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Exploring Influences of Digital Technologies on Business Models in the Automotive Business Ecosystem

Changes of Value Creation due to the Development of Technologies for Autonomous Driving

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Thanks

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Abstract

Die Automobilindustrie steht vor technologischen Veränderungen hin zu elektrifizierten, geteilten, ständig vernetzten, und selbstfahrenden Fahrzeugen. Errungenschaften in digitalen Technologien ermöglichten die Entwicklung autonomer Fahrzeuge, und die Automobilindustrie würde demnächst der digitalen Transformation folgen. Mit dem Aufkommen digitaler Technologien stiegen auch branchenfremde Unternehmen in die Automobilindustrie ein. Das Ziel dieser Arbeit ist die Erkundung von Einflüssen digitaler Technologien auf die Wertschöpfung in Geschäftsmodellen im Automobil-Ökosystem.

Dazu wurde ein „Mixed Methods Design" gewählt. Im Wesentlichen besteht diese Arbeit aus einer Fallstudie in der führende Entwickler von Technologien für autonome Fahrzeuge untersucht wurden. Nach einer Literaturanalyse wurden Sekundärdaten zur Identifikation der führenden Entwickler autonomer Fahrzeuge verwendet, was zur Auswahl von 12 Fällen bestehend aus Automobilunternehmen, Zulieferern, Technologie- und Softwareunternehmen führte. Basierend auf Sekundärdaten wurden deren Technologiebeschaffungs-Initiativen im Bezug auf das automatisierte Fahrsystem, HD-Karten, Lidar-Sensoren, und Transportdienstleistungen gesammelt und analysiert. Die „Cross-Case Synthesis" wurde als Analysemethode gewählt. Diese wurde mit Ergebnissen einer qualitativen Inhaltsanalyse über mögliche Motive für große Investitionen, Übernahmen, und Partnerschaften unterstützt.

Die Ergebnisse dieser Arbeit sind im Einklang mit früheren Studien die eine wechselseitige Abhängigkeit zwischen der Entwicklung von Technologien und Geschäftsmodellen feststellten. „Sustaining Innovation" wurde bei etablierten Firmen in der Automobilindustrie identifiziert. Die Softwareentwickler als Neueinsteiger hatten Kompetenzen in KI, Robotik, und Softwareentwicklung, und konzentrierten sich auf Systeme für Mobilitätsservices. Diese konnten selbstfahrende Systeme ohne substanzielle Übernahmen und Partnerschaften entwickeln. Bei etablierten Unternehmen wurde ein hoher Grad an Partnerschaften und externen Technologieübernahmen festgestellt um digitale Kompetenzen zu erwerben, vorwiegend um komplementäre Fähigkeiten zu nutzen. Partnerschaften sollten Kosten und Risiken senken, während die Gründe für Übernahmen an qualifiziertem Personal in digitalen Technologien sowie der raschen Markteinführung lagen. Die Ergebnisse sind im Einklang mit früheren Studien welche eine erhöhte Bereitschaft an externen Technologieübernahmen identifizierten wenn sich Technologien erheblich von den Kernkompetenzen unterschieden. Weiters wurden frühere Studien bestätigt welche den Einsatz höherer Automatisierungsgrade in Fahrzeugen zunächst in „Produkt-Service Systemen" identifizierten.

Weitere Forschung könnte die Wertschöpfung untersuchen sobald Systeme marktreif sind da anhand der frühen Phase des Ökosystems für autonome Fahrzeuge, dem neuen Markt, und der Vielzahl an neuen Technologien weitere Änderungen an der Wertschöpfung wahrscheinlich sind.

Abstract

The automotive industry faces technology shifts towards electrified, shared, always-connected, and self-driving vehicles. Recent advances in digital technologies enabled the development of autonomous vehicles, and the automotive industry was identified as an industry that would soon follow the path to digital transformation. With the influx of digital technologies, also non-traditional firms entered the automotive segment. Thus, this work aims to explore the influences of digital technologies on business models in the automotive business ecosystem, with a focus on value creation aspects of the business model concept.

A mixed-methods approach was used to investigate the influence on value creation aspects of firms due to the development of technologies for autonomous driving. There is a multiple-case study at the core of this work that investigates the leading business ecosystem actors with respect to technologies for self-driving vehicles. Following a literature review, secondary data was used to identify leading business ecosystem actors. This resulted in 12 cases ranging from OEMs, automotive suppliers, to technology and software companies. Then, secondary data on the firm's technology sourcing initiatives towards the ADS, lidar, HD-maps, and transportation-as-a-service were collected and analyzed. The cross-case synthesis as a method of analysis was supported by the results of qualitative content analyses on potential drivers of major R&D partnerships, investments, and acquisitions as technology sourcing initiatives.

This study is consistent with previous studies that identified the interdependence between technological innovation and the business model as incumbent firms in the automotive business ecosystem also followed the path of sustaining innovation. New firms exclusively focused its R&D efforts towards systems for mobility services. Software companies as new entrants in the automotive segment with key resources in technologies like AI, robotics, and software engineering developed automated driving systems without major R&D partnerships and acquisitions of system developers. The incumbent firms required a high degree of partnerships and external technology acquisitions to get the key resources in digital technologies. Partnerships were mainly entered for the reduction of risk, costs, and uncertainty and leveraging complementary resources. Acquisitions were made for human resources in digital technologies, and complementary resources to accelerate time-to-market with a new business model. The outcome supports previous findings that firms favor external technology acquisitions when the target technology fundamentally differs from the firm's core competencies. The study also concurs with previous findings that higher levels of driving automation require use-oriented product-service systems.

Further research could address the influence on value creation aspects once autonomous vehicles are available at scale. Due to the early phase of the autonomous driving business ecosystem, the new markets, and the variety of new technologies, further changes of value creation are likely.

Contents

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Abbreviations

ADS	Automated Driving System
ADAS	Advanced Driver Assistance Systems
AI	Artificial intelligence
AV	Autonomous vehicle
BE	Business ecosystem
DL	Deep learning
MaaS	Mobility-as-a-Service
ML	Machine learning
ODD	Operational Design Domain
PSS	Product-Service Systems
RQ	Research question
SAV	Shared autonomous vehicle
TaaS	Transportation-as-a-Service

Part I.

Research Intent

1. Introduction

This chapter aims at introducing the aim of this work in section 1.1 and presents the derived research questions in section 1.2.

1.1. Aim of This Work

This thesis considers the field of self-driving vehicles as the main subject of its study. It is one of the dominant technology shifts that are undergoing in the automotive industry that faces a trend towards electrified, shared, always-connected, and self-driving vehicles (Lipson and Kurman, 2017, p. 46).

A challenging problem that arises in this domain is the influx of digital technologies that are required to develop self-driving vehicles (Zhao et al., 2018) in the traditional automotive industry (Iansiti and Levien, 2004*b*). This means that this study explores the influence of digital technologies on business models in the automotive business ecosystem. Business models describe *"the rationale of how an organization creates, delivers, and captures value"* (Osterwalder and Pigneur, 2010, p. 14) and they are used to link technology and ideas with its commercialization (Baden-Fuller and Haefliger, 2013; Zott et al., 2011). In addition, firms evolve in a business ecosystem together with other firms, institutions, customers, and capital around an innovation, either as partners or competitors (Moore, 1993). Business ecosystems are used as a concept to move away from the traditional way of thinking about businesses in industries (Moore, 1996*a*). This is especially useful as technology requirements make industry borders hard to discern (Demont and Paulus-Rohmer, 2017), which leads to companies that operate in a variety of industries (Moore, 1993). Due to the early phase of the business ecosystem, this study focuses on the value creation aspects of the business model. This means that this study focuses on key partnerships, key activities, and key resources (Osterwalder and Pigneur, 2010) that are influenced by the development of technologies for autonomous driving.

As far as the author knows, previous research that has been conducted on the influences of initiatives towards technologies for autonomous driving on value creation aspects of the business model concept in the context of the business ecosystem is scarce.

One way to overcome these problems is to perform case study research to get empirical insights into the emerging business ecosystem around self-driving vehicles. Enabled by the business ecosystem context, this allows investigating firms with a variety of origins other than the automotive industry. The exact methodology is described in chapter 2.

1.2. Research Questions

Based on the information provided in the previous section, the aim here is to investigate the following research questions:

- RQ: How has the value creation aspect of business models in the automotive business ecosystem changed due to the development of technologies for autonomous driving?
  - RQ-Sub1: Who are the leading actors in the automotive business ecosystem with regards to technologies for autonomous driving?
  - RQ-Sub2: What initiatives do firms (RQ-Sub1) undertake towards technologies for autonomous driving?
  - RQ-Sub3: How have initiatives towards technologies for autonomous driving influenced the value creation aspect of investigated firms?

The research questions were answered using secondary data. The methodologies used to answer the research questions were outlined in the following chapter.

2. Methodology

A mixed-methods approach was used to answer the research questions. The core of this thesis is an exploratory multiple-case study involving the technology sourcing and commercialization behavior of 12 actors in the autonomous driving business ecosystem and qualitative content analysis on potential drivers of technology sourcing initiatives. Case study research, in general, was chosen due to its suitability for contemporary events (Yin, 2018, p. 9). This thesis investigates the emerging autonomous driving business ecosystem, and the cases were used as an *"opportunity to shed empirical light on some theoretical concepts or principles"* (Yin, 2018, p. 38).

2.1. Case Selection

Three studies on the leading companies in the autonomous driving business ecosystem with regards to technologies and commercialization of self-driving systems were taken into account (see Abuelsamid and Jerram (2018); Abuelsamid and Gartner (2019); PTOLEMUS (2019) in chapter 7). Those are the three studies that could be found with the Google internet search engine that analyzed companies that develop "turnkey" solutions for autonomous driving that were published beginning from 2018. Thus, the studies did not analyze suppliers of subsystems and components. The combined findings of those studies (what the studies considered as "leading" firms) led to the selection of 12 business ecosystem actors that were investigated as cases in this multiple-case study. Those companies are of different age, size, and type, ranging from established OEMs and suppliers in the automotive industry to software companies as new entrants in the automotive business ecosystem. Thus, the case selection was based on indications that the companies approached the development of selected technologies for autonomous driving.

2.2. Data Collection

Secondary data was used throughout this thesis. Archival data (annual and quarterly reports for reporting years 2016 - 2018, the firms' websites until November 2019, the Lexis Uni[1] database for

[1] URL: http://www.nexisuni.com/

entries between 2016 and November 2019, and the Google internet search engine until February 2020) of the leading BE actors (see RQ-Sub1 in chapter 7: Aptiv, Aurora, BMW, Bosch, Daimler, FCA, Ford Argo AI, GM Cruise, Intel Mobileye, Volkswagen, Waymo, and Zoox) were analyzed to identify the initiatives towards technologies for autonomous driving.

Due to a large amount of text inside those documents, a specific set of keywords was used to find content that is relevant to the research question. The keywords were determined using the following procedure. In section 6.2.1, the different levels of driving automation were elaborated to be able to distinguish between autonomous driving and driver assistance. The archival data was then scanned for the following keywords that derived from theory: *autonomous*, *automated*, *self-driving*, *driving automation*, *level 3*, *level 4*, and *level 5*. After a first sighting of data, these insights led to a further discussion of theory on product-service systems (section 5.1), technology sourcing (section 6.1.3), as well as technologies for autonomous driving (section 6.2.3). Given the limited amount of research resources, the focus on technological components was constrained to the main technological challenges described in theory: lidar sensors, control platform, artificial intelligence, and maps (see section 6.2.3). The following keywords that derived from the iteration between theory and data were used in the material mentioned before to find relevant content:

> *autonomous*, *automated*, *self-driving*, *driving automation*, *level 3*, *level 4*, *level 5*, *lidar*, *mobility service*, *ride-hailing*, *robotaxi*, *AI*, *artificial intelligence*, *machine learning*, *deep learning*, *maps*, *HD-maps*, *investment*, *partnership*, *acquisition*, and *cooperation*.

Searches in databases and internet search engines were combined with the company name or the name of the autonomous driving unit. Databases and general internet search engines were primarily used to fill missing data. The collected information about the companies' initiatives towards autonomous driving was incorporated into a database, as described by Yin (2018), that contains documents, tabular materials, and notes.

2.3. Qualitative Content Analysis to Identify Potential Drivers of Technology Sourcing Initiatives

Searching the Lexis Uni database to identify the initiatives towards technologies for autonomous driving showed that the firm's investor conferences and earnings calls offer insights into the potential drivers of major investments, acquisitions, and partnerships. The transcripts of the events were analyzed using qualitative content analysis with the methodologies proposed by Mayring (2010) and Gioia et al. (2012). The first sighting of transcribed records showed that the events were typically covered within the first three conference or earnings calls following the technology sourcing event. Therefore, the first three transcripts that were published for the firm's investor earnings calls or investor conferences following the events were included in the qualitative content analysis.

Following the procedure proposed by Gioia et al. (2012) and Mayring (2010), the analysis started with an inductive category formation that defined categories and assigned them names that were closely related to the terminology used in the material. Throughout the process, a category analysis was made to help to identify similarities in categories to reduce the overall number of categories. That resulted in *first order concepts* which were the starting point for the transformation into *second order themes* based on theoretical concepts (Gioia et al., 2012). The business model building blocks described by Osterwalder and Pigneur (2010) were used as theoretical concepts for the transformation. The potential drivers of entering into partnerships, make investments, or make acquisitions of major ADS developers were investigated using the research questions *"What are the main reasons for major investments or acquisitions of AV developers?"* (section 9.1.1) and *"What are the main reasons for major partnerships between AV developers?"* (section 9.1.2). The qualitative content analysis followed the selection criteria that the text must relate to the research question. The abstraction level was chosen in a way to preserve the original wording, if possible. It should include specific mentions that relate to reasons, benefits, and similar aspects for investments, acquisitions, and partnerships. The coding unit was chosen as a clear meaning component in the text, and the context unit was the entire case. The evaluation criteria were defined as the entire case.

The potential drivers of acquisitions, major investments, and partnerships, are shown in Figures 11 and 12. A data structure presented in Clark et al. (2010) was used to visualize the resulting first-order concepts and second-order themes. These embedded units of analysis (Yin, 2018) then supported the following cross-case synthesis.

2.4. Cross-Case Synthesis

The cross-case synthesis followed the approach to retain the holistic characteristics of each case while avoiding the decomposition of each case into separate variables as a unit of analysis. This is due to the small number of cases that would not be sufficient to justify a variable-based approach and because variables were not controlled. A vital characteristic of analyzing case study evidence with cross-case synthesis as a technique is that it relies on the argumentation of identified patterns rather than numeric proof. Therefore, each case was analyzed to identify the within-case patterns. (Yin, 2018, p. 196-198)

The analysis focused on "how" and "why" companies approached the development of technologies for autonomous driving, including the components that would be required to operate the business model with self-driving technology. This was supported by the results of the qualitative content analysis on potential drivers of technology sourcing initiatives mentioned before. The analysis also focused on the institutional settings of each case, which helps to make common findings comprehensible (Yin, 2018, p. 198). Once the within-case patterns were identified, and the first tentative conclusions were drawn for each case, the analysis continued with the identification of replicative relationships as well as differences across cases (Yin, 2018, p. 196-198). This was supported by a timeline that presents multi-dimensional process data (Langley, 1999) and diagrams that depict the interconnectedness of BE actors.

Part II.

Related Work

3. Business Ecosystems

The business ecosystem concept describes the mutual influences of businesses on each other, their role within the community, as well as the state of their environment (Iansiti and Levien, 2004*b*; Moore, 1993). Section 3.1 describes the origins of the business ecosystem concept. Then, section 3.2 shows definitions of the business ecosystem concept, and describes the phases of business ecosystems. Furthermore, the different roles of business ecosystem actors are described in that section.

3.1. Origins of the Business Ecosystem Thinking

According to Anggraeni et al. (2007), there are two approaches to business ecosystems. The first *"uses natural ecosystems as a metaphor for understanding business networks"* (Anggraeni et al., 2007, p. 2) whereas the second is a *"reality-based approach which regards business ecosystems as a new organizational form"* (Anggraeni et al., 2007, p. 2).

Moore (1993) and Iansiti and Levien (2004*b*) both compared business ecosystems with ecosystems found in nature. There, no organization or species could evolve completely isolated from everything else. This means that there is a large number of participating entities in business and biological ecosystems that are dependent on each other to survive and thrive (Iansiti and Levien, 2004*b*).

Iansiti and Levien (2004*b*) argued that the biological term *community* would be more accurate to describe the phenomena known as an ecosystem. Communities refer to the organisms that are living in an environment with its resources (Peltoniemi and Vuori, 2008) and *"Community ecology investigates the nature of organismal interactions, their origins, and their ecological and evolutionary consequences"* (Cavender-Bares et al., 2009, p. 693). However, the term *ecosystem* should indicate that it is about a *"complex system and that we are working with a biological analogy"* (Iansiti and Levien, 2004*b*, p. 5).

3.2. The Business Ecosystem Concept: Definitions, Phases, and Actor Roles

According to Moore (1996*b*), a business ecosystem is *"an economic community supported by a foundation of interacting organizations and individuals – the organisms of the business world"* (p. 26). Other scholars argued that *"business ecosystems are formed by large, loosely connected networks of entities"* (Iansiti and Levien, 2004*a*, p.20).

Moore (1993) suggested to stop categorizing businesses into certain industries and to see them in an ecosystem with a variety of industries instead. This is not only because advances in technologies make industry borders hard to discern (Demont and Paulus-Rohmer, 2017) but also because many firms actually operate in several industries and especially because competition happens between different ecosystems (Moore, 1993). According to Moore (1993), companies within an ecosystem can jointly develop capabilities around innovations and offer new solutions, either as competitors or partners. It was further argued that *"In a business ecosystem, companies coevolve capabilities around a new innovation"* (Moore, 1993, p. 76) and these efforts could ultimately lead to new innovations (Moore, 1993).

There are several areas in which a business ecosystem can be defined. In essence, it can be around a certain company (e. g. the Microsoft ecosystem, Toyota ecosystem), a certain type of product in an area (e.g., the US automobile business ecosystem), and each ecosystem can compete against each other. In essence, businesses need an attractive ecosystem to work. This ecosystem must be an environment comprising of other actors such as companies, suppliers, customers, and capital. Only then can companies become successful. (Moore, 1993)

Moore (1996*a*) identified four phases in which a business ecosystem evolves:

1. **Birth:** the initial phase in a business ecosystem aims at creating a value proposition based around innovation. The organization that catches and fulfills the customer needs best typically leads in this phase. Additionally, co-evolution that is established in the first phase tends to pay off later on. The goal is to get the most important customers, suppliers, and channels. (Moore, 1996*a*)

2. **Expansion:** the second phase is about expansion and diversification. There is a competition between the new ecosystem and older and other business ecosystems, and it is the point where firms must think about future initiatives. Therefore, there must be an economically viable use case in the business ecosystem that must be scalable and be able to leverage economies of scale. Furthermore, scaling in this phase often requires a considerable amount of financial resources. (Moore, 1996*a*)

3. **Leadership:** while the second phase was about rivalry among ecosystems, the third phase

adds rivalry for leadership inside the ecosystem. It is the phase when consolidation, as well as the determination of the position inside the ecosystem, happens. The establishment of niches and the definition of products, services, and processes are typical of the leadership phase. Moreover, former partners can become rivals, and due to reduced R&D expenses, a large number of new entrants lead to thinner margins and drives down the prices for consumers. (Moore, 1996*a*)

4. **Either self-renewal or death:** when a business ecosystem cannot cope with changed market behavior, it is about to decline. Self-renewal can be among the most challenging activities. In general, partnerships with innovators can work to bring the ecosystem up-to-date, and measures such as lock-in effects can prevent customers from switching ecosystems for a certain amount of time. (Moore, 1996*a*)

Iansiti and Levien (2004*b*) identified different organizational roles in a business ecosystem, namely *niche players*, *keystone organizations*, and *dominators*. Organizations are not limited to a single role, they can have different roles in a different domain.

