTOR COMPETENCE IN THE AUTOMOTIVE INDUSTRY – QUALIFYING MANAGERS, EMPLOYEES, STUDENTS AND APPRENTICES

> *"There are some in the OEM who really know what they're doing (...) but you get the feeling that they've been brought together in a project to run around as a task force and help. It was never a separate department where they said you are our semiconductor experts (...) you can count them on one or two hands."* Industry expert

The chip crisis has highlighted the need for many companies in the automotive industry to build up expertise in the semiconductor industry and its products. In addition to specialised technological know-how in the design, manufacture and use of semiconductors, this also includes more general knowledge of the essential characteristics of the industry, the organisation of its value-added processes and experiential knowledge in working with the semiconductor industry.

In the immediate measures to overcome the crisis, it was not least such "informal resources of employees" (Pfeiffer/Author's Collective 2023, 19) that strengthened the companies' ability to act.

A central action area is therefore to place not only software but also semiconductor skills on a broader footing in the future and to anchor them more strongly in the minds of managers, employees, students and apprentices.

On the one hand, it is important to promote the training of specialists in the areas of chip design or process and test technology and to create attractive career paths for these groups of employees in companies in the automotive industry.

On the other hand, it is also important to strengthen the basic knowledge of the semiconductor industry among all employees who come into contact with it through broader qualification and further training measures.

This also applies to universities and colleges. As one interviewee described, the development of semiconductor skills, for example, currently plays a very minor role in many engineering courses:

"So in mechanical engineering, automotive engineering is semiconductor technology: I have a chip and I use it. But where it comes from, what I do with it, I can tell you from my own experience, within a ten-semester course was, I think, one semester more or less electrical engineering as a secondary subject, we had discussed semiconductors there." Project Manager, System Supplier

The area of skills development is therefore also seen by our interviewees as an important part of an industrial policy strategy to promote the development of the semiconductor industry in Germany:

"However, in terms of industrial policy there is certainly still something that can be done if we not only set up the factories, but also help with the skilled workers. Meaning the skilled workers in the semiconductor factory and in between, in all the software, also the design of semiconductors, it doesn't have to be just semiconductor production, it also has to be the intermediate levels, the Tier Ones, who then have to define what the semiconductors should look like, the functions and so on." Semiconductor Industry Expert

Action Area 6:

CREATING A CIRCULAR ECONOMY – IMPLEMENTING RECYCLING STRATEGIES FOR SEMICONDUCTORS

"If we want digitalisation, (we need) a raw materials strategy in which recycling plays a very important role. In the sense of a circular economy. The question must be, how can we constructively get to the point where I can either do without the raw materials, the precious metals, on the printed circuit board, or at least replace the individual components, as with the FairPhone. That means making our products repairable."
Works Council Member, System Supplier

The shortage of semiconductors also highlights the finite nature of the planet's resources. The production of chips is very resource-intensive and many of the raw materials used in chips, circuit boards and their packaging, such as copper, tin, aluminium, silver or gold, are rare and expensive to extract. Mining these raw materials also emits large amounts of greenhouse gases and causes environmental damage, which can sow the seeds for future disruptions in the value chain. A strategy that focuses solely on overcoming the semiconductor shortage by expanding production is therefore by no means exhaustive.

For ecological, social and economic reasons, a key action area for the companies in the automotive industry and its partners is to ensure reuse, as with batteries, and to implement recycling strategies to recover the raw materials used in ECUs, gateways and sensors, so that they can be made available for the production of new chips within the framework of a circular economy.

In addition to extending the product life cycles of the vehicles and their semiconductors, important elements in improving material flows can be the improvement of the processing methods to increase the recovery rates and the development of efficient dismantling processes that systematically take the recyclability of ECUs into account at the design stage and reduce dismantling times. Here, too, the aim should be to promote the development of the relevant know-how among managers and employees.

The Crisis as an Opportunity for Change

The individual action areas are interlinked. Next-generation risk management can be significantly strengthened by building partnership relationships with companies in the semiconductor industry. Entering the design of chips is not possible without building up extensive semiconductor expertise, nor is the development of effective recycling strategies. In redefining holistic semiconductor usage strategies in automotive companies, it is therefore important to parallel the work in the different action areas and to embed them in further innovation activities to establish software-defined electric vehicles.

According to our interviewees, some companies in the automotive industry were already working on some of these action areas before the chip crisis. However, after initial successes, many efforts often came up against the inertia of entrenched structures in the companies and thus stalled. The chip crisis, on the other hand, made the need for companies in the automotive industry to redefine their strategies for the use of semiconductors unmistakably clear and thus also created new options for working on the action areas:

> *"Yes, this is an encroachment on 'sovereign territory'. (...) The good thing is that the sense of urgency, which would not have been there two years ago, is there now. If I had raised these issues two, two and a half years ago, there would have been more resistance. Now we have all been through the valley of tears, which is why it was so important to me that we started in the middle of last year, while the sense of urgency is still there, that we then had the Go and the interface function, that this now makes sense. If the caravan now moves on to other issues, participation may suffer, and the lessons learned will disappear in a drawer, considered good but not implemented. And that's what we want, or at least what we are trying to prove, is that it doesn't happen that way."*
> Executive, System Supplier

This window of opportunity for a rethink of semiconductor strategies needs to be taken advantage of.

6.

The Chip Crisis as a Turning Point for Semiconductor Use in the Automotive Industry

The worst effects of the chip crisis on automotive companies have now been cushioned. However, many companies are still reporting ongoing impairments (Irwin 2023b). Most of our interviewees expect that as the global economy slows down, partly as a result of anti-inflationary measures and the expiry of purchase incentives in the main market countries, demand for vehicles will gradually decline and thus supply and demand for semiconductors in the automotive industry will also slowly rebalance. Analysts and consulting firms are making similar predictions.

The analysis of the chip crisis, its background and the companies' strategies for coping with it and the areas in which they are involved makes it clear that "business as usual" is no longer a viable option for companies in the automotive industry. Starting with their first use in car radios in the 1950s, semiconductors have gradually gained in importance in the course of electronification. As information machines, they have increasingly been used not only to support companies' production facilities and business processes, but also in the core products of the automotive industry itself: from engine control to driver assistance and infotainment, they were used in more and more areas of the vehicle. In software-defined electric vehicles, this development is now reaching a new level of quality. Semiconductors are becoming strategic building blocks – both as power electronics in the electrification of the powertrain and as high-performance SoCs, data transmitters and sensors in the redesign of software and electronics architectures and the realisation of market-differentiating software functions. In the design of vehicles, semiconductors can therefore no longer be treated as just another intermediate product on the bill of materials, and chipmakers no longer as mere suppliers of commodities. Instead, a holistic redefinition of strategies for the use of semiconductors and collaboration with semiconductor companies is on the agenda in automotive companies. The chip crisis marks this turning point for the use of semiconductors in the automotive industry.

At the same time, the chip crisis made policymakers aware of the strategic importance of semiconductors to the global economy (Miller 2022). A number of industrial policy initiatives had already been launched in the major industrialised countries, such as the EU's IPCEI support programme to attract new chip factories and promote the semiconductor industry. These programmes have now been significantly expanded, overlaid by new geopolitical tensions. The US Congress, for example, has passed the CHIPS for America Act, which provides $ 52 billion in subsidies to encourage the construction of new semiconductor factories in the US.[43] The EU Commission developed the European Chips Act, which will provide $40 billion for investment in semiconductor facilities in Europe. China prioritised scientific and technological self-sufficiency and upgrading as a strategic pillar for national development in its 14th Five-Year Plan (2021–2025). In this context, it has increased its investment in seven key technologies, including in particular semiconductors and integrated circuits. In Japan, the government is investing €2.4 billion to build a national chip alliance, the core of which is the establishment of the Rapidus joint venture involving eight companies, including Toyota Motor, Sony, NEC, Kioxia, NTT and Softbank (Welter 2022). And similar initiatives are also being launched at leading semiconductor locations such as Taiwan and South Korea (Welter 2023).