- **Niche players** are most commonly found in an ecosystem, and they specialize in specific capabilities. Resources of other niche organizations or keystone organizations are used as a starting point to become an expert in a specific domain. The rise of new niches is a sign of healthy ecosystems, while other niches may disappear. In the business ecosystem, niches could emerge with new technologies, and with that, new businesses and products appear. Iansiti and Levien (2004*b*) described two real-world examples illustrating different occurrences in niches: For example, when IBM's mainframe business collapsed, the niche suffered, but new opportunities came with the rise of the personal computing industry. A different case would be the automotive industry that had a long tradition of preventing the rise of new niches. (Iansiti and Levien, 2004*b*)

- **Keystone organizations** typically create physical or intellectual platforms and enable an efficient way to connect participants or create products by other members of the ecosystem. This can be achieved by providing common assets that support stability within the ecosystem and by providing new solutions that can be used to build on those common assets. Moreover, keystone organizations can incorporate technological innovations in their assets and, therefore, secure the continuance of an ecosystem. Value creation should be designed attractively in the environment of a keystone organization, and often a great amount of value creation is performed by niche players. Therefore, most keystone organizations are only a small part of the entire ecosystem, but due to their impact, the entire ecosystem would fail without them. In general, keystone organizations are relatively immune to single niche organizations. The sheer number of niche organizations, however, has better leverage against a keystone organization. One example of a keystone organization is Microsoft in the personal computer industry. Microsoft provides a platform and common assets to create solutions based on that. However, the organization is only a small part of the ecosystem, but its disappearance would affect the entire ecosystem. (Iansiti and Levien, 2004*b*)

- **Physical dominators** play a more dominating role in an ecosystem. Vertical or horizontal integration can be used to create dominance in a business ecosystem and subsequently dominate value creation and capturing. This leads to the situation that other members of the ecosystem, such as niche players, are hindered in their development. Value dominators, in contrast, have not spread across the ecosystem and may control only a single hub. Whereas physical dominators create value, value dominators create little value but soak up value created from other participants in the ecosystem. This could ultimately lead to a dying ecosystem that would eventually take down the value dominator. (Iansiti and Levien, 2004*b*)

Moore (1993) already demonstrated the applicability of the business ecosystem concept to the automotive industry. It was described that roles in the BE but also leadership changes as the BE progresses. (Moore, 1993)

4. The Business Model

The business model links technologies and ideas with their commercialization (Baden-Fuller and Haefliger, 2013; Zott et al., 2011). Additionally, the business model concept is considered to be something "real" and practical, and not an abstract concept (Baden-Fuller and Mangematin, 2013; Achtenhagen et al., 2013).

Research regarding business model concepts gained momentum in the beginning of the 21st century (Zott et al., 2011) and business models are seen as a *"relatively new concept"* (Baden-Fuller and Mangematin, 2013, p. 419). According to Teece (2010, p. 174) there is a lack of generally accepted theoretical grounding of business models in the research fields of economics or business studies. Some scholars argued that the business model should be considered a stand-alone concept (Baden-Fuller and Haefliger, 2013; Baden-Fuller and Morgan, 2010), whereas others argued that the business model concept is embedded in strategy literature concerning competitive advantage (Osterwalder and Pigneur, 2010).

The remainder of this chapter is structured as follows. First, section 4.1 gives definitions of the business model concept. Then, section 4.2 goes into further detail about value creation, which is a part of the business model concept.

4.1. Definitions of Business Model Concepts

Every organization has at least one business model, regardless of the organization's awareness of the business model concept (Drucker, 1994; Teece, 2010; Zott and Amit, 2013). However, the term business model does neither possess a single definition (Zott et al., 2011; Denicolai et al., 2014) nor relates to a single concept (Zott et al., 2011; Teece, 2010). This is due to the complexity of the topic as well as the great number of different applications of business model concepts (Spieth and Schneider, 2016, p. 689). In addition, an analysis of 19 articles or books on business model literature performed by Clauss (2017) revealed six different conceptualizations and 73 business model components. The results of this analysis showed the fragmented area of business model literature. Table 1 illustrates different business model definitions.

Table 1.: A selection of business model definitions

Author	**Definition**
Amit and Zott (2001, p. 494-495)	*"The business model depicts the design of transaction content, structure, and governance so as to create value through the exploitation of business opportunities"*
Magretta (2002, p. 4)	Business models are *"stories that explain how enterprises work. A good business model answers Peter Drucker's age-old questions: Who is the customer? And what does the customer value? It also answers the fundamental questions every manager must ask: How do we make money in this business? What is the underlying economic logic that explains how we can deliver value to customers at an appropriate cost?"*
Johnson et al. (2008, p. 3)	*"A business model, from our point of view, consists of four interlocking elements that, taken together, create and deliver value"*
Teece (2010, p. 191)	*"A business model describes the design or architecture of the value creation, delivery and capture mechanisms employed."*
Zott and Amit (2010, p. 217)	*"[...] the overall objective of a focal firm's business model is to exploit a business opportunity by creating value for the parties involved, i.e., to fulfill customers' needs and create customer surplus while generating a profit for the focal firm and its partners."*
Osterwalder and Pigneur (2010, p. 14)	*"A business model describes the rationale of how an organization creates, delivers, and captures value"*

The selection of BM definitions in Table 1 shows that value is a crucial component of business model definitions. There is a certain agreement among researchers that business models are firm-focused views that link internal firm activities with the outside world and that the business model concept is focused on value - how value is created and captured (Baden-Fuller and Mangematin, 2013). *Value creation*, *value delivery*, *value proposition*, and *value capture* are business model dimensions that are commonly found in business model definitions (Clauss, 2017; Remane et al., 2017). This categorization into dimensions not only helps to compare business models concepts but also helps to develop and evaluate new business models (Voelpel et al., 2004).

Table 2.: Elements of the business model concept proposed by Osterwalder and Pigneur (2010). Adapted from: Remane et al. (2017, p. 5)

Meta-component	**Business model building block**	**Description**
Value proposition	Value propositions	Gives an overall view of a company's bundle of products and services.
Value delivery	Customer segments	An organization serves one or several customer segments.
	Channels	Value propositions are delivered to customers through communication, distribution, and sales channels.
	Customer relationships	Customer relationships are established and maintained with each customer segment
Value creation	Key resources	Key resources are the assets required to offer and deliver the previously described elements
	Key activities	Number of key activities performed by key resources.
	Key partnerships	Some activities are outsourced and some resources are acquired outside the enterprise.
Value capture	Revenue streams	Revenue streams result from value propositions successfully offered to customers.
	Cost structure	The business model elements result in the cost structure.

Table 2 illustrates the "business model building blocks" of the business model concept of Osterwalder and Pigneur (2010) that can be visualized using the business model canvas illustrated in Figure 1. It also shows the assignment of the business model building blocks to business model dimensions (meta-components). Value creation, in particular, is described in section 4.2.

4.2. Value Creation

Value creation is a dimension of the business model concept together with value delivery, value proposition, and value capture (Clauss, 2017; Remane et al., 2017).

According to Bowman and Ambrosini (2000), there are two types of value. First, use-value is the

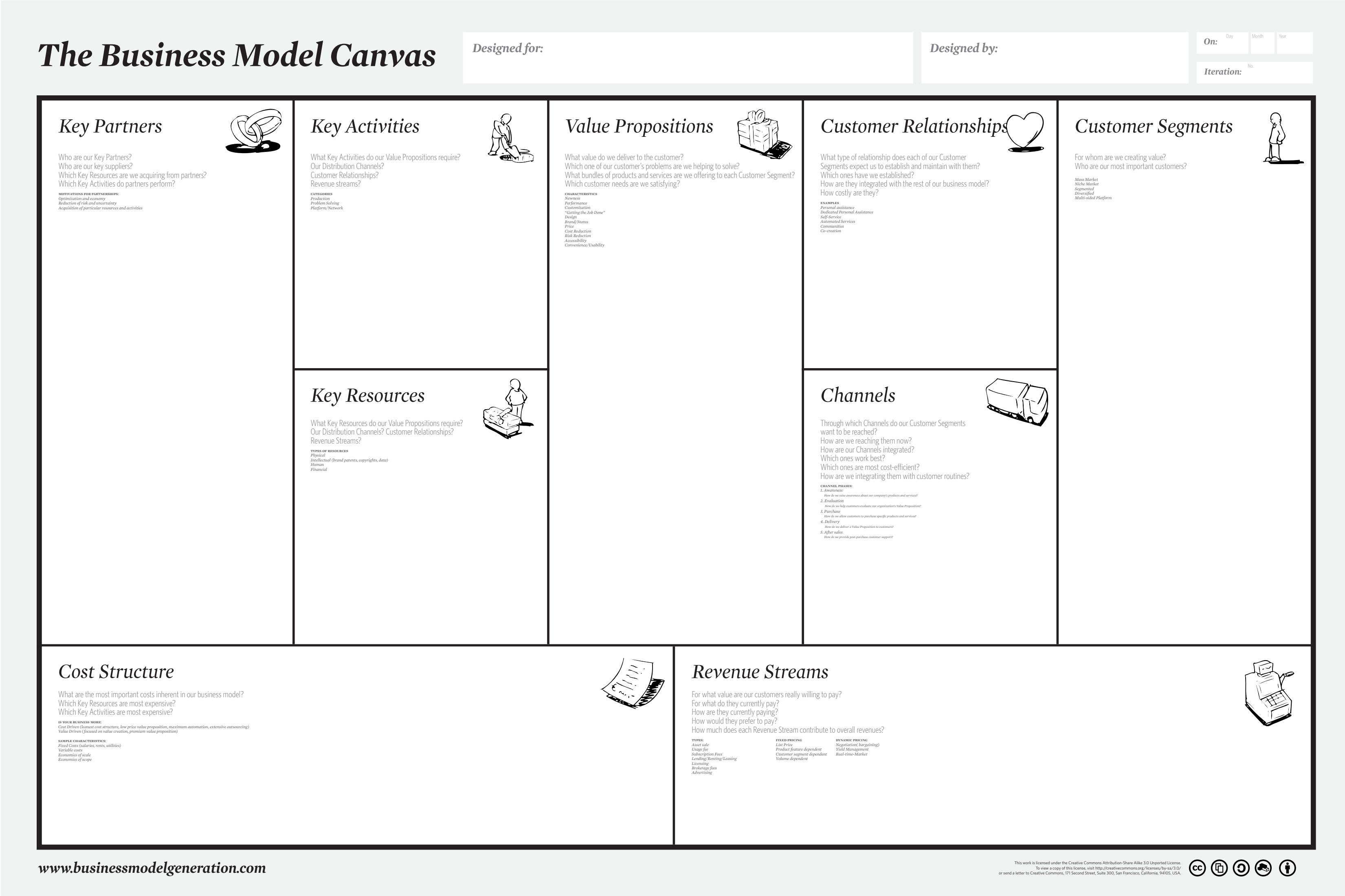


Figure 1.: Business Model Canvas. Reprinted from Strategyzer AG (n.d.)

subjective perception of how much a product satisfies a need. For example, employees of a firm buy machines because there is a need to make a profit. Second, there is an exchange value that is only realized and established when a product is sold. Thus, companies create a use-value (e.g., in a production process), and the product is assigned with an exchange value when it is sold. At the same time, customers find it hard to value the input of a production process, and the simple existence of resources such as raw materials, machinery, computers, and brands does not lead to created use-value. This means that resources and activities are needed to create a use-value. (Bowman and Ambrosini, 2000)

The value creation logic of a business model describes what it takes in terms of activities and processes and, in general, core competencies to make products or services available on the market (Matzler et al., 2013, p. 33). Clauss' business model literature review showed that value creation can be divided into four subconstructs which cover *capabilities*, *technologies*, *processes and structures*, and *partnerships* (Clauss, 2017, p. 387). Capabilities of a firm are made of activities that can be developed through external knowledge integration (Achtenhagen et al., 2013) and learning (Teece et al., 1997; Achtenhagen et al., 2013). Besides, technological resources and equipment are required to create value. The coordination between technology and business models determines whether sustained value creation is possible (Wei et al., 2014). The subconstruct of value creation, which describes processes and structures, is closely related to the activities of a firm (Zott and Amit, 2010). It describes how they are connected and further distinguishes between core activities and supporting activities (Zott and Amit, 2010). In contrast to the capabilities mentioned before, partnerships enable access to external resources (Clauss, 2017).

For example, Johnson et al. (2008) described *key resources* and *key processes* as business model elements which enable value creation. This includes human resources, technologies, products, equipment, information, channels, partnerships, alliances, and brands as possible key resources of a firm. They are the key resources that are required in a firm to deliver the value proposition to the customer. Additionally, key processes show what is needed for repeatable, profitable, and scalable delivery of value propositions. (Johnson et al., 2008)

With regards to the business model concept proposed by Osterwalder and Pigneur (2010) and as illustrated in Table 2 on page 14, the business model building blocks *key partnerships*, *key resources*, and *key activities* refer to the value creation dimension of the business model. According to Osterwalder and Pigneur (2010), the key resources are the assets available to a firm that enable them to execute a business model. They can be physical assets, or intellectual, human, and financial resources. Then, *"the most important actions a company must take to operate successfully"* (Osterwalder and Pigneur, 2010, p. 36) are described in the key activities element of the business model. Typical key activities, depending on the type of business, were described as activities related to production, problem-solving, and those activities related to the operation of a platform and network. Lastly, the key partnerships element comprises of the most important strategic alliances between competitors and non-competitors, joint ventures, and buyer-supplier relationships. They are used to secure and optimize access to important resources and activities and reduce the risk and costs in business areas with a high degree of uncertainty. (Osterwalder and Pigneur, 2010)

5. Product-Service Systems

Management literature suggests manufacturing firms go downstream the value chain and thus combine services and product offerings (Oliva and Kallenberg, 2003, p. 160), which could result in product-service systems (PSS) (Goedkoop et al., 1999). Early use cases of PSS in the automotive industry are car-sharing (Goedkoop et al., 1999, p. 74). Autonomous driving would further accelerate car-sharing, ride-hailing, and cargo ride-sharing as use-oriented PSS (Antonialli et al., 2018). Therefore, this chapter presents definitions of PSS in section 5.1, followed by the categorization of PSS in section 5.2. Lastly, the characteristics of implementing PSS for product and service-focused firms are described in section 5.3.

5.1. Definitions of Product-Service Systems

Table 3 shows a selection of product-service system definitions. In essence, product-service systems combine products with services. The scope of PSS are the services that are offered in addition to the essential services (activities) for the product. Furthermore, it was argued that the services in a PSS should contribute significantly to the value creation aspect of the firm's business model. However, the product can be of equal importance. PSS do not need to be offered by one actor, they can be offered together with partners, too. (Goedkoop et al., 1999, p. 18) Baines et al. (2007) emphasized that PSS are focused on selling the *use* of an asset while avoiding the rights and obligations of asset-ownership.

Table 3.: A selection of PSS definitions

Author	**Definition**
Goedkoop et al. (1999, p. 3)	*"A Product Service system (PS system, or product service combination) is a marketable set of products and services, jointly capable of fulfilling a client's need."*
Goedkoop et al. (1999, p. 1)	They are *"commercial deals containing both a material product and an intangible service"*.
Tukker (2004, p. 246)	*"[..] tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs"*

Table 3.: A selection of PSS definitions (continued)

Author	Definition
Baines et al. (2007, p. 1543)	*"A PSS can be thought of as a market proposition that extends the traditional functionality of a product by incorporating additional services. Here the emphasis is on the 'sale of use' rather than the 'sale of product'."*

5.2. Categorization of Product-Service Systems

Tukker (2004) identified three categories of product-service systems, which are further divided into eight types. With each type, the relevance of the product itself decreases while the provider has more freedom to satisfy customer needs:

- **Product-oriented services**
  With *product-oriented services*, the product sale is still the center of attention, and add-on services could be added to the business model. These services could be *related* to the product and be useful during the product lifecycle, such as maintenance contracts and financing. Besides, *advice and consultancy* for the product are product-oriented services. (Tukker, 2004)

- **Use-oriented services**
  Use-oriented services differ from product-oriented services because the product sale is not a part of the business model anymore. The business model is geared towards product use, and the product remains in the property of the service provider. Several customers could use the product. Popular forms of use-oriented services are product *leases* where the customer pays a fee and is therefore entitled to use the product with unlimited access. Other forms include product *renting or sharing*. In contrast to product leases, customers only get limited access, and others could use the product at a different time. Additionally, *product pooling* is a use-oriented service where the product is shared with other customers at the same time. (Tukker, 2004)

- **Result-oriented services**
  With *result-oriented services*, the client and the service provider only agree on a certain result. The product is, therefore, not an integral part of a result-oriented service. First, *outsourced activities* of a company were categorized as result-oriented services because they are often tied to certain performance indicators. This is, for example, the outsourcing of cleaning services. Second, *pay per service unit* (PSS) let the customer pay for the output of a typically fairly popular product. For example, the customer pays a fee for the number

of printed copies and not for the printer, paper, toner, and maintenance. Lastly, *functional results* are considered more abstract than outsourced activities, and it is the choice of the provider how the result could be delivered. This could be the case when the provider sells a pleasant climate instead of heating or cooling systems. (Tukker, 2004)

5.3. Product-Service Systems for Manufacturing and Service Companies

The implementation of product-service systems offers different advantages and disadvantages to manufacturing and service companies. The implementation of PSS in product-focused firms could impact their business in the following ways:

- *"The fundamental business benefit of a PSS is an improvement in total value for the customer through increasing service elements"* (Baines et al., 2007, p. 1548). The service elements, in addition, can help to achieve a competitive advantage when the added services are hard to copy (Baines et al., 2007, p. 1548).
- PSS could be used to bring additional, recurring revenues (Wise and Baumgartner, 1999).
- PSS can reduce the input of resources (e.g., financial, material) for a similar customer use-value (Baines et al., 2007, p. 1548).
- PSS can bring product-focused firms in direct contact with their customers (Goedkoop et al., 1999, p. 22).

Service-focused firms could implement PSS for the following reasons (Goedkoop et al., 1999, p. 22):

- It was argued that services tend to be easily copied, and adding products could strengthen the position in the industry.
- The goal could be to *"reduce costs (automation)"* (Goedkoop et al., 1999, p. 22).
- The financial entry barrier for clients is lower because the product is not sold.
- Marketing could be easier and profit from the existence of products.

Both product- and service-focused firms may benefit from trends like outsourcing that could increase the consumption of services (Wise and Baumgartner, 1999). This is because the consumption of services could reduce the amount of required capital, but it could also increase the flexibility of firms (Wise and Baumgartner, 1999). Furthermore, the product itself may not be the prime objective when buying decisions are made; customers want an answer to a problem (Teece, 2010, p. 175). Baines et al. (2007, p. 1549) argued that PSS might require a cultural shift of customers to achieve that, and this is one of the main difficulties when PSS are implemented. Furthermore, implementing PSS requires organizational change across all elements of the business model (Baines et al., 2007, p. 1549)

6. Technological Innovation

According to Lipson and Kurman (2017, p. 46), car companies face technology shifts towards electrified, shared, always-connected, and self-driving cars. This shows that autonomous driving is one of the emerging major topics in the automotive business ecosystem (BE), an ecosystem that successfully suppressed many niches from emerging in the past (Iansiti and Levien, 2004*b*, p. 5). Therefore, this chapter discusses how companies can approach technological innovation in section 6.1, and explains technological innovation on the basis of autonomous vehicles in section 6.2.

6.1. Technological Innovation in Companies

Changes in technology can affect existing companies and provide significant potential to new entrants in the business ecosystem (Christensen, 2016). Therefore, section 6.1.1 describes the principles of sustaining and disruptive innovation and how they can affect both new and existing firms. Then, section 6.1.2 describes how technological innovation and the business model are dependent on each other, followed by the technology sourcing initiatives a firm could make in section 6.1.3.