Against this background, in the midst of the crisis, many companies in the automotive industry launched longer-term initiatives to reshape their semiconductor strategies, in addition to short-term measures to maintain production and supply commitments. The trade press regularly reported that automotive companies were entering into exclusive contracts with semiconductor manufacturers that guaranteed purchase volumes in order to secure manufacturing capacity for the long term (Boudette 2023). Some invested jointly with semiconductor companies to build new production facilities and development sites (Hammerschmidt 2023), or entered into agreements to develop new products in close collaboration with semiconductor companies and even to share potential revenues to be generated from these products. There are also reports that some companies are preparing to follow in Tesla's footsteps by designing their own chips (Flaherty 2021).

It is now a matter of translating these initiatives in the companies into consistent overall strategies for the use of semiconductors in vehicles and for cooperation with the semiconductor industry, and of embedding them permanently in the organisations. The six action areas identified in this study can provide an orienting framework for this. At the same time, their implementation in companies will generate an extended need for research. Important questions are: What solutions are being developed in the companies? How can managers and employees be supported in this process? What are appropriate metrics and maturity models to measure progress/setbacks in the action areas? How can the exchange of experience between companies be organised and how can the overall ecosystem perspective be strengthened?

Appendix

Endnotes

1 In 2019, a total of 25.7 million passenger cars were sold in China, compared to 17 million in the US and 15.75 million in the EU. German manufacturers in particular have been able to steadily increase their sales in China during this period. The Chinese market accounted for 38.4% of VW Group's total sales in 2019, 29,6% for Mercedes and 28.7% for BMW (figures from JATO Dynamics, CMBI).

2 From the perspective of German industrial sociology, see the pioneering work of Halfmann 1984; Welsch 1990; Bieber/Möll 1993; Buss/Wittke 2000; Lüthje 2001.

3 The three-phase alternator was originally driven by the internal combustion engine via a belt and supplied electrical power to the low-voltage vehicle electrical system for the starter battery and various consumers.

4 In 1956, Bendix introduced the Electrojector electronic injection system, which was to be used as an option by AMC and Chrysler (Walton 1957). However, it proved unreliable and was again replaced by conventional carburettors. Robert Bosch GmbH later acquired the Bendix patents. In 1967, Bosch succeeded in producing the "D-Jetronic" injection pump, one of the first electronic applications to go into series production, for the VW 1600 (Bingmann 1993, 762).

5 Motronic was the first freely programmable engine control system based on a Bosch microcontroller for petrol engines. The first vehicle to be fitted with Motronic as standard was the BMW 732i presented in 1979 (Bähr/Erker 2013, 459).

6 In 1998, the IEC 61508 series of standards, Functional Safety of Safety-Related Electrical/Electronic/Programmable Electronic Systems, defined the requirements for safety-critical systems and specified methods for fault control. In IS0 26262 (Road vehicles – Functional safety), adopted in 2011, IEC 61508 has been adapted as a process model for the automotive industry. Depending on the risk classification specified by the standard (ASIL – Automotive Safety Integrity Level), which takes into account the factors "severity", "exposure" and "controllability" of the system to be developed, the standard makes recommendations for the design of the development process.

7 The focus of the development efforts had been primarily on reducing the cost of these components, e.g., by reducing the resource consumption of the ECU through small changes in the source code (Broy et al. 2007).

8 In addition to the firmware installed on the read-only memory (ROM) (later flash memory), this required a control program (operating system) for the ECU to manage the various application programs that access the hardware.

9 The ECUs themselves consist of several different semiconductors (e.g., memory, CPU, and peripheral functions). According to a tear-down by Porsche Consulting (2022), the number of semiconductors in vehicles with 50 to 90 ECUs ranges between 5,000 and 7,000.

10 For all this work, however, many OEMs also make use of the work of engineering service providers and other partners (Boes/Ziegler 2021, 161ff).

11 For example in the development of ABS, the "design and development work was done by Bosch, while the practical testing work on the vehicle was carried out by Daimler-Benz" (Bingmann 1993, 741).

12 Consequently, the structure of the software and electronics architecture reflects the organisation of its creation. In the software industry, such a phenomenon was already observed in the 1960s and became known as Conway's Law (Zerfowski/Crepin 2019).

13 In 2005, the Automotive Special Interest Group, an association of leading OEMs, published Automotive SPICE®, a standard for software-based system development in the automotive industry based on the ISO/IEC 330xx series. It includes a process reference model for the design of software-based system development and a process assessment model with six maturity dimensions for analysing and evaluating it – for example, in terms of its reliability.