6.1.1. Disruptive and Sustaining Innovation

Christensen (2016) described two types of innovation, namely sustaining innovation and disruptive innovation. Innovation mostly happens as sustaining innovation, where good products become improved based on the needs of the most valuable customer segments. Sustaining innovation can vary in difficulty between incremental and radical changes, but it improves products or services along trajectories that high-end customers value the most. This increases product performance and moves the firm upmarket. This process, however, often neglects the needs of low-end customer segments and exceeds the needs of some other customer segments. In general, the dominating companies of an industry excel at sustaining innovation. (Christensen, 2016)

Disruption, on the other hand, *"describes a process whereby a smaller company with fewer resources is able to successfully challenge established incumbent businesses"* (Christensen et al., 2015, p. 4). Disruptive innovation, therefore, starts in low-end or new markets that were neglected by the industry's dominating firms. Disrupters address these markets with low-performance products or services which do not satisfy mainstream customers. These innovations offer a different value proposition to customers. Moreover, solutions based on disruptive innovation tend to offer attributes like better affordability, simpler and more convenient usage, and reduced size. Disruptive innovations can improve their performance to the point where mainstream customers start switching from the old established products and services to the new offerings based on disruptive innovation. This would be the point when disruption happened. The disruptive innovation must not necessarily excel or intersect the product performance trajectories of established products. It was argued that there would be no need to outperform in these dimensions as long as products based on disruptive innovation are good enough for mainstream customers. Disruption is, therefore, not happening as an event. Disruption is rather a process that can take a significant amount of time. This means that disruption theory does neither define a certain amount of time until disruption must have happened nor a time until the disrupted offers would have to disappear. Hence, the disruptive and the disrupted offers can coexist for a significant amount of time. In addition, success is not part of the definition of disruption. This means that having an extremely successful innovation does not imply having a disruptive innovation. (Christensen, 2016, 2006; Christensen et al., 2015)

Moreover, disruption is not an absolute appearance as it is relative to another company's business model (Christensen, 2006, p. 48). Therefore, the same innovation can be disruptive in relation to the business model of one company, whereas innovation can be sustaining relative to the business model of another company. On the one hand, technology can be disruptive to another technology, but on the other hand, the business model may not be disrupted. Hence, *"It is a business model problem, not a technology problem"* (Christensen, 2006, p. 48). As a result, Christensen (2006) summarized these technology and business model related phenomena as disruptive innovation. Moreover, disruptive innovations tend to be financially unattractive to incumbent firms' business models and, therefore, often experience a lack of interest. (Christensen, 2006)

Schuelke-Leech (2018) adds that there are two levels of disruptive technologies. This means that first-order disruptive technologies are limited to disruptions within single markets, and they are typically commercial disruptions. Christensen's disruption theory mainly covers this type of disruption. It was emphasized that there is a second, wide-reaching level of disruptive technologies:

> *"The second order disruptions are technological disruptions, where the disruptions ripple through society, creating large scale change. That is, these technologies disrupt social interactions and relationships, organizational structures, institutions, public policies, and (sometimes) the physical environment."* (Schuelke-Leech, 2018, p. 262)

Artificial Intelligence (AI), one of the most critical technologies for autonomous driving (Lipson and Kurman, 2017), has the potential of being a second-order disruptive technology as it mimics human intelligence (Schuelke-Leech, 2018).

6.1.2. Technological Innovation and the Business Model

According to Tongur and Engwall (2014), changes in technology are among the most dangerous situations for successful incumbent firms. It was argued that the business model should not be neglected because the competitive advantage of firms can not be guaranteed by exclusively performing technological innovation (Tongur and Engwall, 2014). Thus, technological innovation and business model innovation should go hand-in-hand (Chesbrough and Rosenbloom, 2002). As the definitions of business model innovation in Table 4 show, they are mainly concerned about changing the dominant business model in existing firms. Nonetheless, both incumbent firms and new entrants should adapt the business model to the technologies they use. This is because the business model determines the economic output of technology (Chesbrough and Rosenbloom, 2002; Christensen, 2016). It was argued that *"the same idea or technology taken to market through two different business models will yield two different economic outcomes"* (Chesbrough, 2010, p. 354). Besides, Baden-Fuller and Haefliger (2013, p. 424) identified a two-way correlation between the development of business models and technologies.

Table 4.: A selection of business model innovation definitions

Author	**Definition**
Markides (2006, p. 20)	*"Business-model innovation is the discovery of a fundamentally different business model in an existing business."*
Casadesus-Masanell and Zhu (2013, p. 464)	*"the search for new logics of the firm and new ways to create and capture value for its stake-holders"*
Amit and Zott (2010, p. 2)	*"designing a new, or modifying the firm's ex-tant activity system"*
Schneider and Spieth (2013, p. 4)	*"is simultaneously about the (re-) deployment and usage of existing resources and capabili-ties to develop new value offerings or forms of value creation"*

Tongur and Engwall (2014) state that innovation research, in general, suggests to either invest in research and development to secure core competencies or to broaden the value proposition and perform forward integration. Both options, however, have its uncertainties. Investments in research and development do not guarantee the fulfillment of customer demands, whereas a "servitization" strategy creates a risk of losing the edge in technological core competencies due to the shift of the firm's activities from technologies to services (Tongur and Engwall, 2014, p. 525). Product-service systems, as discussed in section 4.2, could bridge the gap between the development of technologies and the servitization strategy. However, it is challenging to perform changes to technology and meet expectations of an unknown new market environment at the same time (Tongur and Engwall, 2014, p. 525). This results in a constant trial and error procedure to adjust the business model (Chesbrough, 2010; Teece, 2010).

6.1.3. Technology Sourcing

Veugelers and Cassiman (1999) listed several ways of pursuing new technologies that were categorized into make or buy-strategies. The make strategy relates to building technological capabilities through in-house research and development, whereas the buy-strategy is used to acquire technology from externals. Veugelers and Cassiman (1999) identified *in-house R&D with a non-negative R&D budget* as make-related attempt. With regards to buy-strategies, however, Kurokawa (1997, p. 132) listed the following activities: *licensing*, *R&D contracts*, *collaborative R&D projects*, and entering *R&D joint ventures and mergers to get access to technology*. Veugelers and Cassiman (1999, p. 77) similarly argued that *licensing*, *R&D contracts*, *consultancy services*, *purchase of another enterprise*, and *hiring skilled employees* are buy-related activities. In general, a typical example of a buy-strategy would be a technology that *"is embodied in an asset that is acquired such as new personnel or (parts of) other firms or equipment"* (Veugelers and Cassiman, 1999, p. 66). Moreover, Veugelers and Cassiman (1999) mentioned a technology sourcing strategy based on the open availability of innovation. This means the technology can be copied without the need of any commercial interaction with the innovator (Veugelers and Cassiman, 1999).

Additionally, there is a hybrid approach, which is technology development in partnerships between firms (Veugelers and Cassiman, 1999). The hybrid approach is a common way to work toward new technologies that combine and complement internal and external resources (Veugelers and Cassiman, 1999; Elvers and Song, 2014). Thus, partnerships result from the need for resources (Eisenhardt and Schoonhoven, 1996), but it also means that *"firms must have resources to get resources"* (Eisenhardt and Schoonhoven, 1996, p. 137). Working in a partnership is a way to reduce the costs for each partner and speed up the development (Veugelers and Cassiman, 1999; Kurokawa, 1997), but it comes with the caveat that development partnerships have uncertain outcomes and partners may act selfishly (Veugelers and Cassiman, 1999). This could reduce their efforts which affects the final result (Veugelers and Cassiman, 1999). Elvers and Song (2014) described that this behavior especially exists in open partnerships where a larger number of contributors is welcome to add value.

In addition to the overall categorization into make, buy, or hybrid approaches, Elvers and Song

(2014) categorized the approaches of firms toward technological innovation into three groups, namely *doing-it-alone*, *concentration on single partners*, and *open strategic partnering*. Open strategic partnering refers to collaborations, where a larger number of contributors is welcome to add value. It thus consists of multiple partners at the same time for the same R&D topic. The concentration on single partners, in contrast, requires a careful selection and analysis of potential partners prior to entering the partnership. Elvers and Song (2014) explained that open partnering leads to decreased trust between partners, and there is a lack of predictability of R&D outcomes compared to concentrated partnerships. The doing-it-alone approach, in contrast, does not involve any external R&D cooperations. (Elvers and Song, 2014)

In general, the combination of make and buy strategies was recommended due to the increased complexity of technologies as well as to maximize complementary effects. It was argued that a firm's increased awareness about costs and risks, as well as being in high-tech industries, reduces the likelihood of an exclusive buy strategy. On the other hand, when firms try to close the gap to leading competitors, the chance of executing buy strategies increases. (Veugelers and Cassiman, 1999) Moreover, Kurokawa (1997) found out that businesses favor external technology acquisitions when the target technology fundamentally differs from the firm's core competencies and rivalry among firms is high. In accordance with that, firms favor make strategies when the required resources are already available to the firm (Cruz-Cázares et al., 2013, p. 228).

The emergence of new technologies and new markets in a highly competitive environment that leads to increased uncertainty favors the existence of cooperations (Elvers and Song, 2014; Eisenhardt and Schoonhoven, 1996; Kurokawa, 1997). Eisenhardt and Schoonhoven (1996) noticed an increased willingness to form partnerships when the target markets are new but a decline in partnerships when the markets enter the growth phase. They suspected that partnerships are disadvantageous in growth markets due to their inability to act and respond quickly. Furthermore, late entrants and firms with a previous history of successful cooperations are more likely to enter info new cooperations (Eisenhardt and Schoonhoven, 1996). Besides, Eisenhardt and Schoonhoven (1996) found out that large firms led by well-connected and experienced managers with experience in leading positions in other firms are more likely to cooperate. Eisenhardt and Schoonhoven (1996) concluded that *"firms cooperated when they need to, when they were able to, and perhaps when it was popular"* (p. 148).

Acs and Audretsch (1987) researched how the firm's innovativeness is dependent on the industry, technological maturity, and the firm's size. They found out that *"capital-intensive, concentrated, and advertising-intensive"* (Acs and Audretsch, 1987, p. 573) industries were advantageous for larger firms (>500 employees). Small firms, however, typically excelled in new segments of high-tech industries in the early phase of the ecosystem. Additionally, smaller firms could better leverage situations where skilled employees and in-depth knowledge make a bigger difference than pure monetary resources, and where large firms were dominant in the existing ecosystem. (Acs and Audretsch, 1987)

6.2. Autonomous Vehicles as Technological Innovation

This section discusses autonomous vehicles as an example that shows what could be enabled by technological innovation. Prior to autonomous driving, firms in the automotive business ecosystem acknowledged the potential of active safety systems: Mitsubishi, for example, introduced a distance warning system in 1992 (Mitsubishi Motors, n.d.), a radar-based distance control feature in 1995, and a lane departure warning system in 1998 (Mitsubishi Motors, 1998). In 2017, driver assistance systems such as autonomous emergency braking, lane-keeping assist systems, autosteer, self-parking, and adaptive cruise control were available to customers (Sault et al., 2017). These systems, however, did not work in every situation and relied on a human driver who still monitored the environment and needed to intervene in risky situations (SAE International, 2018).

Additional skills were required to make the step from driver assistance systems to autonomous vehicles as they are the result of the recent advances in technologies and methods in areas such as computer science, control technology, and pattern recognition (Zhao et al., 2018). Advances in all these innovations and active safety systems would lead to self-driving vehicles (Zetsche, 2015, p. 72) what would describe a more incremental approach toward autonomous vehicles. In addition, the commercialization of self-driving technology became an issue due to high R&D expenses and costs to integrate self-driving technology on the one hand (Clifford, 2020), and the revenue opportunities of transportation-as-a-service on the other hand (Mohr et al., 2016). This means that the ability to offer self-driving vehicles in a commercial environment led to the acquisition of new capabilities for value creation in areas such as mobility platforms.

The remainder of this section on autonomous vehicles is structured as follows. The different levels of driving automation are explained in section 6.2.1. Then, selected use cases of self-driving systems are described in section 6.2.2. Lastly, the key technologies and key components to operate self-driving vehicles are described in section 6.2.3.

6.2.1. Categorization of Autonomous Vehicles

Autonomous vehicles are capable of driving without human intervention (SAE International, 2018). Developers used various names to refer to this concept: autonomous driving (BMW Group, 2019*b*; Audi, 2019; Aptiv, 2019*b*; Daimler, 2019*a*), self-driving cars (Krafcik, 2018; Audi, 2019), autonomous vehicles (Aptiv, 2019*b*; Daimler, 2019*a*), automated driving (BMW Group, 2019*a*; Audi, 2019; Daimler, 2019*a*; Aptiv, 2019*b*) and driverless cars (Daimler, 2019*a*). As the categorization of autonomous vehicles shows, driverless cars and self-driving cars refer not necessarily to the same level of technology. SAE International (2018) recommend using the term *"level [1 or 2] driving automation system-equipped vehicle"* or *"level [3, 4, or 5] ADS-equipped vehicle"* to refer to a vehicle with driving automation capability. Thus, *Automated Driving Systems (ADS)* refer to level 3-5 systems. In general, this bundle of technology can be described as *"motor* *vehicle driving automation systems that perform part or all of the dynamic driving tasks (DDT) on a sustained basis"* (SAE International, 2018, p. 3). It is a common practice in the autonomous driving business ecosystem to describe and categorize autonomous vehicles based on six levels of driving automation (Watzenig and Horn, 2017). To describe the six levels of driving automation in detail, several subject-specific terms are described briefly (SAE International, 2018):

- **ODD**
  The *operational design domain (ODD)* describes the operating conditions in which the driving automation system (or a part of it) is designed for, such as highways at low-speed traffic and good visibility of lane markings.

- **DDT**
  The *dynamic driving task (DDT)*, in essence, describes everything a human driver does to operate a vehicle, except trip scheduling, and the input of driving destinations.

- **DDTF**
  The *dynamic driving task fallback (DDTF)* occurs when the system state goes outside its specified boundaries or when system errors occur and either the human driver must handle the situation or the system must bring the vehicle in a safe state.

- **Active Safety Systems**
  Active safety systems are focused on security and can warn or intervene at risky situations.

- **OEDR**
  Object and event detection and response (OEDR) handles the monitoring of the driving environment. It responds as needed and therefore is a subtask of a dynamic driving task (DDT).

SAE International (2018) define six levels of driving automation ranging from no driving automation (level 0) to full driving automation (level 5):

- **Level 0: No Driving Automation**
  At driving automation level 0, which describes *no driving automation*, the driver performs the whole dynamic driving task and remains responsible at all times. The driver may be supported by active safety systems that can warn or intervene in risky situations.

- **Level 1: Driver Assistance**
  In vehicles equipped with level 1 *driver assistance* systems, the system can either perform steering (lateral) or accelerating and decelerating (longitudinal) vehicle motion control in certain operational design domains (ODD). The driver must supervise the system and may be required to take immediate control of the vehicle.

- **Level 2: Partial Driving Automation**
  Level 2 describes *partial driving automation*, where the system is capable of sustained lateral and longitudinal vehicle motion control in operational design domain (ODD) specific boundaries. Like level 1, the driver must supervise the DDT and must be able to perform the entire dynamic driving task immediately.

- **Level 3: Conditional Driving Automation**
  Beginning at level 3, the automated driving system (ADS) can perform the whole dynamic driving task while being engaged. Level 3 systems which provide *conditional driving automation* can manage the full dynamic driving task (DDT) in its defined operational design domain (OOD). When engaged, the system handles object and event detection and response (OEDR) and can perform the dynamic driving task. Nonetheless, there are still situations that can not be handled by the level 3 automated driving system. When the vehicle moves outside the operational design domain or when an ADS-related system error occurs, the dynamic driving task fallback user must be able to take control of the vehicle upon a request to intervene within seconds.

- **Level 4: High Driving Automation**
  Level 4 systems that offer *high driving automation* are expected to perform the whole dynamic driving task (DDT) within the limited operational design domain (OOD). Even requests to the human in a dynamic driving task fallback are not expected to get a response. Therefore, a level 4 system must be able to handle difficult situations and errors, for instance, by turning the hazard lights on and parking the vehicle on the hard shoulder.

- **Level 5: Full Driving Automation**
  Level 5 systems offer *full driving automation*. They are able to perform the whole dynamic driving task (DDT), and just like level 4, the dynamic driving task fallback does not need human intervention. Moreover, there are no technical limitations in the operational design domain. Legal limitations may continue to exist. This means that a level 5 ADS-equipped vehicle can navigate to a programmed destination on public roads during all weather and traffic conditions.

Figure 2 briefly summarizes the six SAE levels of driving automation ranging from no driving automation to full driving automation. All systems capable of SAE levels 1 - 2 are driver assistance systems. This means the driver remains responsible at all times, and the system assists the driver. Systems according to SAE levels 3 - 5 are automated driving systems and thus refer to functionality known as automated driving. There, the human driver gradually hands over the responsibility of the driving task to the system. (SAE International, 2018)

This means driver assistance systems assist the driver and provide either more comfort or safety. They provide technical assistance during the driving task in the form of improved stability and assist the navigation of the vehicle (Niehsen et al., 2005). Its technology (e.g., cameras, radar,

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 2.: SAE level summary table. Reproduced from: SAE International (n.d., p. 2)

and other methods for environment perception) is the foundation for automated driving systems (Mathes and Barth, 2015).

The definition and naming conventions of levels of driving automation are not consistent throughout different organizations. For example, the German Federal Highway Research Institute (BASt) did not define a driving automation level similar to SAE level 5 (full automation). BASt, in contrast, defined *fully automated* systems that are similar to SAE level 4 (high automation) and *highly automated* systems that are similar to SAE level 3 (conditional automation). (Smith, 2013)

6.2.2. Range of Applications

Automated driving systems were developed for the common types of motorized vehicles, both on and off the road. That includes on-road vehicles used for the transportation of passengers and goods (e.g., Volkswagen Aktiengesellschaft (2018) and Daimler (2018*c*)) as well as off-road vehicles used for the transportation of goods (Komatsu, n.d.).

Off-road transportation of goods

Special purpose vehicles, such as Autonomous Haul Systems, operated for years without a human driver behind the steering wheel (Komatsu, n.d.). For instance, they were used in the mining industry to operate a haul and dump cycle.

Autonomous driving technology helped to reduce the amount of staff needed to operate a business, especially in remote areas. It furthermore reduced staff costs and removed humans from dangerous sites. However, the vehicles were limited to a specific use case. (Maurer et al., 2015)

On-road transportation of goods

The advances in driving automation of on-road goods vehicles promised new opportunities for the freight transport industry. The elimination of staff and costs was not the only benefit in mind when developing autonomous vehicles. For example, drivers were often confronted with long and monotonous driving sessions. It was furthermore argued that autonomous vehicle-on-demand services could be the answer to the needs of company supply chains. These supply chains are often based on just in time deliveries. (Maurer et al., 2015)

Another use case is the delivery of smaller goods in self-driving vehicles. Those vehicles could be capable of delivering food, goods for retail, and mail (Maurer et al., 2015).

In China, driverless trucks are in a transition phase toward commercialization. It was argued that replacing the driver in applications such as the transportation of goods is simpler where fixed routes are more commonly found. Therefore, the transportation of goods between cities could be the first attempt to commercialize self-driving technology. (Yu, 2018, 2019)

In other regions, testing on-road transportation of goods in self-driving vehicles already begun. For example, there were already tests with autonomous vehicles used for the delivery of food in North America in 2017 (Ford Motor Company, 2018*a*). Other developers of automated driving systems such as Waymo, the self-driving unit of Alphabet, began testing autonomous trucks to deliver freight between Google's data centers (Waymo, 2018*b*).

On-road transportation of passengers

Bösch et al. (2018) described various use cases of self-driving vehicles for the transportation of passengers. They described autonomous buses, taxis, and private cars as potential vehicles that could be equipped with automated driving systems. Additionally, the development of self-driving motorcycles began (BMW, 2018*f*).

Driverless *taxis* represent the evolution of conventional taxis and mobility services such as carsharing and ride-hailing. They represent a business model that eliminates the costs of human drivers and tries to distribute fixed costs on a multitude of users (Bösch et al., 2018). As shown in Figure 3, taxis could significantly benefit from adopting driverless technology.

The operation of autonomous mobility services like self-driving taxis would promise lower costs per passenger-kilometer compared to conventional taxis (Bösch et al., 2018). It would typically be an app-based service where potential riders could call a ride via the app. The vehicle would drive without a human driver to the pick-up location and then drives without a human driver to the desired drop-off location (Waymo, 2019*c*; Ford, 2019*b*; Davies, 2017). It was estimated that one shared ADS-equipped car used in a fleet of autonomous cars in a mobility-on-demand service could replace up to eleven conventional private cars (Fagnant and Kockelman, 2014).

Privately-owned *cars* equipped with an automated driving system could extend the user base compared to conventional cars when L4 ADS are integrated. As soon as a driver's license would become unnecessary, customer segments such as children, elderly people, disabled, and people who either can not or do not want to drive would be able to use cars independently. Besides, tiredness and a lack of attention during driving is a risk in conventional vehicles. Therefore, one goal of using self-driving cars is to reduce the number of accidents (Khayatt et al., 2017) as cars were a significant threat to humans (Lipson and Kurman, 2017).