14 AUTOSAR has become the leading reference architecture for the design of ECUs for safety-relevant embedded systems (e.g. powertrain, chassis, etc.), but it is not suitable for the software of ECUs with larger and more complex source code (e.g. infotainment or autonomous driving functions). Therefore, work started in 2016 to develop specifications for an Adaptive AUTOSAR Platform, which is also intended to improve software updateability.

15 For a concise overview of the key characteristics of the semiconductor industry, see SIA/Nathan Associates 2016 and Miller 2022.

16 According to McKinsey the cost of semiconductors in an average car was $350 in 2012, and $1,000 in the luxury segment (Parker/Thomas 2013, 35).

17 The share of the automotive industry has increased steadily. In the mid-1980s, only 4.6% of semiconductors produced in Europe were used in the automotive industry (cited in Bieber/Möll 1993, 160).

18 These companies often also supply their products to other sectors. The automotive industry is then one of the target markets. For Infineon and NXP, the automotive industry is the segment with the highest turnover.

19 The smaller the nodes, the faster and more efficient the chips can compute. At the end of last year, TSMC's first 3-nanometre fab, Fab 18 at TSMC's Hisnchu headquarters, went into operation (Labs 2022).

20 Tighter regulations on emissions were first introduced in the US by the California Resources Board (CARB) in 1990 and have been adopted in both Europe and China (Meng Fang/Zhou 2022).

21 For example, the inverter controls the torque of the electric motor by adjusting the voltage level, the speed by adjusting the frequency of the AC voltage, and enables reverse driving by reversing the polarity and changing the direction of rotation of the motor.

22 While Tesla uses 400-volt on-board power systems, the Porsche Taycan and Hyundai's Ioniq 5, for example, use 800-volt systems. The technology was developed by the Croatian start-up Rimac (Wittich/Lang 2022).

23 SiC semiconductors have higher conductivity and allow higher switching frequencies than silicon semiconductors. They also dissipate 50% less energy in the form of heat. Because less heat is dissipated, SiC components can be operated at higher temperatures and the power electronics cooling system can be smaller. This results in energy savings and, through more compact cooling systems, weight and cost reductions. The world's first 200-millimetre wafer production facility for SiC power semiconductors was opened by Wolfspeed (formerly Cree) in the Mohawk Valley in the US in April 2022 (Birch 2022).

24 According to a customer survey conducted by McKinsey in China, the relevance of the "digital experience" of a vehicle in the purchase decisions is growing in the Chinese market and has become one of the most important factors (Guan et al. 2021, 16).

25 At Volkswagen, for example, problems with the integration of vehicle software were said to be responsible for delays in the start of production of the ID.3 and the Golf (Slavik 2020).

26 Zerfowski/Crepin (2019, 38f), for example, expect the size of the software on these computing units to increase by a factor of 10,000, from around 8 MB to date to up to 80 GB.

27 Virtualisation technologies such as the DriveOS or PikeOS hypervisor make it possible to run multiple operating systems for heterogeneous requirements (e.g., operating systems with and without real-time requirements) simultaneously and securely separated from each other on the same SoC (Sinha/West 2021).

28 Initially, Tesla worked with partners in many areas, such as developing the Autopilot driver assistance system with Mobileye, before the collaboration was terminated in 2016 (Auchard 2016). Following the termination of the Mobileye partnership, Tesla entered into a partnership with Nvidia, which was also terminated in 2018. Specifically for Autopilot, Tesla then decided to design its own chips (Boes/Ziegler 2021, 32) and has since established a "Silicon Development Group" alongside the Vehicle Software Organisation, in which further chips are being designed.

29 For example, according to a teardown of the Model Y by Munro Associates (2021), a total of 26 ECUs are installed.

30 As soon as a client is connected to the vehicle via the ODB-2 diagnostic socket, it can use the UDS protocol to make contact with the control units, to read out the fault memory and to upload new firmware.

31 When the NHTS ordered a Model S recall in 2014 due to a safety risk with the charging ports, Tesla was able to fix the issue with an OTA software update, setting a new precedent for handling recalls for software issues (Brisbourne 2014).

32 This also makes it possible to adapt tech company practices such as A/B testing. In A/B testing, new functionalities are first tested with a certain group of (real) users in order to use this feedback for their further development before they are made available to all users (Ziegler 2022, 11).

33 Traditionally, OEMs and system suppliers have used a variety of different tools for version control. Often, each department responsible for developing an ECU had its own system. In a distributed version control system for the entire vehicle software, however, all developers involved in the development process should have access.

34 At Tesla, for example, vehicle software upgrades are implemented on average every four weeks (Daum 2022, 17). For this purpose, the developers have set up an automated tool chain, which reportedly makes it possible to perform regression tests on new vehicle software builds, validate the software and release it in less than a day. A HiL system has also been integrated into this tool chain (Rohde 2020).

35 For example, switching from Intel Atom chips for infotainment to the more powerful but more power-hungry AMD Ryzen chips initially reduced Tesla's Model 3 range by 22 km (Günsch 2022).

36 Following this example, the open-source Uptane framework for secure OTA software updates in the automotive industry was developed and became an IEEE standard in 2018. The framework ensures that only OEM-signed/authorised images are installed on ECUs.

37 A 2016 study by McKinsey and Stanford University projected that the total volume of automotive recurring revenues would grow to $1.5 trillion by 2030 (Mohr et al. 2016). Other consulting firms provide similar forecasts. In February 2023, Mercedes CFO Harald Wilhelm told journalists that Mercedes had already generated more than 1 billion euros in revenue from software services in the past year (Hohensee 2023).

38 A great deal of effort is also being put into the design of the semiconductors used in the supercomputers located in the data centres outside the vehicle (Talpes et al. 2023).

39 In 2022, Mobileye was again listed on the stock exchange by Intel. However, Intel still holds 94.2% of the shares.

40 In supply chain management, the term "bullwhip effect" has been coined to describe a phenomenon in which fluctuations in demand build up along multi-stage supply chains, leading to a situation where the quantity ordered significantly exceeds actual demand, or vice versa – as in the case of the chip crisis. Often triggered by distortions in information transmission and a lack of coordination between different stages, this effect can become more pronounced the more branched the sub-supplier structure is (Lee et al. 1997).

41 Renesas is a major supplier to Japanese manufacturers Toyota, Nissan and Honda.

42 The development of cross-company chip standard designs for certain ECUs is also conceivable, in order to increase the overall volumes at semiconductor manufacturers.

43 Steven Rattner (2023) comments in the NYT on this programme as the "largest foray into the private sector since World War II" by the US government.

Glossary

5G = Fifth generation mobile communications standard.

A/B testing = Software development practice in which two versions of an application are tested with groups of users to determine which performs better.

Anti-lock braking system (ABS) = Technical system that counteracts possible wheel locking by reducing the brake pressure when a motor vehicle is braked, thus enabling steerability, directional stability, and a reduced braking distance on wet roads.

Application Specific Integrated Circuit (ASIC) = An electronic circuit realised as an integrated circuit adapted for use in a specific application whose function cannot be modified.

ASIL (Automotive Safety Integrity Level) = Safety requirement level specified by ISO 26262 for safety-related systems in motor vehicles.

Automotive SPICE = Industry standard for evaluating the performance of development processes of ECU suppliers in the automotive industry.

AUTOSAR (AUTomotive Open System Architecture) = Initiative launched by a consortium of leading OEMs and system suppliers to establish a hardware-independent, standardised reference architecture for the design of electronic control unit software (middleware).

Bootloader = A software program that allows a computer or control unit to be started up.

Build = Process step in software development in which files containing new source code are converted into software artefacts that can be run and tested on a computer (usually before the software is released).

Bullwhip Effect = Supply chain management term for a phenomenon in which fluctuations in demand build up along multi-stage supply chains.

C = Imperative programming language developed at Bell Laboratories in the 1970s and one of the world's most widely used programming languages.

Calibration = Process step in vehicle development in which the vehicle behavior is determined by setting the ECU parameters.

CAN (Controller Area Network) = Serial bus system for data transmission in the vehicle without a host, linking several control units.

CAN-FD (Controller Area Network Flexible Data-Rate) = Further development of CAN, which enables faster data transmission rates and the transmission of larger payloads.

Continous Deployment (CD) = A software development practice in which tested new software is continuously and automatically deployed.