The costs to equip a taxi or private car with ADS significantly depends on the SAE level of driving automation. The costs to equip vehicles with SAE level 4/5 ADS for the use in driverless taxis were estimated between € 25.000 and € 100.000 per vehicle (Vogt, 2019*b*). The integration of SAE level 3 ADS, in contrast, was estimated with additional costs between € 5000 and € 10.000 per vehicle (Vogt, 2019*b*). L3 ADS, however, do not enable the driverless operation of vehicles

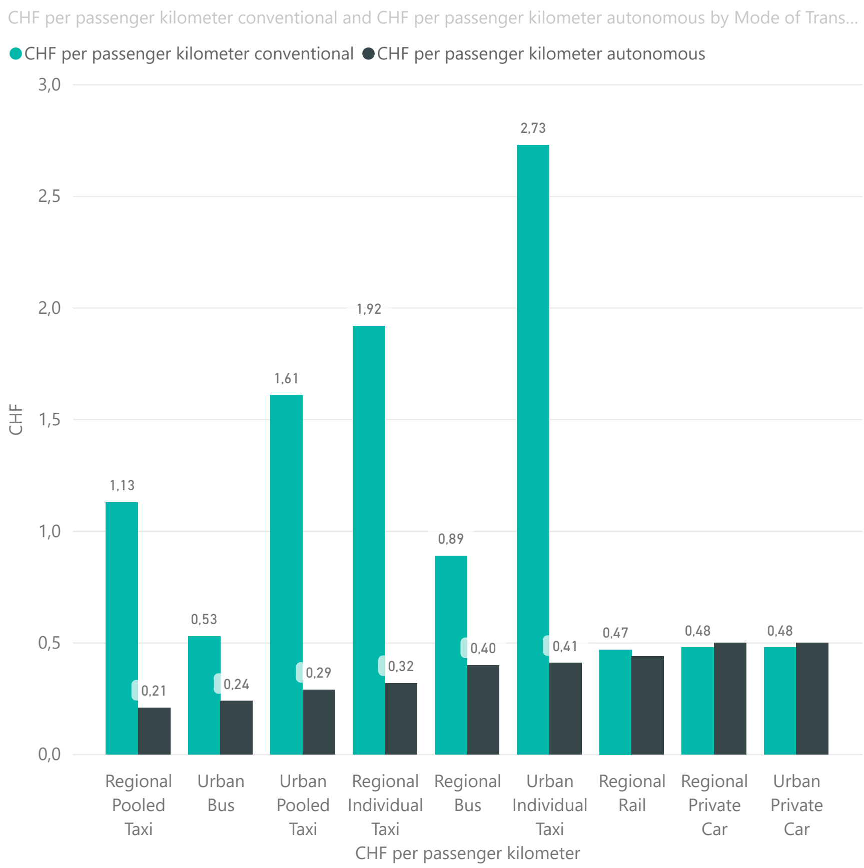


Figure 3.: Costs per passenger kilometer for autonomous and non-autonomous modes of transportation. Adapted from: Bösch et al. (2018, p. 82)

(SAE International, 2018). This would mean that privately-owned cars are equipped with L3 ADS first (e.g. highway pilot). This evolutionary route would lead from current ADAS to ADS in private vehicles (Zetsche, 2015) what could be interpreted as sustaining innovation where products (e.g., L2+ driver assistance systems) were improved for high-end customers.

Another use case of ADS are buses. According to Bösch et al. (2018), ADS-equipped *buses* could lower the costs per passenger-kilometer considerably. At the same time, timetables could be improved, and vehicles with the required passenger capacity could be used.

6.2.3. Key Technologies Used in Self-Driving Vehicles

Finding out the initiatives toward technologies that are used in self-driving vehicles requires the identification of the key technologies. This section, therefore, discusses the basic technical architecture that is used to make self-driving vehicles work. It first gives a broad overview of the basic idea that originates in the area of robotics and then identifies the actual technologies. This section primarily focuses on technological innovations and challenges that arise when automated driving systems were developed.

There were four rather new trends in the automotive business ecosystem, namely drivetrain electrification, connected and shared vehicles, and the automation of the driving process. According to Lipson and Kurman (2017, p. 46), this combination would lead to autonomous vehicles in practice. Autonomous vehicles are cyber-physical systems (Degenhart, 2015; Seiberth and Gruendinger, 2018; Leitner et al., 2017) that *"connect information, objects and people due to the convergence of the physical and the virtual (cyberspace) worlds"* (Ibarra et al., 2018, p. 4). They can be described as *"controlled agents integrating environment perception and modeling, localization and map generation, path planning, and decision making"* (Watzenig and Horn, 2017, p. 6).

According to Siegel (2003), autonomous systems in the area of robotics follow the *sense - think - act* paradigm. This paradigm holds for automated driving systems, for example, automated vehicles need components to perceive the environment, make assumptions about upcoming situations and use the information to generate a driving strategy, and ultimately translate that into real-world actions (Watzenig and Horn, 2017). Similar to that, Zhao et al. (2018) describe technologies grouped into four modules that are required to turn a conventional vehicle into a driverless vehicle, namely *"car navigation system, path planning, environment perception, and car control"* (Zhao et al., 2018, p. 4). Additionally, Siegel (2003) proposed to add a fourth component to the sense - think - act paradigm, namely *communication*. It was argued that communication is vital to the usability of autonomous systems in the mobile space (Siegel, 2003). Developers of automated driving systems address this issue with built-in vehicle connectivity and the integration of their vehicles into app-based driverless mobility services as their primary way to monetize the technology (see the cross-case synthesis in section 9.2.2).

Watzenig and Horn (2017) describe the key components for automated driving based on the building blocks in Figure 4. This hierarchy-based approach to the key components that are used in autonomous vehicles describes the areas of information processing and decision-making as *intelligence*, the areas of vehicle sensors, fusion, and connectivity as *sensing* and the areas of acceleration, steering, braking, suspension and transmission as *vehicle control*.

6.2.3.1. Sense: Sensing in Autonomous Vehicles

An autonomous vehicle needs a model of its environment that is built on data originating either inside or outside the car (Watzenig and Horn, 2017). Figure 5 illustrates the key sensors used in autonomous vehicles divided into individual sections regarding internal (proprioception), external (perception), and communication (data) sensors. A significant amount of sensors is needed to

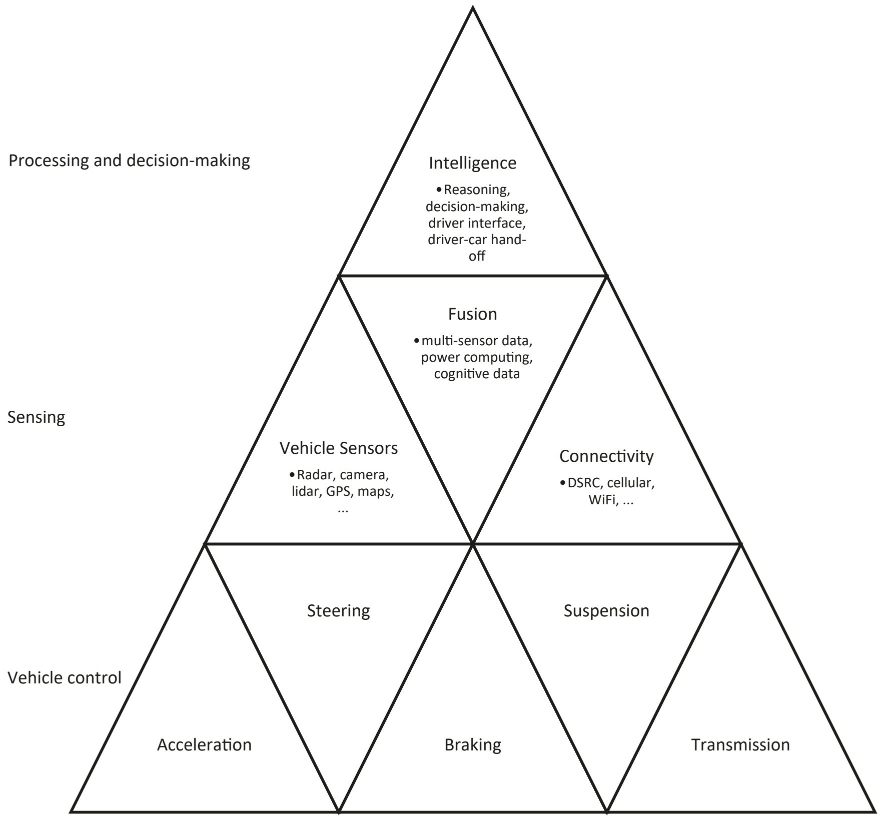


Figure 4.: Building blocks for automated driving. Adapted from: Watzenig and Horn (2017, p. 6)

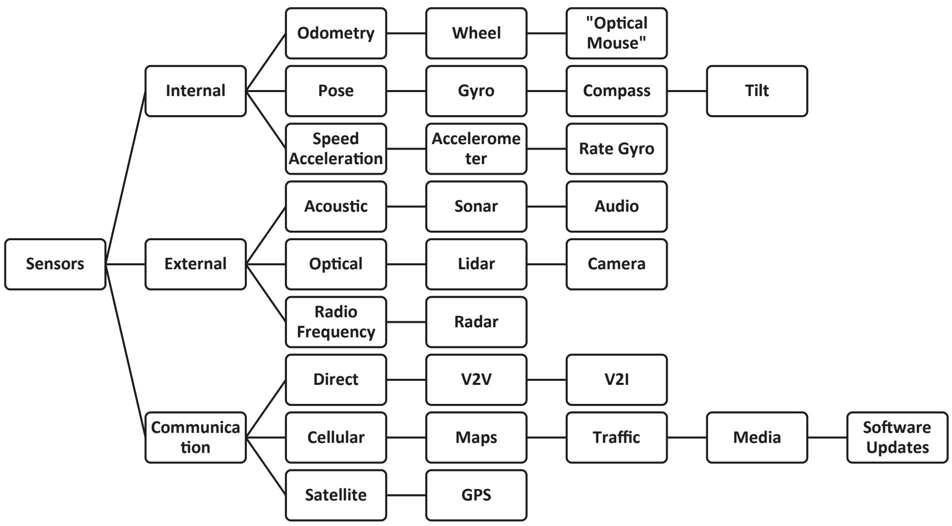


Figure 5.: Key sensors used in autonomous vehicles. Adapted from: Lipson and Kurman (2017, p. 189)

enable self-driving vehicles, but these are the sensors that are the main focus of developers of automated driving systems:

Lidar (light detection and ranging) emits pulsed laser light to create a 3D map of the surrounding area. In contrast to camera-based visual perception, lidar is less prone to distraction by light. The downside was that lidar sensors were expensive, with prices up to $ 80000. (Zhao et al., 2018) There were attempts to make lidar significantly less expensive, which should lower the prices to approximately $ 1000 (Spencer, 2019).

Camera-based visual perception offers a more cost-effective environment perception. The downside is that the information gained by the sensors is more dependent on external conditions such as lighting. As roads were built for human drivers, cameras need to read relevant information such as lane markings, road signs, and traffic signals that cannot be interpreted by sensors such as radar and lidar. (Zhao et al., 2018)

Radar sensors could be used to create an image of surrounding objects and measure distances. This technology, however, was in a mature state (Zhao et al., 2018) and even came as standard with some cars in features such as adaptive cruise control (Toyota, 2017).

In addition to visual and radar-based sensors placed inside the vehicle, *Car2Car* and *Car2X* could be used to increase the perception of a vehicle. Car2Car means that there exists communication between two vehicles, whereas Car2X enables the communication between a vehicle and the infrastructure. (Degenhart, 2015)

Connectivity between cars and other cars, the cloud, and the road infrastructure was a controversial issue. Whereas Hungerland et al. (2015) and Watzenig and Horn (2017) argued that a high degree of connectivity would be needed to enable autonomous vehicles, at Waymo it was argued that connectivity should be limited to the absolute minimum to increase security and increase protection against hackers (Campbell and Waldmeir, 2017). Likewise, Lipson and Kurman (2017) argued against a high degree of connectivity: *"place the intelligence into the car, not into the road"* (Lipson and Kurman, 2017, p. 17) and demand better road markings instead of wireless equipment and suggest to enable autonomous vehicles based on computer vision and high definition maps. Nonetheless, it was argued that connectivity between cars and the infrastructure could be used to significantly enhance the perception of autonomous vehicles (Degenhart, 2015), especially at high speed traveling (Kopetz, 2018).

Highly accurate and up-to-date *high definition maps* are another key component of self-driving vehicles. This means that maps for self-driving vehicles not only include traditional map data. Those maps are becoming more accurate than traditional maps and add more layers such as traffic information, road condition, road signs, information about lanes, and other relevant objects. (Zhao et al., 2018)

To gain the advantage of high definition maps, the vehicle needs to know its exact location. Therefore, the location system of a vehicle uses different techniques such as the relative, absolute, and hybrid location to get the precise location of the vehicle. In addition to satellite-based techniques such as *GPS* to get the position, the location system can further improve accuracy by combining the information of various sensors such as angular velocity and steering angle. (Zhao et al., 2018)

The combination of sensor data could enhance the accuracy of the information. In general, self-driving vehicles need a combination of sensors to perceive their environment. However, it was noted that the combination (fusion) of information originating from different sensors could be the wrong way to enhance the perception of a vehicle. Vehicles should rather rely on one type of environment perception (e.g. camera-based) and add a second type for redundancy and security (e.g. lidar) (Mobileye, 2019*b*; Lipson and Kurman, 2017; Becker et al., 2017).

6.2.3.2. Think: Processing and Decision-Making in Autonomous Vehicles

The intelligence of autonomous vehicles is one of the main challenges that need to be addressed to enable driverless vehicles.

Lipson and Kurman (2017) argued that conventional vehicles are comparatively "brainless" and autonomous driving is mainly a software challenge that relies on artificial intelligence and machine learning. There, the main challenge is to get the system's artificial perception from accuracy of 99 % to 99.9999 % (Lipson and Kurman, 2017). The vehicle's intelligence includes the recognition of objects in various environments as well as the prediction of future scenarios and dealing with incomplete data and uncertain information, as well as path planning, path tracking, decision-making, and operating the vehicle-control systems (Watzenig and Horn, 2017, p. 13).

Artificial intelligence, a potential second-order disruptive technology (Schuelke-Leech, 2018), plays a critical role among the technologies for autonomous vehicles. Lipson and Kurman (2017) explained that machine learning is a data-driven bottom-up way used for object recognition, obstacle detection, and the analysis and prediction of the traffic situation. It thus requires a considerable amount of training data that also covers extremely rare cases to achieve the required accuracy of artificial perception. Those situations are called corner cases. They described that developers face the fact that *"Driving might be mostly repetitive, but it is fraught with an endless supply of potentially deadly corner cases"* (Lipson and Kurman, 2017, p. 5). Lipson and Kurman (2017) argued that this is among the most challenging parts of the development of self-driving vehicles. Machine learning and, more precisely, deep learning is favored in unstructured environments such as chaotic traffic situations in a real-world where programmers would have no chance to create a working model of the world and build functionality using formal logic and rules. Symbolic reasoning, in contrast, is a rule-based type of artificial intelligence that is coded top-down and is used for functionalities such as route calculation, driving according to the rules, and low-level control of supporting functionality such as ABS.

Processing the sensor output and performing the activities that are necessary to replace a human driver requires a significant amount of processing power and therefore, an updated compute-platform. For example, it is expected that the entire sensing layer generates and receives about 1 GB of data per second (Watzenig and Horn, 2017, p. 12). It was argued that the actual requirements for the vehicle's computation platform only become apparent when automated driving systems achieve production-readiness because of the vast number of uncertainties (Leitner et al., 2017; Smith, 2019). Not only attributes such as CPU power, memory availability, and communication bandwidths need a significant upgrade compared to conventional vehicles (Leitner et al., 2017), also the architecture itself is likely to change (Martin et al., 2017). Whereas conventional vehicles consist of many sub-systems that only handle their part ("many ECUs"), the computing architecture of self-driving vehicles shifts toward less, but more centralized computing units ("host ECUs") (Martin et al., 2017).

6.2.3.3. Act: Vehicle Control in Autonomous Vehicles

The *vehicle architecture* needs to be adapted for automated driving systems. It requires components similar to conventional vehicles that enable the movement of the vehicle. The main difference is that all components must be computer-operated and have a fail-tolerant design. In fact, what distinguishes advanced driver assistance systems and automated driving systems is the step from fail-safe to fail-tolerant designs (Martin et al., 2017). This is because automated driving systems are highly safety-critical systems (Leitner et al., 2017, p. 357). The vehicles, therefore, need an architecture that provides redundancy for its most critical parts (Becker et al., 2017).

The vehicle architecture for automated driving systems will introduce sub-systems such as steer-by-wire, drive-by-wire, and brakes that are designed for machine use. Additionally, redundancy and the automatic detection of faults must be implemented for the safety-critical sub-systems as well as their operation. This includes systems that provide lateral and longitudinal movement as well as the intelligence that operates them. Moreover, all systems require a constant reliable energy supply that must be implemented redundantly. (Martin et al., 2017; Becker et al., 2017)

In general, the translation of commands into lateral or longitudinal movement has not been identified as one of the main challenges in automated driving (Watzenig and Horn, 2017), and the prediction and control of the vehicle movement itself is a fairly well-understood task (Lipson and Kurman, 2017).

6.2.3.4. Mobility Platforms

Technological innovation on its own does neither guarantee nor automatically lead to commercial success (Chesbrough and Rosenbloom, 2002). Developers of automated driving systems were, therefore, looking into ways to appropriately commercialize this new technology. It was expected that the deployment of autonomous vehicles through mobility platforms would be among the most probable commercialization strategies for this new technology (Skeete, 2018). Digital platforms are one way to enable business operations across various industries (Burgelman and Grove, 2007), and are a component of product-service systems with autonomous vehicles. Antonialli et al. (2018) identified autonomous vehicles as use-oriented services in product-service systems. This means that customers do not buy products, they use it instead (Tukker, 2004), and digital mobility platforms are one way to connect customers who want transportation of goods or mobility of passengers to the vehicle that performs the transportation task.

The physical product side of the mobility platform requires the connectivity of self-driving vehicles to the internet. According to (Dellios et al., 2016, p. 55), *"Modern vehicles are being transformed into autonomous cyber instances of unique IDs, reforming the entire transportation domain"*. The Internet of Things (IoT) is one key component to enable the autonomy of vehicles (Dellios et al., 2016). IoT, in general, is a *"global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies"* (International Telecommunication Union, 2012, p. 1). The integrated connectivity of the vehicles does not only enable their use in mobility service platforms, but it is also a noteworthy source of data that provides insights into society (Loebbecke and Picot, 2015).

Part III.

Empirical Work

7. Leading Actors in the Autonomous Driving Business Ecosystem

This chapter aims to answer RQ-Sub1: *Who are the leading actors in the automotive business ecosystem with regards to technologies for autonomous driving?*

As described in chapter 2 on methodologies, this chapter first discusses three studies on the leading actors in the autonomous driving business ecosystem with regards to technology and commercialization in section 7.1. Then, secondary data on real-world testing and the performance of autonomous driving is shown in section 7.2. Lastly, the identified actors were then categorized by their business origins in section 7.3.

7.1. Studies on Leading Actors in the Field of Autonomous Driving

Numerous organizations researched and developed technologies for autonomous driving (California DMV, 2019). Therefore, studies assessed the potential of businesses in the autonomous driving business ecosystem to succeed in the development and deployment of driverless vehicles. As described in section 2.1 on the case study case selection, three studies could be found that analyzed developers of automated driving systems with regards to the development and commercialization of the system that were published beginning from 2018. The first two studies were published by Navigant Research, who analyze the leading developers of automated driving systems on a yearly basis. The third and most recent study on leading companies in the field of autonomous driving in this thesis was published by the market research institution "PTOLEMUS".