Continous Integration (CI) = A software development practice in which changes to the source code of a piece of software are continuously merged into a central version control system and automatically tested.

Code Refactoring = A software development practice in which existing software is simplified, e.g. to improve readability and maintainability, without changing the external behaviour of the program.

Commodity = Highly standardised and therefore interchangeable product. Commoditisation describes the process by which products lose their differentiating characteristics and become interchangeable commodities.

Conway's Law = Named after the US computer scientist Melvin Edward Conway, Conway's Law states that organisations that design systems inevitably create system designs that reflect the communication structures of those organisations.

Deployment = A process step in software development where new software artefacts are put into production.

DevOps = A portmanteau of Dev (development) and Ops (operations) that refers to a set of processes, methods and tools for improving collaboration between all stakeholders involved in the development and operation of software.

Digital Signal Processor (DSP) = A chip that specialises in the continuous processing of specific digital signals such as video or audio.

Electrical/Electronical Architecture (E/E Architecture) = The term used to describe the structure of the vehicle's electrical and electronic systems.

E-Fuels = Fuels produced by the synthesis of carbon dioxide and hydrogen using electricity from renewable energy sources (e.g., e-kerosene, e-methane, or e-methanol).

Electronic Control Unit (ECU) = Electronic module for controlling, regulating, and monitoring, e.g. processes in motor vehicles.

Electromagnetic compatibility = The ability of a technical system not to be disturbed by electrical or electromagnetic effects from other systems and, conversely, not to disturb other systems by such effects.

Electron Tube = Device by which an electrical voltage can be controlled between two electrodes in an evacuated or gas-filled tube.

Electronic Stability Control (ESC) = A technical system that counteracts swerving by selectively braking individual wheels.

Ethernet = Family of network technologies for wired digital data exchange between devices connected in (local) networks.

Fab = A factory for the fabrication of semiconductors

Firmware = Software that performs essential functions between the hardware of the electronic device and the application software (e.g. loading the operating system kernel).

Flash Memory = A type of memory that retains its data in a de-energised state. Unlike read-only memory, flash memory can be reprogrammed.

FlexRay = A serial bus system for in-vehicle data transmission that can transfer higher data rates than CAN in a fault-tolerant manner and is often used for driver assistance systems.

Foundry = Microelectronics manufacturing company that uses its facilities to produce chips for other semiconductor companies.

Functional Safety = A set of practices defined in IEC 61508 for developing safety-related electrical and electronic systems to ensure that the systems function correctly and behave in a safe and predictable manner when a fault occurs.

Gallium Nitride (GaN) = Wide bandgap semiconductor material consisting of gallium and nitrogen for power electronics in electric vehicles.

GPU (Graphics Processing Unit) = A chip that can perform parallel calculations, used primarily for graphics and AI applications.

Hardware in the Loop (HiL) = A method by which the inputs and outputs of an embedded system are connected to and tested on a test bench that simulates the natural environment of the system (e.g. to validate an ECU).

Hypervisor = Software that enables multiple guest systems to run simultaneously on a single piece of hardware and manages resource allocation.

Integrated Circuit = A set of electronic components deposited on a single semiconductor substrate, the elements of which are fully integrated.

Inverter = Electronic device that can convert DC voltage into AC voltage and vice versa. In a vehicle, it controls the electric motor, among other things.

ISO 26262 = Standard defined by the International Organisation for Standardisation to ensure the functional safety of motor vehicles.

Just-in-Time Production = Production strategy in which material is delivered and produced in the quantity and at the time required to fill customer orders.

Just-in-Sequence Production = A further development of just-in-time production in the automotive industry, in which material is delivered in the order in which assembly takes place.

Lines of Code = Metric used in software development to measure the size of a computer program by the number of lines of its source code.

LIN (Local Interconnect Network) = Serial bus system for data transmission in vehicles, offering lower transmission rates than CAN but at a lower cost.

Logic Chip = A chip that processes data.

MATLAB/Simulink = Proprietary software solution from The Mathworks Company for modelling engineering, physical, financial, mathematical and other systems.

Memory chip = A chip that stores data

Microprocessor = Chip on which all the components of the data processing logic unit are implemented on a single integrated circuit.