Abuelsamid and Gartner (2019) from Navigant Research performed a study to assess the potential of 20 businesses or partnerships between businesses in the field of autonomous driving. The study was mainly based on expert interviews and secondary research and focused on providers of full turnkey solutions. Figure 7 shows the results of the 2019 Navigant Research Leaderboard, and Figure 6 shows the results of the 2018 Navigant Research Leaderboard. The main difference is the number of leading actors in the field of autonomous driving that narrowed down from eight to three companies. Figure 7 shows that Waymo, GM Cruise, and Ford Autonomous Vehicles were leading in the field of autonomous driving, whereas Figure 6 illustrates Waymo, GM, Ford, Daimler-Bosch, Volkswagen, BMW-Intel-FCA, and Aptiv as leading actors in the field of autonomous driving. These changes of identified leading actors mean that the remaining leaders were able to increase their lead as Abuelsamid and Gartner (2019) scored the results relative to the current state of the industry (Abuelsamid and Gartner, 2019). Abuelsamid and Gartner (2019) and Abuelsamid and Jerram (2018) scored the companies on an execution and strategy scale. The strategy scale included the following criteria: vision, go-to-market strategy, partners, production strategy, and technology (Abuelsamid and Gartner, 2019). The execution scale included criteria concerning sales, marketing and distribution, product capability, product quality and reliability, product portfolio, and staying power (Abuelsamid and Gartner, 2019). This means that firms with a strong track record of financial stability and bringing safety features to the market in the past could outrank technology leaders in the field of autonomous driving (Abuelsamid et al., 2017).

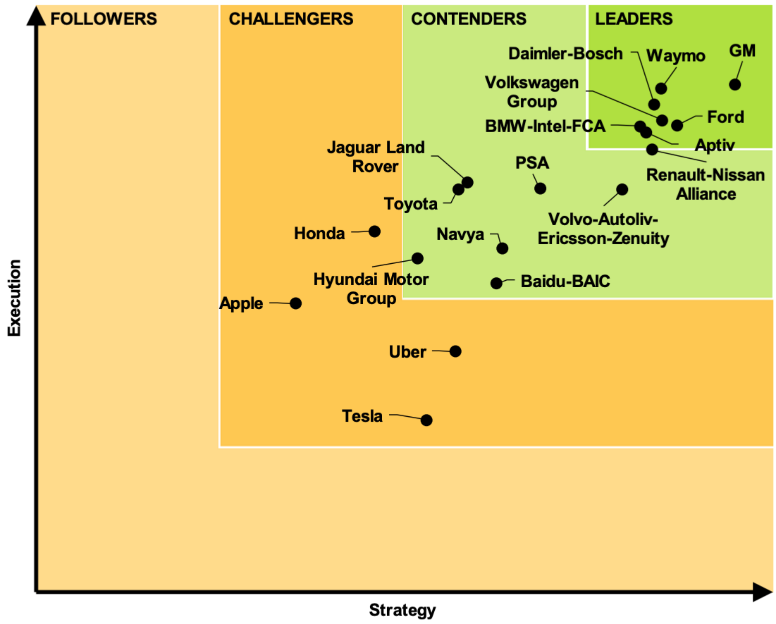


Figure 6.: The Navigant Research Leaderboard Grid 2018. Reproduced from: Abuelsamid and Jerram (2018, p. 3)

PTOLEMUS (2019) published a study that assessed 16 developers or cooperations between developers and came to a similar conclusion. There, Waymo was considered to be the leading firm in the field of autonomous driving, followed by GM Cruise and Zoox. Additionally, Aurora, a firm specialized in the development of automated driving systems for its customers, was considered being a promising actor in the business ecosystem. The study assessed the AV sensor stack, computing hardware, perception and planning systems, contextualization, simulation, testing, security, and data management. According to PTOLEMUS (2019), technology companies such as Waymo, Cruise, and Zoox had the advantage of being capable of leveraging their core competencies in data science and unsupervised learning. Furthermore, Waymo was considered to be the leading company in the field of autonomous driving due to Google's vast financial resources and capabilities

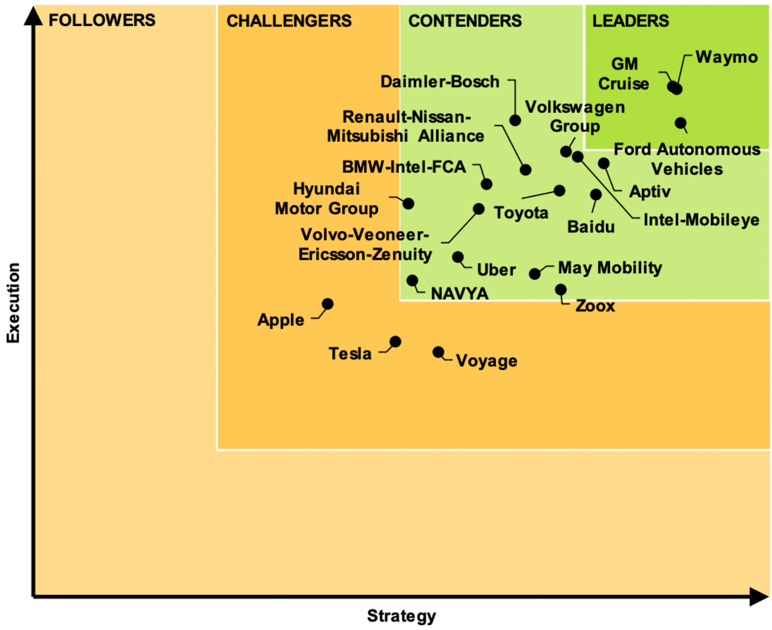


Figure 7.: The Navigant Research Leaderboard Grid 2019. Reproduced from: Abuelsamid and Gartner (2019, p. 3)

in AI, as well as Waymo's in-house capabilities with regards to sensors and computing hardware. The study also pointed out the regional differences in the development of automated driving systems. Whereas US-based firms were among the leading developers, PTOLEMUS (2019) identified a group of Chinese contenders such as Baidu, Pony AI, and AutoX. (PTOLEMUS, 2019).

As described in section 2.1, the results of the studies were used for the case study case selection. Based on the results, the following companies were investigated as cases in the multiple-case study: Aptiv, Aurora, BMW, Bosch, Daimler, FCA, Ford Argo AI, GM Cruise, Intel Mobileye, Volkswagen, Waymo, and Zoox.

7.2. Public Road Testing

To gain insight into the leading companies in the field of autonomous driving, additional indicators besides the analysis of Abuelsamid and Jerram (2018), Abuelsamid and Gartner (2019), and PTOLEMUS (2019) were considered.

The State of California Department of Motor Vehicles published automated driving system disengagement reports for vehicles tested on public roads in California on a yearly basis (California DMV, n.d.). It is *"the only publicly available metric"* (Vogt, 2020, par. 1) with regards to autonomous vehicle testing. The California DMV (2019) listed 63 organizations that had permission to test autonomous vehicles on public roads with a safety driver in California.

The disengagement rate puts the distance an ADS was used and the total number of its disengagements in relation. Firms that performed test drives in the state of California were obligated to report the distance they had used the vehicles in a self-driving mode and the corresponding number of disengagements of the system (California DMV, 2019). However, there was a lack of a common reporting standard that defined what to include in the disengagement reports. For example, Nissan declared that expected failures of the system and the following disengagements were not included in the disengagement report (Nissan, 2018). Apple, in contrast, first reported every disengagement and changed its approach to reporting only *"important"* disengagements (Apple, 2018*b*). Thus, Apple reported more than 40000 disengagements (Apple, 2018*b*) whereas Nissan reported 26 disengagements (Nissan, 2018). Furthermore, the disengagement reports included the type of road where disengagements occurred, but companies were not obligated to share information about their testing environment (Apple, 2018*a*). According to Vogt (2017*b*), it is more likely to encounter complex maneuvers like making left turns, lane changes, passing using the opposite lane, dealing with emergency vehicles, blocked lanes, and handling construction navigation in busy cities than suburbs. However, the numbers (number of disengagements and total distance driven) were treated equally due to the lack of further information about the testing environment. Besides, developers of ADS could test various levels of driver assistance or driving automation according to SAE, ranging from level 1 to level 5, separately or simultaneously. AImotive (2018), for example, reported all miles traveled in any SAE level engaged, but only reported disengagements related to autonomous driving (SAE level 3-5). This means that disengagement rates would be an inaccurate tool to measure the performance of the automated driving system (Vogt, 2020).

Nonetheless, the disengagement reports reveal the distance the autonomous vehicles have traveled. As discussed in section 6.2.3.2 on technologies for autonomous driving, experiencing extremely rare cases (corner cases) in order to be able to train the vehicle's artificial intelligence is relevant to enable safe autonomous driving and test drives could be used to collect data about corner cases. Figure 8 shows how the AV testing distance differed between companies, and Waymo and GM were leading by a considerable margin. In 2018, Waymo tested its autonomous vehicles for more than 2 million kilometers on public roads in California, whereas GM did 720.000 kilometers of testing, followed by Apple with 128.000 kilometers of testing. From the technological point of view discussed in section 6.2.3.2, the numbers would concur with the findings of Abuelsamid and Gartner (2019) and PTOLEMUS (2019) that both Waymo and GM would be among the leading firms in the development of ADS.

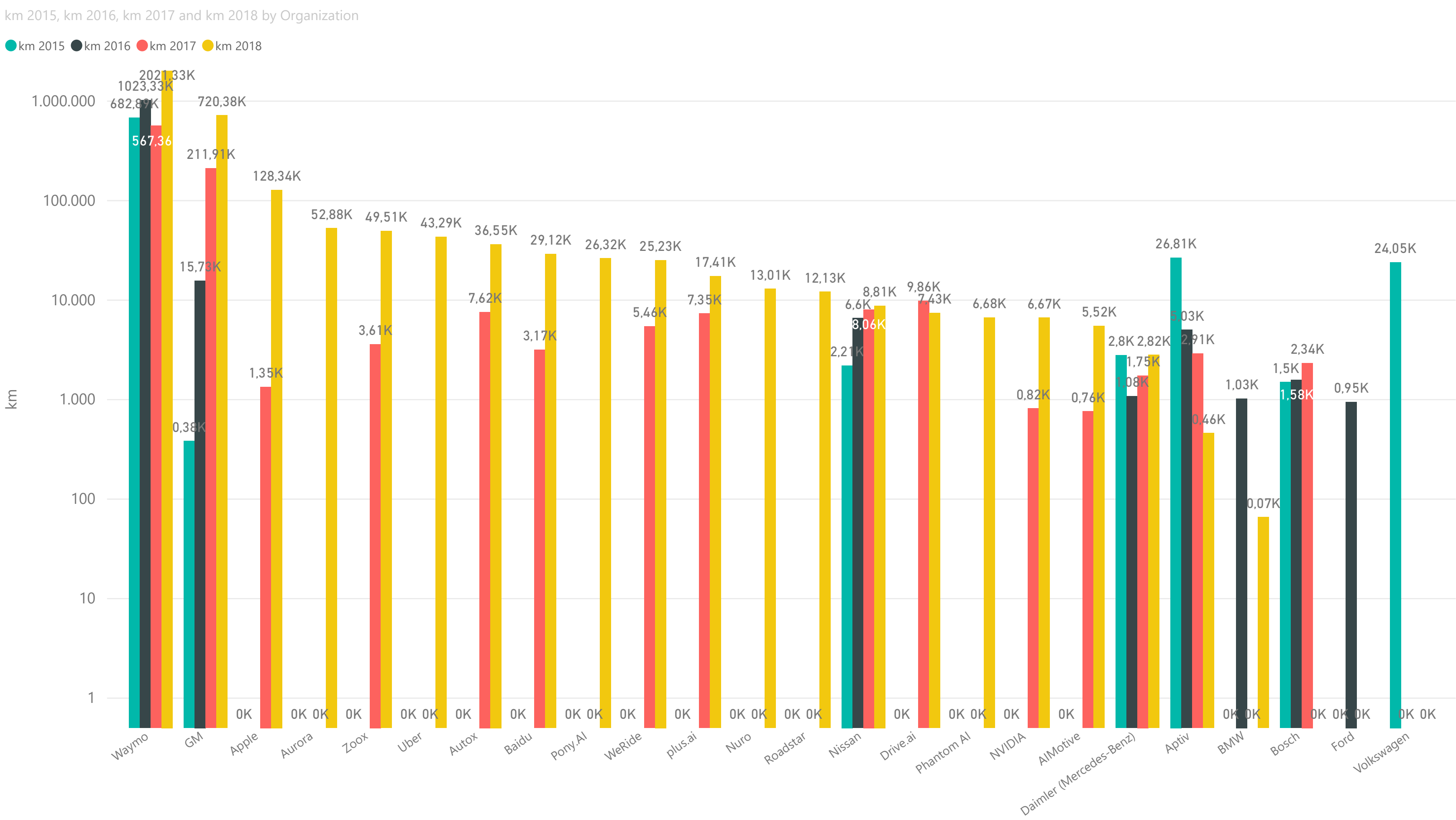
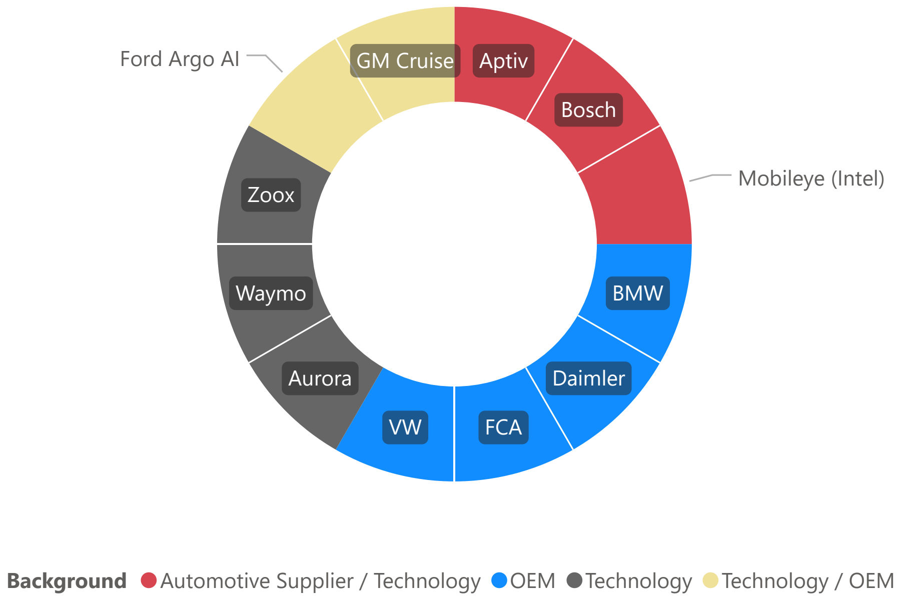


Figure 8.: Kilometers of autonomous testing in California from 2015 to 2018, based on Tables 14, 15, 16, and 17 (own creation)

7.3. Origins of Identified Business Ecosystem Actors

The companies that were identified in section 7.1 that resulted from the analysis of three studies (Abuelsamid and Jerram, 2018; Abuelsamid and Gartner, 2019; PTOLEMUS, 2019), namely Aptiv, Aurora, BMW, Bosch, Daimler, FCA, Ford Argo AI, GM Cruise, Intel-Mobileye, Volkswagen, Waymo, and Zoox had different technological and business origins. To support the further analysis, the firms were categorized into their business origins as Figure 9 illustrates: *technology companies*, *automotive suppliers*, and *OEMs*.



Sources: The origins are described in Table 18 on page 100 in the appendix.

Figure 9.: Origins of identified BE actors (own creation)

8. Initiatives Towards Technologies for Autonomous Driving

This chapter aims to answer RQ-Sub2: *What initiatives do firms (RQ-Sub1) undertake towards technologies for autonomous driving?*

The focus on firms in this chapter is based on the findings that the companies Aptiv, Aurora, BMW, Bosch, Daimler, FCA, Ford Argo AI, GM Cruise, Intel Mobileye, Volkswagen, Waymo, and Zoox were the leading actors in the field of autonomous driving (see chapter 7). The data collection procedure for the cases is described in chapter 2 on methodologies.

The remainder of this chapter is structured as follows. Section 8.1 shows the findings of the data collection that describe the initiatives of analyzed firms towards the development of the automated driving system and selected sub-components (HD-maps, lidar). Then, section 8.2 describes which testing and commercialization initiatives for higher levels of driving automation were identified during the data collection.

8.1. The Automated Driving System

This section discusses the companies' initiatives towards the automated driving system. The ADS is made up of a number of different components and underlying technologies, and this section's focus is on the critical but most challenging ADS components derived from theory in section 6.2.3, namely the control platform, lidar sensors, and high-definition maps. While Figure 19 on page 103 in the appendix shows that the leading actors in the BE had interests in firms that were specialized in control-platform related technologies such as AI, computer vision, and semi-conductors, it was not possible to estimate the effects on the actual development of their ADS due to a lack of insight knowledge and a lack of publicly available information. However, section 8.1.4 discusses the acquisitions and investments in major ADS developers that typically also included control-platform related technology.

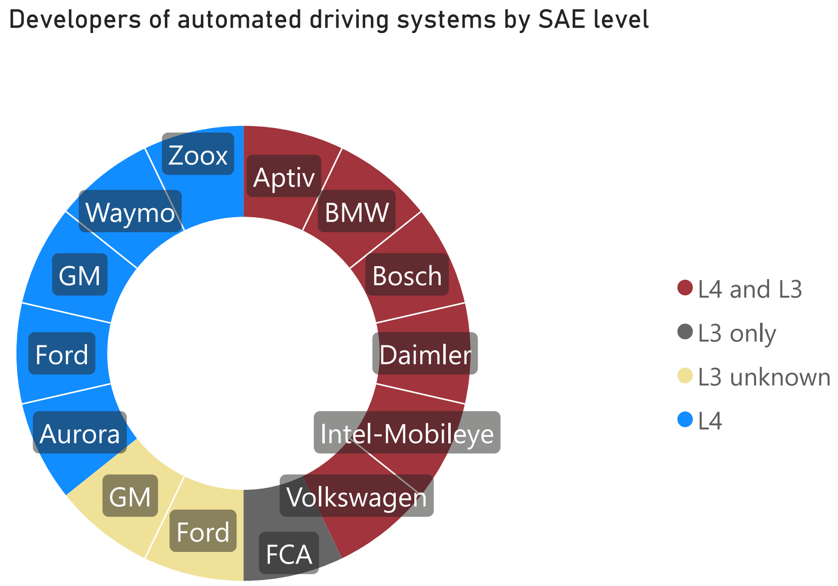
The findings were structured into the following types of technology sourcing: *investments and acquisitions* as buy-related strategies, *R&D partnerships* as hybrid approaches, and *doing-it-alone* approaches. The aim was to distinguish between different approaches, and literature on technology sourcing did not agree on the definition of make and buy strategies (see section 6.1.3). Veugelers and Cassiman (1999) argued that the hiring of skilled employees embodies a buy-strategy, and the analysis showed that all identified actors hired skilled employees (see Table 13 on page 71). That would mean that all actors pursued a buy-strategy, and no actor pursued a make-strategy. However, the aim was to distinguish between different approaches. Therefore, *doing-it-alone* was used to categorize and distinguish between companies meaningfully that neither invested or acquired a major ADS developer nor entered into an R&D partnership for their core technology.

The remainder of this section is structured as follows. The automated driving systems that were developed by the identified actors are categorized by their level of driving automation in section 8.1.1 to give a broad overview of the development. Then the firm's initiatives towards major components of the ADS (lidar and HD-maps) are discussed in sections 8.1.2 and 8.1.3. Initiatives towards the ADS as a system that included the acquisition of major ADS developers are discussed in section 8.1.4. Then, the identified major partnerships to develop the ADS are described in section 8.1.5. Lastly, firms that followed the doing-it-alone approach are described in section 8.1.6.

8.1.1. SAE Levels of Driving Automation Under Development

The functionality of automated driving systems significantly depends on the level of driving automation (see section 6.2.1 on SAE levels of driving automation). Therefore, this section aims at finding out what SAE level of driving automation the leading actors in the autonomous driving business ecosystem pursued. Figure 10 shows the intentions of leading BE actors by SAE levels of driving automation at a glance.

Waymo decided to skip the development of level 3 conditional driving automation systems and focused on systems where no human intervention was needed instead. The decision was made because tests at Google revealed that passengers trusted the machine when the system worked well in most cases. The former drivers got distracted even though they were obligated to watch the traffic and had to take over the control of the vehicle within seconds as required by the SAE level 3 ADS specification. (Google, 2015*a*) Aurora, likewise, argued against SAE level 3 ADS: *"Drivers cannot be inattentively attentive"* (Urmson et al., 2018, par. 3) and focused on SAE level 4 ADS instead (Urmson et al., 2018). Ford Motor Company (2016) similarly decided against SAE level 3 vehicles due to safety concerns. This is because Ford could not find a secure way to handle the take-over-request that gives back control to the driver when the vehicle leaves the operational design domain (Ford Motor Company, 2016). However, in 2019 it was discussed whether vehicles capable of level 3 ADS could be introduced as an intermediate step towards level 4 ADS-equipped vehicles as potential solutions to the take over request were positively evaluated (Martinez, 2019). This lower level of driving automation would not enable business models that



*Sources: L4 and L3: Aptiv: Aptiv (2019*d*); BMW: Vogt and Gerster (2019); BMW Group (2019*b*); Bosch: Ebberg (2018); Daimler: Mercedes-Benz (2019); Ebberg (2018); Intel-Mobileye: Mobileye (2020); Volkswagen: Audi (2018, 2019); Volkswagen (2019*a*); L3 only: FCA: Wester (2018); L3 unknown: Ford: Ford Motor Company (2016); Martinez (2019); GM: the data collection did not reveal GM's approach towards L3 ADS; L4: Aurora: Urmson et al. (2018); Ford: Ford Motor Company (2016); GM: GM (2018); Waymo: Google (2015*a*); Zoox: Zoox (2018*b*);*

Figure 10.: The development of ADS by SAE level and BE actor (own creation)

require driverless vehicles, according to SAE International (2018). Like Waymo and Aurora, Zoox focused its development efforts on L4 ADS (Zoox, 2018*b*). GM developed technology for vehicles that require no human supervision within a defined operational design domain (SAE level 4) (GM, 2018), but no information concerning GM's SAE level 3 intentions could be found. VW worked on both L3 (Audi, 2018) and L4 ADS (Audi, 2019) and eventually joined Ford's L4 ADS development (Volkswagen, 2019*a*). BMW, Daimler, Bosch, Aptiv, and Intel-Mobileye, likewise, worked on ADS ranging from SAE level 3 to 4 (Vogt and Gerster, 2019; BMW Group, 2019*b*; Aptiv, 2019*d*; Mobileye, 2020; Ebberg, 2018). FCA, in contrast, joined the BMW-Intel-Mobileye partnership for L3 ADS but decided against the development of L4 ADS due to high R&D efforts and the unpredictability of outcomes (Wester, 2018). In essence, Figure 10 shows that new entrants in the automotive business ecosystem exclusively focused on SAE level 4 ADS, whereas long-established firms (OEMs and automotive suppliers) in the automotive business ecosystem also developed L3 ADS.

8.1.2. Lidar Sensors

Lidar was identified as a critical component of the ADS sensor suite (see section 6.2.3). As shown in Table 20 on page 103 in the appendix, the leading actors in the field of autonomous driving not only built but also acquired capabilities in lidar technology.

As shown in Table 20 on page 103 in the appendix, Aurora, Aptiv, BMW, Bosch, Ford, GM, and Intel made investments in companies that developed lidar sensors. However, this does not necessarily mean that products originating from these companies would be used in production vehicles. BMW, for example, ordered lidar sensors for its production vehicles from Magna and Innoviz (Magna, 2018), and Daimler ordered Velodyne lidar sensors (BusinessWire, 2017*b*). Waymo, on the other hand, switched to in-house development of lidar sensors (Waymo Team, 2017). Waymo said this was done due to the high costs and limited capability of lidar sensors provided by suppliers, which were more expensive than the car itself (Waymo Team, 2017). The costs of lidar sensors were a concern for other developers of automated driving systems, too. Aptiv invested in LeddarTech for low-cost lidar sensors (Delphi Automotive PLC, 2017) and GM acquired Strobe with the aim to cut sensor costs by 99 % (General Motors, 2018*b*). In order to cut lidar sensor costs, Waymo announced to sell lidar sensors to organizations that were not related to autonomous vehicles (non-competitors). The goal would be to reduce costs due to economies of scale with mass production (Verghese, 2019). Intel's Mobileye did not show significant efforts toward lidar technology because it primarily focused the ADS on camera-based perception. However, the company would add lidar and radar-based systems as a backup to camera-based perception in the future (Mobileye, 2019*b*).

8.1.3. HD Maps

High-definition map technology was identified as a key component for autonomous vehicles (see section 6.2.3). Table 21 on page 104 in the appendix shows the findings of the archival analysis with regards to investments and acquisitions of firms that were specialized in technologies for high-definition maps. While Table 21 shows the interest in dedicated high-definition maps firms, those capabilities could also come with one of the major ADS developer shown in Table 5 on page 49.

Audi, Volkswagen, and Daimler acquired the map provider *Nokia Here* and Intel, Bosch, and Continental joined with further investments into the company (Audi, 2016; Continental, 2018; Bosch, 2018*e*; Intel, 2017*d*). Daimler and Bosch used HERE maps in their ADS (BoschGlobal, 2018). HERE investors were participating in the development and operation of high definition live maps where data collection was supported by crowdsourcing. Bosch used radar and cameras to generate and update high-definition maps (Bosch, 2018*f*), similarly to that Mobileye used its cameras to extract information for its maps (REM) (Mobileye, n.d.*c*). In addition, Mobileye started leveraging conventional production vehicles equipped with its ADAS systems to generate and update HD maps automatically (Mobileye, 2020). Vehicles, therefore, must be connected to create, receive, and update HD maps. Waymo developed its own lidar-based high-definition maps that were not comparable to Google's map service because Waymo required 3D maps, whereas Google Maps offers 2D maps (Weddeling, 2018). Ford invested in Civil Maps (BusinessWire, 2016). Additionally, the company started a cooperation with DeepMap to create HD maps (Luo, 2017). GM did not have intentions to acquire a map provider and preferred to keep mapping in-house (Bergen, 2018). Aurora and Zoox, likewise, developed their HD maps in-house with data that was acquired with their vehicle sensors (Aurora Team, 2019*e*; Zoox, 2018*b*).

8.1.4. Acquisitions and Investments in Major ADS Developers

As shown in Table 5, mostly suppliers and OEMs either acquired or invested in major developers of automated driving systems. SAE level 4 ADS developers, in particular, were the main target of those initiatives. As Table 5 illustrates, the amount to be invested had gradually increased.

Table 5.: Selection of investments in major ADS developers

Year	**Investor**	**Company**	**Type**	**Investment**	**Scope**	**Source**
2016	GM	Cruise	acquisition	$ 581 M	L4 ADS and mobility service developer	General Motors Company (2018)
2017	Aptiv	nuTonomy	acquisition	$ 454 M	ADS and mobility service developer	Aptiv (2018*a*)
2017	Ford	Argo AI	majority investment	$ 1 B	L4 ADS, robotics and AI, majority investment	Ford (2017*a*)
2017	Intel	Mobileye	acquisition	$ 14.5 B	ADAS and ADS developer	Intel (2018*a*)

Table 5.: Selection of investments in major ADS developers (continued)

Year	Investor	Company	Type	Investment	Scope	Source
2018	Honda	GM Cruise	investment	$ 2 B, 5.7 %	joint SAV development, exclusive right in a foreign market	General Motors (2018*a*)
2019	VW	Argo AI	investment	$ 2.6 B to become equal stake holder with Ford	L4 ADS developer, VW contributes AV unit "AID"	Volkswagen (2019*a*)
2019	Daimler	TORC	acquisition		L4 ADS for trucks	TORC (2019)
2019	Hyundai	Aurora	investment	minority invest	L4 ADS developer	Aurora Team (2019*d*)

Both General Motors and Ford acquired a company specialized in the development of SAE level 4 ADS and used it as the main foundation of their driverless vehicle development (General Motors Company, 2018; Ford, 2017*a*). GM acquired Cruise Automation in 2016 (General Motors Company, 2018), and Honda joined as an automotive investor in 2018 and invested $ 2 B for 5.7 % of Cruise (General Motors, 2018*a*). Ford, too, decided to team up with other automakers. Ford acquired the majority stake of Argo AI in 2017 (Ford, 2017*a*), and Volkswagen invested $ 2.6 B in 2019 in Argo AI and brought its autonomous driving unit into Argo AI and became an equal stake holder with Ford (Volkswagen, 2019*a*).

Both Cruise and Argo AI were in charge of developing the self-driving system for their owners, but the responsibilities in terms of commercialization differed. GM's Cruise developed both the automated driving system and the mobility platform for its new business model (Suryadevara et al., 2018). In contrast, Argo AI acted as a self-driving system provider for its majority stake investors Ford and Volkswagen. In the case of Volkswagen and Ford, Argo AI would deliver the automated driving system to both investors and would not be involved in the commercialization (Larkin et al., 2019*a*). The commercial availability of Cruise's ADS was postponed until further notice (Ammann, 2019). Ford announced that services based on autonomous vehicles would be introduced in 2021 (Marakby, 2018)

In 2017, Intel made a major acquisition with Mobileye. The technology firm acquired the supplier of advanced driver assistance systems to the automotive industry and developer of automated driving systems with a focus on capabilities in computer vision for $ 14.5 B (Intel, 2018*a*). Mobileye's ADS would be used in a commercial ride-hailing service in Jerusalem that was expected to launch in 2022 (Intel, 2018*c*). Furthermore, both Intel and Mobileye had a ADS development cooperation with BMW (see section 8.1.5), and Mobileye cooperated with Aptiv on an ADS solution (see section 8.1.5). However, Mobileye's ADS for the commercial ride-hailing service would not be based on either of those cooperations and is, therefore, their own platform (Spak et al., 2018).

Aptiv acquired nuTonomy in 2017. nuTonomy was a developer of ADS and autonomous mobility services but got integrated into Aptiv's existing structure (Aptiv, 2018*a*). The company announced to remove the safety driver from its self-driving vehicles in the Lyft ride-hailing network in Las Vegas by mid-2020 (Sigal, 2019).

In 2019, Daimler acquired TORC, a company specialized in the development of automated driving systems for trucks, and subsequently announced to shift its main focus from level 4 ADS for mobility services in urban areas to level 4 ADS for autonomous trucks logistics on US highways due to technological challenges and risk and uncertainty of the ride-hailing business model (Daimler, 2019*b*).

In the same year, Hyundai expanded its autonomous driving capabilities and came together with two of the BE actors that were analyzed as cases, namely Aurora and Aptiv. The OEM made a minority investment in Aurora (Aurora Team, 2019*d*) and formed a joint venture with Aptiv a few weeks later (see section 8.1.5).

The identified initiatives showed that a large number of leading actors in the field of autonomous driving, mostly OEMs and suppliers, acquired major control over an SAE level 4 ADS developer. However, responsibilities in terms of commercialization differed between the acquired firms.

8.1.5. R&D Partnerships Between ADS Developers

The literature on technology sourcing described R&D partnerships as a common way to work towards a technological solution (Veugelers and Cassiman, 1999; Kurokawa, 1997; Elvers and Song, 2014).

As the analyzed data showed, the leading actors in the field of autonomous driving not only made major investments or acquisitions as described in the previous section, but they also entered into R&D partnerships that were between OEMs, suppliers, and technology companies in any combination. This section shows which partnerships were identified and describe the roles of each partner.

BMW - Intel - FCA

In 2016, BMW, Intel, and Mobileye entered into an open partnership to develop SAE level 3-5 ADS (Intel, 2016*a*). Later on, as shown in Table 6, other suppliers and carmakers joined the project in various roles. In 2017, FCA joined the partnership as a major contributor and beneficiary (Intel, 2017*b*). Based on the results of this collaboration, BMW announced to launch its first production vehicle with an SAE level 3 highway pilot in 2021 (BMW Group, 2019*b*).

The BMW - Intel - Mobileye partnership was considered being a buyer-supplier relationship (Scheib et al., 2016) where Intel and Mobileye would provide key components such as camera-based sensing, HD-maps, and the compute platform, which is shown in Table 6. It furthermore included the joint development of sensor fusion and driving policy algorithms (Aviram et al., 2016). It was argued that driving policy algorithms require the involvement of the OEM *"because this is something that requires adaptation to specific car manufacturer legacy"* (Aviram et al., 2016, par. 80).

Table 6.: Roles in the BMW - Intel - FCA partnership

Year	Company	Resources	Source
2016	BMW	system validation, data collection, system specification	Aviram et al. (2016)
2016	Mobileye	vehicle intelligence, computer vision algorithms, camera sensing, driving policy, high definition maps	Aviram et al. (2016)
2016	Intel	compute platform	Aviram et al. (2016)
2017	Delphi (Aptiv)	system integrator, automotive grade compute platform	Intel (2017*a*)
2017	Continental	system integrator, motion control, function development, driver monitoring, system validation, system testing	Continental (2016)
2017	FCA	financial resources, engineering resources	Intel (2017*b*)
2017	Magna	system integrator, industrialization of components	Magna (2017)

Aptiv - Mobileye

In 2016, Aptiv and Mobileye announced the joint development of an SAE level 4 turnkey solution called "CSLP" for interested customers such as OEMs and mobility service providers. That would be available for integration into vehicles in the 2019 - 2021 timeframe. Together they would develop the system that is capable of running the driving algorithms and understanding the input from sensors such as lidar, radar, and camera vision. (Clark et al., 2016)

Table 7.: Roles in the Aptiv - Mobileye partnership

Year	Company	Resources	Source
2016	Delphi (Aptiv)	system integration, multi-domain controller, path, motion planning algorithms, sensors	Clark et al. (2016)
2016	Mobileye	deep learning, high definition maps, chips, vision system, driving policy	Delphi and Mobileye (n.d.)

Bosch - Daimler

In 2017, Bosch and Daimler announced their partnership to develop an SAE level 4 ADS for urban environments (Daimler, 2017*c*). Together, both firms would develop the self-driving system consisting of the sensor algorithms and sensor fusion, motion control, path planning, and the IT for the operation of autonomous vehicles (Daimler, 2019*d*). Both partners scheduled the deployment of a test fleet of self-driving vehicles for ride-hailing services in San Jose, California for 2019 (Daimler, 2019*d*) and planned the commercial release by 2020 - 2023 (Daimler, 2019*f*). In 2019, however, Daimler announced a shift of resources towards autonomous trucking applications on US highways for hub-to-hub connections following its TORC (ADS for trucks) acquisition (Daimler, 2019*b*).

Table 8.: Roles in the Bosch - Daimler partnership

Year	Company	Resources	Source
2017	Bosch	sensors, computing units, actuators, software for hardware	Daimler (2019*d*)
2017	Daimler	system integration, vehicle expertise	Daimler (2019*d*)

BMW - Daimler

In 2019, BMW and Daimler announced their partnership to develop driver assistance systems and SAE level 3-4 automated driving systems for highway use and parking. That would result in their second generation level 3 highway pilot for private customers that would be launched in 2024. The results of this partnership would be primarily targeted at vehicles for private customers. (Daimler, 2019*c*)

Table 9.: Roles in the BMW - Daimler partnership

Year	Company	Resources	Source
2019	BMW	current AV hardware and software	Daimler (2019*c*)
2019	Daimler	current AV hardware and software	Daimler (2019*c*)

Aptiv - Hyundai

In 2019, Aptiv and Hyundai formed a joint venture to develop an SAE level 4 platform for the use in ride-hailing services by 2022. Both firms would be equal partners, whereby Aptiv would contribute its autonomous driving capabilities, and Hyundai would mainly contribute financial resources. Aptiv would also supply the partnership with its other solutions (e.g. computing hardware and sensors). (Fox et al., 2019)

Table 10.: Roles in the Aptiv - Hyundai joint venture

Year	Company	Resources	Source
2019	Aptiv	AV technology, IP, human resources	Fox et al. (2019)
2019	Hyundai	$ 1.6 B financial resources, $ 400 M R&D resources, access to IP	Fox et al. (2019)

8.1.6. Doing-it-Alone

According to the literature on technology sourcing of firms (see section 6.1.3), *doing-it-alone* describes initiatives towards technologies that do not involve external R&D cooperations. As the archival analysis revealed, Waymo, Zoox, and Aurora were three leading actors in the field of autonomous driving where their R&D activities for the core ADS were rather independent.

Aurora

Aurora developed an automated driving system for customers, such as OEMs. This means the company would sell or license its sensors, hardware, data services, and software that are required for L4 ADS to its customers for the use in transportation-as-a-service applications. (Aurora, n.d.*a*) The company was founded in 2017 by former leading employees at Waymo, Tesla, and Uber, with backgrounds in robotics, computer vision, and machine learning (Aurora, n.d.*b*; Crunchbase, n.d.*b*).

Aurora partnered with a number of companies such as Hyundai, FCA, and Byton on the integration of Aurora's ADS into the manufacturer's vehicles (Volkswagen, 2018*a*; Thomasson, 2019). This means that Aurora would supply the OEMs with its full turnkey autonomous driving solution. The partnerships are, therefore, not R&D partnerships for Aurora's core ADS. Between 2018 and 2019, Aurora also cooperated with VW to integrate its system into VW vehicles (Volkswagen, 2018*a*), and VW wanted to acquire Aurora, but Aurora decided to stay independent (Thomasson, 2019). The company had, however, several investors and was valuated at $ 2.5 B (Deutscher, 2019). The archival analysis did not reveal major R&D cooperations, but Aurora hired more than 400 skilled employees (Aurora, 2019; Wolpin, 2019) and thus, the company pursued a buy-strategy in terms of employees.

Waymo

Waymo originated in 2009 when Google started its self-driving car project (Waymo, n.d.*a*). The company developed its SAE L4 automated driving systems in-house for the use in transportation-as-a-service applications such as ride-hailing and autonomous trucks (Waymo, 2018*b*). This means there was no co-development of the automated driving system with other firms, and Waymo thus followed the "doing-it-alone" approach based on obtained data, but the firm hired more than 900 skilled employees (Efrati, 2019; Waymo, 2019*b*) and thus did not follow a clear make-strategy. In addition, Waymo partnered with Magna for the system integration into the vehicles (Waymo Team, 2019).

Being a part of Google equipped the company with strong competencies in software and artificial intelligence (Weddeling, 2018). In 2014, Waymo's parent company Google acquired DeepMind, a company specialized in artificial intelligence. In general, DeepMind and Google's AI capabilities helped to get Waymo started, and its support in AI continued (Weddeling, 2018; Murgia, 2019). Waymo tested its systems in autonomous truck operations (Waymo, 2018*b*) as well as ride-hailing applications.

Zoox

Zoox was founded in 2014 by a computer scientist (Crunchbase, n.d.*d*) and an art-designer (Kentley-Klay, n.d.). The company built the level 4 ADS in-house for transportation-as-a-service applications as well as a purpose-built vehicle optimized for mobility services (Zoox, 2018*b*). Zoox received $ 950 M in total funding by 2019 (Crunchbase, n.d.*f*) and had a $ 3.2 B valuation in 2018 (Dickey, 2019). The archival analysis did not reveal any major R&D partnerships, but the company hired more than 1000 employees (Zoox, 2019) and thus did not follow a clear make-strategy.

This section showed that three tech companies with core competencies in technologies such as software engineering, AI, and robotics followed the doing-it-alone approach. However, no firm followed a clear make-strategy due to the hiring of skilled employees, and the firms had financial support from their owners or investors.

8.2. Commercialization and Testing of ADS with Transportation-as-a-Service Offerings

Systems capable of higher levels of driving automation (SAE L4+) would be too expensive to be integrated into vehicles for private customers (Vogt, 2019*b*; Clifford, 2020). At the same time, their integration into use-oriented PSS offers new business opportunities (Mohr et al., 2016). Due to the two-way correlation between the business model and the development of technologies (Baden-Fuller and Haefliger, 2013, p. 424), this section describes the findings of how companies that developed L4 ADS approached testing and using their own ADS in product-service systems.