Microcontroller = Chip on which, in addition to the processor, other peripheral functions such as memory, input/output and serial interfaces are implemented on a single integrated circuit.

MOST (Media Oriented Systems Transport) = Serial bus system used primarily for data transmission in in-vehicle multimedia applications.

National Highway Traffic Safety Administration (NHTSA) = U.S. federal civilian highway and vehicle safety agency.

Photolithography = Semiconductor manufacturing techniques in which light or UV radiation is passed through photomasks; the radiation then reacts with photoresists to create patterns on silicon wafers.

OBD-2 (On-Board Diagnostics) Connector = Standardised hardware interface in the vehicle through which the fault memory of the vehicle's diagnostic system can be read.

Operational Design Domain (ODD) = Specification of the conditions (e.g., weather, driving situation) for which an autonomous driving system is designed to operate safely.

Over-The-Air (OTA) update = Software update performed over a wireless interface such as WLAN or cellular network.

Planar Process = A process for manufacturing transistors and integrated circuits that made it possible to place several semiconductor components on one substrate for the first time.

Product Requirements Document (PRD) = Document describing the totality of the customer's requirements for a product.

Read-Only Memory (ROM) = A type of memory that can only be accessed for reading during normal operation and whose data can be retrieved in a de-energised state. It is often used in embedded systems where the software cannot be modified.

Regression Testing = A software development practice in which test cases are repeated to ensure that changes to previously tested parts of the software do not cause new bugs ("regressions").

RTOS (Real-Time Operating System) = Operating system that safely processes time-critical requests from an application program or signals from hardware interfaces within a specified period of time.

Scope statement = Project plan prepared by the supplier showing how it will meet the customer's requirements as specified in the Product Requirements Document.

Semiconductors = Solids whose electrical conductivity is between electrical conductors and non-conductors.

Silicon = Chemical element that, as a semi-metal, has properties of both metals and non-metals and is the basic material for most products in the semiconductor industry.

Silicon Carbide = Chemical compound of silicon and carbon used as a material, particularly for power electronic components.

Superfracking = A set of extraction methods for fossil fuels in which a mixture of water, sand and chemicals is injected deep underground at high pressure.

System-on-a-Chip (SoC) = Chip in which all components of a programmable electronic system are typically implemented on a semiconductor device as a monolithic integrated circuit.

Teardown = Engineering practice whereby a vehicle or component of a vehicle is disassembled (e.g., to record the components used).

Technical Debt = A metaphor used in software development to describe the significant burdens accumulated in the development process due to poor technical implementation. It can be created both consciously (e.g. due to time constraints) and unconsciously.

Toolchain = A consistent set of software tools that are used in the development of software.

Transistor = A tiny electronic switch that is either turned on (produces a 1) or turned off (produces a 0) and generates the ones and zeros that underpin all digitisation processes.

Traction Control System (TCS) = A technical system that prevents wheel spin during vehicle acceleration by reducing drive torque.

UDS (Unified Diagnostic Services) = Diagnostic communication protocol specified in ISO 14229 for contacting and servicing all ECUs in the vehicle.

Uptane-Framework = An open source framework that specifies a process for secure over-the-air (OTA) software updates for in-vehicle ECUs.

V-model = Linear process model originally designed for managing software development projects. It divides tasks into successive phases and, in addition to the waterfall model, defines test phases for quality assurance. The "V" that gives the model its name is formed by the juxtaposition of the development and testing phases.

Validation = A process step in the development of vehicle components, following verification, in which field tests are used to verify that specific customer usage objectives are met.

Verification = A process step in the development of vehicle components to check that a product meets the requirements specified in the functional specification prior to validation.

Version Control System = Software program for distributed version management of files, designed to improve collaboration between software developers on a product.

Virtualisation = Technology that allows the physical resources of a computer to be divided between different virtual environments. This allows, for example, multiple operating systems to be run on a single computer.

Wafer = A round piece, usually of monocrystalline silicon, from which chips are made and which can be up to 300mm in diameter.

Zonal Architecture = A variant of an E/E architecture in which a few high-performance computers perform all the essential computing tasks for specific areas of the vehicle, and a number of smaller computers are grouped around them to perform subordinate functions on the periphery.

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