As the compiled list of investments and acquisitions in Table 22 on page 104 in the appendix shows, almost all leading actors in the field of autonomous driving expanded their resources in the transportation-as-a-service domain through investments or acquisitions. It furthermore shows that there was a widespread interest in multi-sided platforms that connect riders and mobility providers. In general, the operation of autonomous mobility services that operate with vehicles without human supervision would require at least SAE level 4 ADS-equipped vehicles that offer high driving automation (SAE International, 2018). As discussed in section 8.1.1, FCA did not participate in the development of L4 ADS and is, therefore, not represented in this section as an active player with its own ADS. The following list concludes the findings for the BE actors and describes how the development of automated driving systems impacts their future business by offering platform-based services:

- The **Daimler-Bosch alliance** started testing autonomous vehicles in a self-driving ride-hailing service in San Jose, California, in December 2019. This app-based service was used to test their level 4 ADS in real-world scenarios as well as to gain insights into the integration of autonomous vehicles into a multi-modal mobility ecosystem. The service required safety drivers and was only available to employees. (Daimler, 2019*e*; Abuelsamid, 2019*a*)

  Both partners expected the release of product-service systems with driverless fleets based on technologies originating from the Daimler-Bosch cooperation in the 2020 - 2023 timeframe (Daimler, 2019*f*). In 2019, however, Daimler announced to shift its main focus from autonomous ride-hailing to autonomous transportation-as-a-service for goods with trucks on US highways due to technological challenges and risk and uncertainty of the "robotaxi" ride-hailing business model (Daimler, 2019*b*). Nonetheless, Daimler invested in several mobility service platforms. Therefore the company established *Daimler Mobility Services* to bundle its mobility service offerings like *Moovel* and *car2go* that were shown in Table 22 (Daimler, 2013*a*). One goal of operating these mobility platforms was to gain insights into customer demands to be prepared for fleets of autonomous vehicles in the network (Daimler, 2018*b*).

- In 2019, **BMW and Daimler** announced to bundle their mobility services in a joint venture. Their vision was *"to form a single mobility service portfolio with an all-electric, self-driving fleet of vehicles that [...] interconnect with the other modes of transport"* (BMW, 2019*a*, par. 5). The aim of the joint venture was to increase the market share to become a leading provider for mobility services, which were mainly focused on the urban environment (BMW, 2019*a*). Daimler started testing autonomous vehicles for mobility services in cities in 2019 (Daimler, 2019*e*), whereas BMW would roll out of a fleet of 500 vehicles to test SAE level 4 functionality in urban environments in 2021 (BMW Group, 2019*a*,*c*).

- **Bosch** intended to transform into a mobility service provider and therefore bundled its resources in the *Connected Mobility Solutions* division. Those services would include *"vehicle sharing, ridesharing, and connectivity-based services for car drivers"* (Bosch, 2018*d*, par. 1). Some of those services, however, were designed for traditional conventional cars and their drivers. The company furthermore acquired the mobility startup SPLT. (Bosch, 2018*d*)

- In July 2017, **GM** launched the self-driving ride-hailing service *"Cruise Anywhere"* for employees of General Motors in San Francisco to test automated driving systems in a fleet of self-driving cars. Safety drivers were still required behind the steering wheel of the vehicles. (Davies, 2017) The commercial launch in specific operational design domains in the US was scheduled for 2019 (General Motors Company, 2018), but this was postponed in mid-2019 to an undefined date due to the required additional testing and validation of the automated driving system (Ammann, 2019). Besides, the company established its own car-sharing service and acquired assets such as intellectual property and taking over former employees of Sidecar (Lunden, 2016) with the aim to position the company to be ready for autonomous vehicles (Abril, 2019). GM also invested in Lyft, a mobility-on-demand service (General Motors Company, 2017). Moreover, in 2016 GM acquired Cruise, which not only developed the automated driving system but also developed GM's autonomous ride-sharing services (General Motors, 2018*a*, p. 5).

- **Ford** established the *Ford Smart Mobility* subsidy to develop a mobility-as-a-service network based on autonomous vehicles (Ford Motor Company, 2018*b*). Ford argued that autonomous vehicles would be commercialized in a service environment due to the costs of the AVs itself as well as the entire ecosystem like the app (Holland, 2018). Ford tested its autonomous vehicles in an autonomous delivery service (Ford, n.d.) and expected the commercial launch in the US in 2021 (Marakby, 2018), whereas Ford's AV unit Argo AI argued that truly autonomous vehicles without human supervision would take years to come without mentioning a specific date (Salesky, 2019*b*). Nevertheless, Ford teamed up with Lyft to launch its autonomous vehicles on the Lyft platform in 2021 (Campbell, 2017).

- In 2016, **Volkswagen** founded the mobility business *MOIA* and also made an investment in the mobility-on-demand service provider *Gett*. Gett would be used by Volkswagen to get the first step into mobility services, and MOIA was established to become a ride-hailing business. For the development of mobility services, Volkswagen created the *Digital:Lab* team. The company furthermore stated that creating mobility services was one of its key initiatives for future business. Moreover, VW noticed an increased popularity of services for vehicle usage rather than ownage. (Volkswagen, 2017) Due to VW's investment in Argo AI and the following integration of VW's AV unit into Argo AI, the use of autonomous vehicles in VW's mobility services would most likely depend on Argo AI.

- In 2018, **Intel** announced that Mobileye, Volkswagen, and Champion Motors would create a mobility-as-a-service platform in a joint venture to commercialize autonomous vehicles in Israel. Volkswagen would provide electric vehicles, whereas Mobileye would integrate its level 4 self-driving technology. Champion Motors would be responsible for the operation of the fleet. This joint venture would be used to gain experience with mobility-as-a-service platforms based on self-driving vehicles for future global expansions. According to Intel, the full commercial operation would be expected by 2022. (Intel, 2018*c*)

- **Waymo** and its parent company made various attempts towards mobility platforms. On the one hand, Waymo's parent company Alphabet invested in Uber and Lyft, which provide mobility-on-demand services (Geron, 2013; Fiegerman, 2017). On the other hand, Alphabet gained experience in building and operating digital platforms itself. In April 2017, Waymo initially offered rides primarily focused on people without the ability or willingness to drive, such as children, elderly people, and disabled upon registration and invitation (Waymo, 2018*c*, 2017*a*). The company used its own platform to deploy its self-driving vehicles with a safety driver in Phoenix, Arizona (Waymo, 2017*a*). Waymo launched its commercial service in 2018, although it was accessible to a selected group of riders only (Krafcik, 2018). In late 2019, Waymo started removing safety drivers on a limited amount of routes in its autonomous vehicles (Chu, 2019). In addition, Waymo partnered with the ride-hailing service Lyft to deploy its vehicles on the Lyft platform (Krafcik, 2019). In order to scale up resources for its autonomous ride-hailing service, Waymo ordered up to 62.000 vehicles from Fiat Chrysler Automobiles (FCA) that would be equipped with Waymo's automated driving system by 2021 (Wester, 2018). Furthermore, similar to Daimler, Waymo argued that autonomous trucks and thus freight transportation-as-a-service would be more likely to succeed in the near future due to their often repeated, more predictable routes (Naughton, 2019).

- **Aptiv** launched a fleet of self-driving vehicles on the platform of the mobility-as-a-service provider Lyft (Aptiv, 2018*c*). There, their vehicles could be used on an opt-in basis to travel between popular destinations in Las Vegas, USA (Aptiv, 2018*c*). To strengthen their resources in mobility-on-demand solutions, Aptiv acquired nuTonomy (Aptiv, 2018*a*) that started testing autonomous vehicles in Singapore in transportation-as-a-service applications in 2016 (EDB, 2016). The company focused its development on providing turnkey solutions for both their traditional and new mobility partners (Aptiv, 2018*a*). However, it was argued that Aptiv needed to operate its own vehicles in a mobility service to advance the underlying technologies (Lache et al., 2018). Aptiv expected to remove its safety drivers from certain routes in Las Vegas in mid-2020 (Vogt, 2019*a*). Furthermore, Aptiv's autonomous driving joint venture with Hyundai aimed at developing the ADS for Hyundai's ride-hailing service (Aptiv, 2019*c*).

- **Aurora** developed ADS for its customers that could be used in ride-hailing or freight transportation-as-a-service (Aurora Team, 2019*c*). Aurora's customers that would acquire self-driving systems included Hyundai for its ride-hailing business by 2021 (Aurora Team, 2019*d*) and FCA for the use in logistics (Aurora Team, 2019*a*).

- **Zoox** developed the automated driving system, the ride-hailing applications, and the purpose-built vehicle for its mobility service. The company planned the commercial launch of a ride-hailing service by 2021 in Las Vegas, USA (Somerville, 2018; Welch, 2019; Korosec, 2019).

Major events and announcements with regards to testing and commercializing ADS in transportation-as-a-service offerings that were identified as relevant by the author were also included in the autonomous driving timeline in Figure 14 on page 84. As described in this section and shown in the autonomous driving timeline, not every leading company in the autonomous driving business ecosystem intended to operate its own mobility service. Aurora, for example, developed its technologies to be used in mobility services but did not want to operate one on its own (Aurora Team, 2019*c*,*d*,*a*). Aptiv, in contrast, argued that the operation of a mobility service would not be among the firms' primary business objectives (Lache et al., 2018). However, the firm argued that the mobility service operation would be required to advance the technology for its customers (Lache et al., 2018). In the 2016 - 2017 timeframe, the first autonomous mobility service initiatives started with real-world testing with a predefined and limited customer segment such as employees of the company or people that were not able to drive. Furthermore, most initial initiatives towards autonomous transportation-as-a-service offerings would be in the USA. It was also identified that offering autonomous mobility services and testing of autonomous vehicles goes hand in hand.

In essence, all firms that developed systems capable of higher levels of driving automation (SAE level 4/5) developed systems to integrate their ADS in a transportation-as-a-service environment. Furthermore, only two companies, Aptiv and Aurora, as ADS suppliers, argued that offering driverless transportation-as-a-service solutions with their own vehicles would not be a crucial component of their future business model.

9. Influence of Initiatives Towards Technologies for AD on Value Creation

This chapter aims to answer RQ-Sub 3: *How have initiatives towards technologies for autonomous driving influenced the value creation aspect of investigated firms?* It is focused on the automated driving system as well as driverless mobility services that are used for commercializing self-driving technology.

The remainder of this chapter is structured as follows. Section 9.1 analyzes the potential drivers of the investments, acquisitions, and partnerships that were identified in chapter 8 to develop the ADS. With the help of these insights, the case analysis follows in section 9.2.

9.1. Potential Drivers of Selected Technology Sourcing Initiatives

This section elaborates potential drivers of BE actors with regards to investments and acquisitions in section 9.1.1, and entering into partnerships to develop the automated driving systems in section 9.1.2. The aim is to find insights into the business model components that were most decisive for those actions to allow a conclusion to be drawn about the influence of initiatives towards technologies for AD on the value creation aspect of firms. The following qualitative content analyses were made with the methodologies described in chapter 2. The investment, acquisition, and partnership cases in Tables 11 and 12 depict embedded units of analysis of the main cases described in chapter 7.

9.1.1. Analysis of Potential Drivers of Investments in ADS Developers

Table 5 in the previous chapter showed that the BE actors GM (Cruise), Aptiv (nuTonomy), Ford (Argo AI), Intel (Mobileye), VW (Argo AI), and Daimler (TORC) either made investments or acquired major developers of automated driving systems. This section aims at identifying potential drivers that led to these initiatives towards technologies for autonomous driving.

This analysis was based on material originating from earnings call and investor conference transcripts of the firms for the investment and acquisition cases shown in Table 11. Not every event could be analyzed (Daimler's investment in TORC Robotics) due to insufficient coverage in the target material.

Table 11.: Analyzed investments and acquisitions of firms

Technology Sourcing Case	**Year**	**Actor**	**Target**	**Type**	**Coverage**
GC	2016	GM	Cruise	acquisition	GM Q1 2016 (Randy et al., 2016), GM Q2 2016 (Barra et al., 2016)
FA	2017	Ford	Argo AI	maj. investment	Ford Q2 2017 (Cannis et al., 2017), Ford Q3 2017 (Tyson et al., 2017), Ford Q4 2017 (Tyson et al., 2018)
IM	2017	Intel	Mobileye	acquisition	Intel Q1 2017 (Swan et al., 2017), Intel Q2 2017 (Krzanich et al., 2017), Intel Q3 2017 (Ramsay et al., 2017), Intel Corp at Deutsche Bank Global Auto Industry Conference (Galves and Lache, 2018)
AN	2017	Aptiv	nuTonomy	acquisition	Delphi Q3 2017 (Johnson et al., 2017), Aptiv Q4 2017 (McNally et al., 2018), Aptiv Q1 2018 (Lache et al., 2018)
VA	2019	VW	Argo AI	investment	Volkswagen Q2 2019 (Larkin et al., 2019*b*), Ford Q2 2019 (Tyson et al., 2019)

Table 13 on page 71 shows which first-order concepts were identified in which cases.

Based on those results, Figure 11 is used to present the findings of the qualitative content analysis. It consists of the second-order themes as well as the first-order concepts on which the second-order themes were formed[1].

Four firms tried to *"achieve a leading position in the industry" (I1)* with their interest in other firms. They, therefore, saw valuable resources in the target firm that helped them get in a better competitive situation. Most noticeably, firms were not very specific in this context, e.g.: *"[...]*

[1]The second-order themes that resulted from the first-order concepts were formed based on the following considerations: As the research question aims at finding out the impact of initiatives towards technologies for autonomous driving on business models in the business ecosystem, the second-order themes were assigned based on the business model building blocks described by Osterwalder and Pigneur (2010). If the assignment to a business model building block was not possible, *"Other"* was used instead of the BM building block.

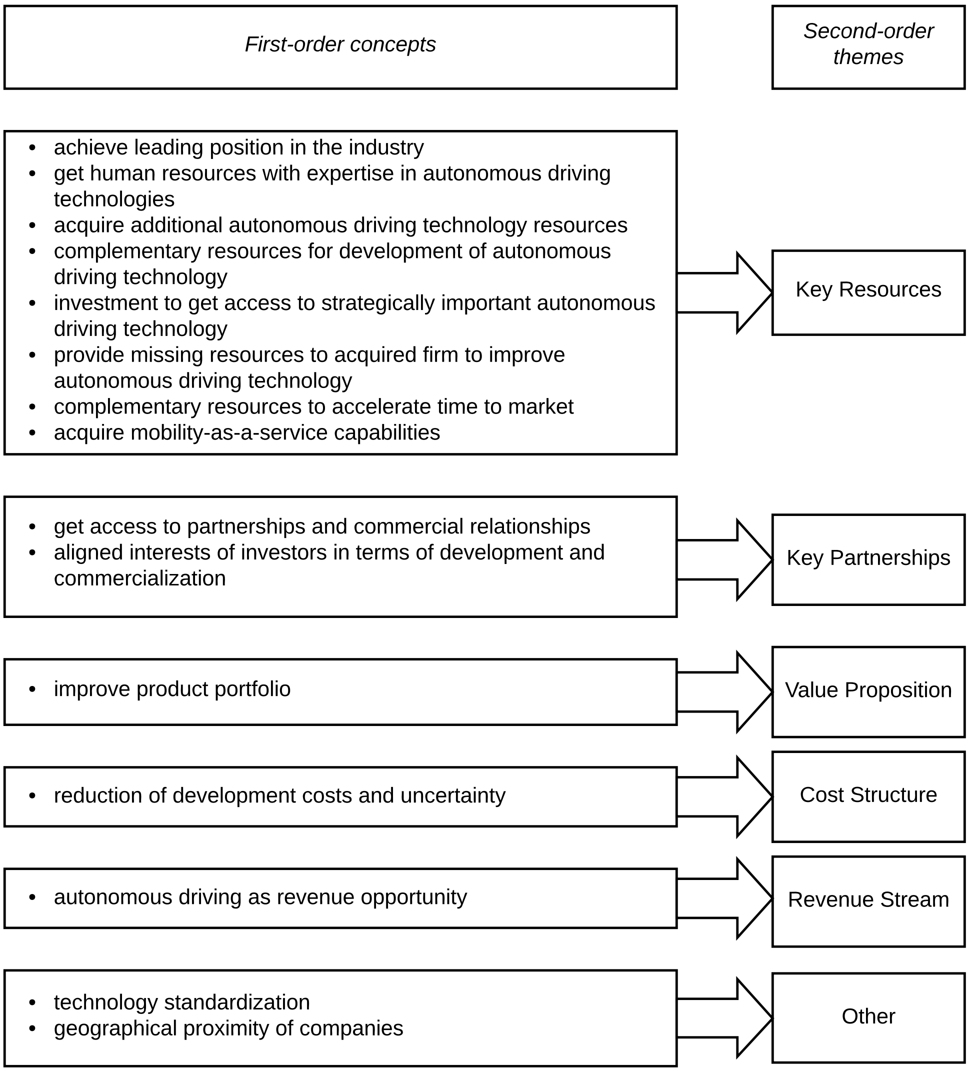


Figure 11.: Data structure consisting of first-order concepts and second-order themes for analyzed investments and acquisitions. Based on the findings of the QCA and the results shown in Table 13. (own creation)

we are very committed to being among the leaders or leading in autonomous technology. Clearly the Cruise Automation was a big piece of that [...]" (Barra et al., 2016, par. 56). The only case where this second-order theme did not occur was Volkswagen's investment in Argo AI. This case, however, revealed that Volkswagen needed access to the technology (see concept *I12*), which was of primary importance. Concept I1 means that the bundle of AD resources would put the actors in a better position. In view of the resources that were acquired, the concept was, therefore, assigned to *key resources* as the second-order theme.

The first-order concept *"acquire additional AD technology resources" (I2)* also occurred in four of the analyzed cases. In general, it is strongly related to another first-order concept that occurred in the same amount of the analyzed cases, which is *"complementary resources for the development of AD technology" (I7)*. I2 refers to technology acquisitions regardless of prior technological expertise in a specific domain (e.g. acquisition of AD-related intellectual property *(case AN)*), whereas I7 refers to specific combinations of firm's competencies (e.g. Cruise's expertise in software engineering would complement GM's expertise in vehicle engineering (Barra et al., 2016)). As shown in Figure 13, *I7* was not identified in the case *FA*. Both first-order concepts were assigned to the second-order theme *key resources*.

The first-order concept *"get human resources with expertise in AD technologies" (I10)* is the fourth concept that occurred in four out of five cases. This ranged from skilled engineers in the field of autonomous driving in general to more specific needs like talent in AI, a capable management team, and staff that already had experience with commercial solutions in automotive-grade commercial applications in the ADS/ADAS domain. This first-order concept shows that investors wanted skilled human resources in technologies that are relevant to autonomous driving. It was, therefore, assigned to *key resources* as the second-order theme.

"AD as revenue opportunity" (I4) is the last first-order concept that occurred in four of all analyzed investment or partnership cases. In the case of Intel *(IM)*, it was the opportunity to grow in the automotive business ecosystem. In contrast, other companies saw the target's capabilities as a way to achieve their desired growth in the future. In general, it depended on the background of the investor. Whereas the suppliers Aptiv and Intel referred to selling systems or individual components, the OEMs Ford and GM referred to the revenue opportunities with regards to autonomous mobility services. In general, the *revenue opportunities* should affect their *Revenue Stream*, which was chosen as the corresponding second-order theme.

The first-order concept *"complementary resources to accelerate time to market" (I6)* was identified in two cases. Firms were not very specific in this context. However, the combination of both existing and acquired resources would accelerate time-to-market. The occurrence of the concept *I6* in two cases could signify how ambitious the two actors (Aptiv, GM) were to get solutions based on autonomous vehicles on the street as soon as possible. This first-order concept was assigned to *key resources* as the second-order theme due to its relation to the resources of both firms that would accelerate time-to-market.

"Get access to partnerships and commercial relationships" (I9) as a first-order concept was present in the cases of Aptiv *(AN)* and Intel *(IM)* where both companies were interested in mobility services and manufacturing relationships as well as the contact to OEM customers. The interests were, therefore, rooted in the firm's *key partnerships* business model building block.

Another first-order concept that only occurred in the cases of Aptiv *(AN)* and Intel *(IM)* was *"provide missing resources to acquired firm to improve AD technology" (I13)*. Autonomous driving was said to be a complex field as Mobileye explained and smaller firms sought for additional resources that the investor could provide:

> *"[...] autonomous vehicles are not a product, it's an industry. It's interdisciplinary. It goes beyond computer vision, AI, Systems on Chip. It's infrastructure of mapping. It's cloud computing. It's custom data centers. It's systems engineering to build test vehicles, sophisticated agreements with the car industry, interaction with regulators, 5G communications. How can a company of 650 people do this all on our own?"* (Galves and Lache, 2018, par. 8)

Due to the relevance of resources that this first-order concept describes, it was assigned to *key resources* as the second-order theme.

The first-order concept *"investment to get access to strategically important AD technology" (I12)* was identified in two cases: Intel *(IM)* and Volkswagen *(VA)*. While Intel's acquisition of Mobileye was a part of their *"strategy to transform from a PC-centric company to a data-centric company"* (Krzanich et al., 2017, par. 30), VW argued that *"for us we deem it to be strategically important. We believe that we can't afford not to invest."* (Larkin et al., 2019*b*, par. 222). It thus refers to VW's need to get access to technological solutions for autonomous driving that could be used in their vehicles. This first-order concept refers to the value the ADS could have for a firm. It was thus assigned to *key resources* as the second-order theme.

"Improve product portfolio" (I11) was identified in one case: *IM*. In this case, the package of Intel's computing platform capabilities, as well as Mobileye's ADS capabilities, were believed to be advantageous: *"[...] individually these businesses are great. But when you put all these together into one package and you're able to walk into a customer with a complete solution, they're truly world-class [...]"* (Ramsay et al., 2017, par. 183). The ability to offer complete system solutions from one source was assigned to the second-order theme *value proposition*.

The first-order concepts *"reduction of development costs and uncertainty" (I15)*, *"ADS technology standardization" (I17)*, and *"aligned interests of investors in terms of development and commercialization" (I18)* were only identified in one case: *VA*. It was argued that autonomous driving would be *"[...] a costly endeavor and nobody can be absolutely certain when technology will be ready."* (Larkin et al., 2019*b*, par. 221) and one main motivation behind the investment was to share the costs of AV development with Ford: *"That is obviously a multi-billion investment decision over time, but definitely a lower bill to be paid compared to doing it all on our own grounds."* (Larkin et al., 2019*b*, par. 222). *I15* thus refers to the *cost structure* of the business model as the aim was to reduce costs.

Concept *I18 "aligned interests of investors in terms of development and commercialization"* means that VW found a partner with Ford and Argo AI where the strategy in terms of ADS technology commercialization was aligned. Argo AI would supply the ADS to both investors (Ford and VW), and they would be able to commercialize products with ADS independently. The opposite would be GM's Cruise, where Cruise was in charge of the development and commercialization for its investors. This first-order concept was assigned to the second-order theme *key partnerships* due to its type that could be a buyer-supplier relationship as well as coopetition.

The first-order concept *"ADS technology standardization" (I17)* referred to the ability to *"co-create common AV standards"* (Tyson et al., 2019, par. 39). This first-order concept could not be clearly assigned to a business model building block as a second-order theme. It was, therefore, categorized as *"other"*.

I3 "acquire MaaS capabilities" is a first-order concept that was identified in in one case: *AN*. The firm identified a customer interest in mobility-on-demand services. It acquired nuTonomy that already gained experience in operating mobility-as-a-service applications with a fleet of its own vehicles (Johnson et al., 2017). Mobility service capabilities were, therefore, assigned to the *key resources* of a firm's business model as the second-order theme.

The last first-order concept *"geographical proximity of companies" (I8)* was identified in one case: *FA*. It was argued that *"the configuration of the entity in Pittsburgh allows us to have them be us and them be them. They can be both together"* (Cannis et al., 2017, par. 270). This first-order concept could not be clearly assigned to a business model building block and was therefore categorized as second-order theme *"other"*.

This section showed that the need for key resources to develop ADS was identified as one of the possible main reasons to invest in or acquire major ADS developers. Most specifically, human resources with expertise in key technologies for autonomous driving were acquired. The frequency analysis also shows that the anticipation of new revenue streams that would come with the firm and the self-driving technology in use was one of the possible main motives behind the investments and acquisitions. It is noteworthy, however, that one case (*VA* - VW's investment in Argo AI) often differed from most other cases. As the following section shows, it resembles many elements found in typical motives to enter into partnerships: reduction of risk, costs, and uncertainty, as well as aligned interests with partners.

9.1.2. Analysis of Potential Drivers of Entering Into ADS Development Partnerships

Section 8.1.5 in the previous chapter identified that the following BE actors entered into partnerships to develop the automated driving system: BMW - Intel - FCA, Aptiv - Mobileye, Bosch - Daimler, BMW - Daimler, and Aptiv - Hyundai. This section aims at identifying potential drivers that led to these joint initiatives towards technologies for autonomous driving.

This analysis was based on the earnings call and investor conference transcripts of the firms for the partnership and joint venture cases shown in Table 12. Not every partnership could be analyzed (Daimler-Bosch alliance) due to insufficient coverage in the target material. As described in chapter 2, a qualitative content analysis was made.

Table 12.: Analyzed ADS development partnerships between firms

Technology Sourcing Case	**Year**	**Actor**	**Partnership**	**Coverage**
BIM	2016	BMW	BMW - Intel - Mobileye	BMW Q2 2016 (Krueger et al., 2016), BMW Q4 2016 (Krueger et al., 2017)
IBM	2016	Intel	BMW - Intel - Mobileye	Intel Q2 2016 (Henninger et al., 2016), Intel Q3 2016 (Smith et al., 2016), Intel Q4 2016 (Henninger et al., 2017)
MBI	2016	Mobileye	BMW - Intel - Mobileye	Mobileye Q2 2016 (Aviram et al., 2016), Mobileye Q3 2016 (Galves et al., 2016), Mobileye Q4 2016 (Maharshak et al., 2017)
AM	2016	Aptiv	Aptiv - Mobileye	Delphi Q3 2016 (Rosman et al., 2016), Delphi Q4 2016 (Chatterjee et al., 2016), Delphi Q1 2017 (Massaro et al., 2017)
MA	2016	Mobileye	Aptiv - Mobileye	Mobileye's Management on Mobileye and Delphi Partnership (Clark et al., 2016), Mobileye Q3 2016 (Galves et al., 2016), Mobileye Q4 2016 (Maharshak et al., 2017)
FBI	2017	FCA	BMW - Intel - FCA	FCA Q3 2017 (Veltri et al., 2017)
BD	2019	BMW	BMW - Daimler	BMW Q1 2019 (Schoeberl et al., 2019)
DB	2019	Daimler	BMW - Daimler	Daimler Q1 2019 (Scheib et al., 2019), Daimler Q2 2019 (Källenius et al., 2019)
AH	2019	Aptiv	Aptiv - Hyundai JV	Aptiv Q3 2019 (Fox et al., 2019)

Table 13 on page 71 shows which first-order concepts were identified in which cases. Figure 12 depicts the findings of the qualitative content analysis. It consists of the second-order themes as well as the first-order concepts on which the second-order themes were formed[1].

[1]The second-order themes in Figure 12 that resulted from the first-order concepts were based on the following considerations: As the research question aims at finding out the impact of initiatives towards technologies for autonomous driving on business models in the business ecosystem, the second-order themes were assigned based on the business model building blocks described by Osterwalder and Pigneur (2010). If the clear assignment to a business model building block was not possible, *"Other"* was used instead of a business model building block.

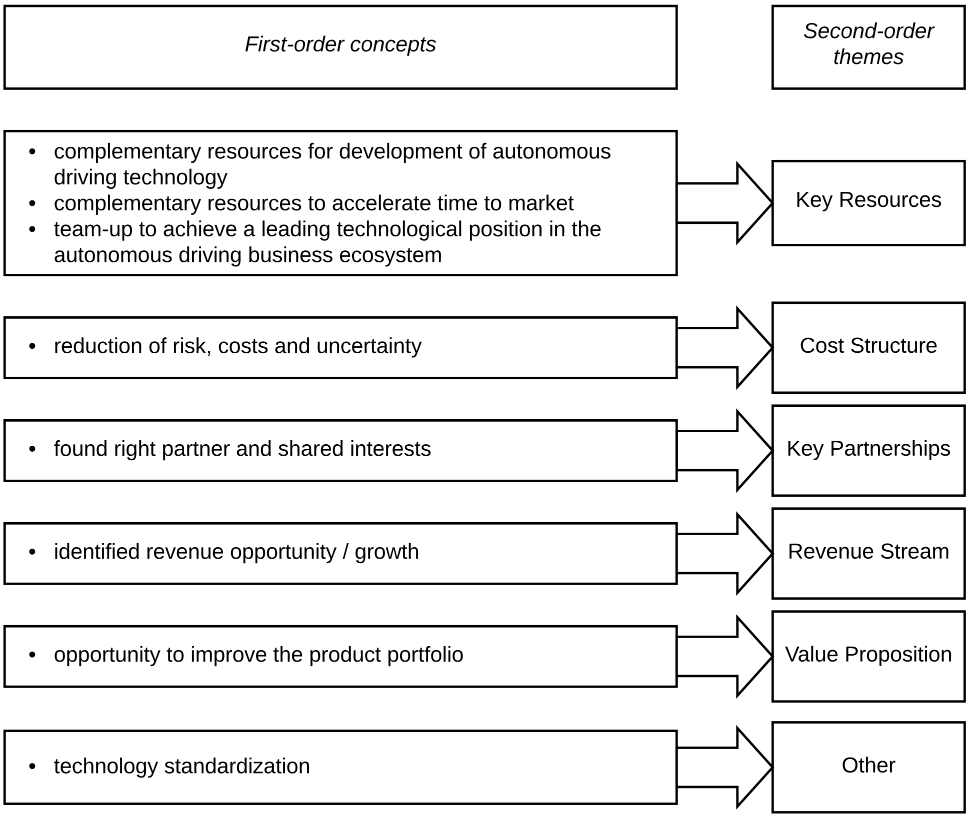


Figure 12.: Data structure consisting of first-order concepts and second-order themes for analyzed partnerships. Based on the findings of the QCA and the results shown in Table 13 on page 71. (own creation)

The first-order concepts *"reduction of risk, costs, and uncertainty" (P3)* and *"complementary resources for development of AD technology" (P7)* were most commonly identified in the analysis. For *P3*, the main motive was to reduce R&D costs and to enhance the chances of getting a commercially viable solution. Suppliers such as Aptiv argued that they would require a solution that *"can be done at a very competitive cost? Because as you know our OEs are very, very focused on cost as it relates to technology"* (Rosman et al., 2016, par. 138) thus reducing costs of solutions that could be sold to commercial customers. Similar to that, partnerships between OEMs also had the goal of reducing R&D costs for their own solutions due to the transformation and uncertainties in the industry, as Daimler argued: *"[...] it's important to work even more efficiently on future technologies as part of the transformation that the industry is in"* (Källenius et al., 2019, par. 35). At FCA, it was argued against a high number of individual solutions as *"Some of these and a lot of these will end up being for naught. [...] most of these businesses, but especially the startup will just disappear and vanish."* (Veltri et al., 2017, par. 137) and therefore was in favor of entering into a partnership for the *"ability to deliver a product that's commercially viable and technically* *defensible in the marketplace"* (Veltri et al., 2017, par. 136). It is noteworthy that *P3 reduction of risk, costs, and uncertainty* was not identified as a motive for any partner to enter into the BMW-Intel-Mobileye partnership. This is probably due to the role of each partner in the partnership where Intel and Mobileye identified a revenue opportunity (see *P4*) to sell their technology to the partnership, and BMW wanted the complementary resources to enable the development of ADS. It was argued that BMW's attempt to develop ADS would be more expensive than alternatives such as purchasing the self-driving systems from suppliers (Clark et al., 2016). However, the attempt would accelerate time-to-market *(P6)*. The first-order concept *P3* was considered to be related to the *cost structure* of a business model (as a second-order theme) due to the main reason to reduce costs.

The first-order concept *"complementary resources for development of AD technology" (P7)* was identified in six out of nine cases. It typically occurred when partners with strengths in different areas found together. Aptiv argued in what areas the suppliers would complement each other in the Aptiv (Delphi) - Mobileye partnership:

> *"When you combine Mobileye's vision and road experience management systems with Delphi's sensor suite, automated driving software from Ottomatika, and our Multi-Domain Controller, no other entity comes close to matching the quality or the capability of this automated driving system."* (Rosman et al., 2016, par. 27)

Noticeable exceptions where the first-order concept *P7 "complementary resources for development of AD technology"* were not identified were the cases DB and BD (Daimler-BMW) where the main focus was on efficiency and cost reduction and IBM (Intel-BMW-Mobileye) where the motive was to sell Intel's technology to the partnership. *P7* refers to the resources of firms and was thus considered being related to *key resources* as the second-order theme.

The first-order concept *"found right partner with shared interests" (P1)* was identified in five out of nine cases. Aptiv, for example, described it as *"a perfect alignment on strategy as it relates to timing of introduction of product initial approach to the robotaxi market in 2022 "* (Fox et al., 2019, par. 227). Other firms pointed out that they already had previous experience with the partner (cases *MA*, *DB*), which also helped to get into a partnership. FCA, on the other hand, argued that the reputation of their partners mattered with complex technologies such as autonomous driving: *"it's the safest bet, the safest way for us to get into that market. We're doing it with a reputable organization and there are reputable suppliers at the table too"* (Veltri et al., 2017, par. 77). This might go hand-in-hand with *"reduction of risk, costs, and uncertainty" (P3)*. Because of the qualities the firms identified in their partners, this first-order concept was considered being related to *key partnerships* of a firm.

The first-order concept *"complementary resources to accelerate time-to-market" (P6)* was identified in five out of nine cases. In general, it means that the combined bundle of resources would accelerate time-to-market. It is noteworthy that this first-order concept was often found in cases where only suppliers were involved. There, the goal was to quickly develop a solution that could be adopted by OEMs or mobility service providers. The aim to be able to use complementary resources means that this first-order concept was assigned to the firm's *key resources* as the second-order theme.

"Revenue opportunity / growth" (P4) is a first-order concept that was identified as a potential driver in four cases. It was found in most relationships with suppliers and tech companies. In the case of Intel (IBM), for example, the reason to enter into partnerships was to get the foot into the automotive segment and to sell its technologies to partners. In another example, Aptiv (AH) argued that they *"continue to sell technology to the joint venture and have access to it"* (Fox et al., 2019, par. 227) which means they would profit in selling their existing technology and get access to the joint development at the same time. Initiatives behind *P4* would aim to increase the firm's revenue. It was thus considered being related to a firm's *revenue stream* as the second-order theme.

A first-order concept that occurred less often was *"team-up to achieve a leading technological position in the AD BE" (P5)*. It was identified in three cases. Most noticeably, firms were not very specific in this context. As this first-order concept refers to substantial resources in autonomous driving, it was considered being related to *key resources* as the second-order theme.

The first-order concept *"technology standardization" (P8)* was identified in the BMW - Intel - Mobileye partnership. It was argued that they wanted to *"create an open standard platform [...] other partners could join that because [...] a platform and a standard in the autonomous driving would make it much more safer"* (Krueger et al., 2016, par. 107). Mobileye, likewise, argued against a great number of individual solutions:

> *"If you have 30 car manufacturers trying to compete one against the other in such an ambitious project, which in my view it's no less than sending a man to the moon in terms of being able to reach Level 4 autonomy in a safe manner, there should be some consolidation in terms of deciding on a uniform standardization on what sensors are going to be in the car, how they are going to be placed, what software stack is there."* (Aviram et al., 2016, par. 174)

The first-order concept *P8* could not be clearly assigned to a second-order theme (business model building block).

The last first-order concept *"opportunity to improve the product portfolio" (P2)* was only identified in the Aptiv - Mobileye partnership (cases *AM* and *MA*). As both suppliers identified customer interest in an SAE level 4 turnkey solution, they entered into a partnership to develop a solution that would satisfy their customer's needs. To create a customer value proposition, *P2* was considered being related to the *value proposition* as the second-order theme.

The qualitative content analysis revealed that complementary resources *(P7)* as well as the desire to reduce costs and uncertainty that come with the development of ADS *(P3)* were identified as the most likely possible reasons to enter into an R&D partnership for autonomous driving. It is noticeable that *P3* was not identified with any partner in the BMW - Intel - Mobileye partnership. *P7*, in contrast, was not identified in the partnership between BMW and Daimler as both partners were mainly concerned about costs, and Intel's role in the BMW - Intel - Mobileye partnership that was mainly about being a supplier of computing resources in the partnership.

9.2. Case Analysis

As described in chapter 2 on methodologies, the case analysis follows the data collection. Table 13 illustrates the characteristics of each case that result from the data collection in chapter 8 and the identified potential drivers of R&D partnerships, investments, and acquisitions to develop the ADS in section 9.1. Section 9.2.1 contains the analysis of each case, the cross-case synthesis follows in section 9.2.2.

9.2.1. Analysis of Each Case

Prior to the cross-case synthesis in section 9.2.2, the within-case patterns are identified for each case, and the first tentative conclusions are drawn (Yin, 2018, p. 196-198).

9.2.1.1. Case C1 Aurora

The US-based software company Aurora focused its R&D efforts exclusively on the development of L4 ADS. This is because the driver's lack of attentiveness that results from the use of L3 ADS and the need for the driver's attentiveness within seconds upon the system's request was not considered to be safe (Urmson et al., 2018). The archival analysis did not reveal any R&D partnerships to develop the ADS, and the firm thus followed the doing-it-alone approach as the firm was founded in 2017 by former employees of other ADS developers. They had expertise in robotics, computer vision, and machine learning (Aurora, n.d.*b*; Crunchbase, n.d.*b*). Furthermore, Aurora hired a significant amount of skilled employees (Aurora, 2019; Wolpin, 2019), and the company got financial support from investors, including the automotive investor Hyundai (Deutscher, 2019). Prior to that, Volkswagen wanted to acquire Aurora (Thomasson, 2019). This is in line with most other OEMs that required L4 ADS resources (C4 - Ford Argo AI, C5 - GM Cruise, C10 - Daimler). In terms of components and technologies for their automated driving system, Aurora preferred to keep R&D in-house. The firm developed its own HD-maps and acquired a company specialized in lidar sensors with the aim to integrate the components better and to reduce the sensor costs (Aurora Team, 2019*e*,*b*). In contrast to most other cases, Aurora did not want to participate in the operation of driverless transportation-as-a-service offerings with own vehicles. It would sell the L4 ADS

Table 13.: Characteristics of investigated cases

Characteristic	**C1 Aurora**	**C2 Waymo (Alpha-bet)**	**C3 Zoox**	**C4 Ford Argo AI**	**C5 GM Cruise**	**C6 Intel Mobil-eye**	**C7 Aptiv**	**C8 Bosch**	**C9 BMW**	**C10 Daim-ler**	**C11 FCA**	**C12 VW Audi AID**
Foundation (unit investigated)	2017	2009	2014	2016	2013	1999						2017
Headquartered	US	US	US	US	US	US/IL	IE	DE	DE	DE	IT/US	DE
Company origins (see section 7.3)												
Software	✓	✓	✓									
Technology						✓	✓	✓				
Supplier						✓	✓	✓				
OEM				✓	✓				✓	✓	✓	✓
Number of employees												
Entire company	> 400	98000	> 1000	199000	173000	102000	143000	410000	134000	298000	192000	664000
Unit investigated	> 400	> 900	> 1000	500	1800	1700	700					200
Automated Driving System (see section 8.1)												
Hired skilled employees	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
L3 ADS development				?	?	✓	✓	✓	✓	✓	✓	✓
L4 ADS development	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
ADS sourcing: doing-it-alone	✓	✓	✓									
ADS sourcing: partnership / JV (cases, see section 9.1)						IBM, MBI, MA	AH, AM	Daimler	BIM, BD	Bosch, DB	FBI	
Potential drivers (ADS sourcing: partnerships / joint ventures, see section 9.1.2)												
P3 red. risk, costs, uncertainty						0 / 0 / ✓	✓/ ✓		0 / ✓	? / ✓	✓	
P7 compl. res. dev. of AD tech						0 / ✓/ ✓	✓/ ✓		✓/ 0		✓	
P6 compl. res. acc. TTM						0 / 0 / ✓	✓/ ✓		✓/ ✓			
P1 right partner, shared inter.						0 / 0 / ✓	✓/ 0		✓/ 0	? / ✓	✓	
P4 revenue opportunity / growth						✓/✓/✓	✓/ 0					
P5 ach. lead. tech. pos. AD BE							✓/ ✓		✓/ 0			
P8 technology standardization						✓/ ✓/ 0			✓/ 0			
P2 opport. impr. prod. portf.						0 / 0 / ✓	0 / ✓					

Table 13.: Characteristics of investigated cases (continued)

Characteristics	**C1 Aurora**	**C2 Waymo (Alpha-bet)**	**C3 Zoox**	**C4 Ford Argo AI**	**C5 GM Cruise**	**C6 Intel Mobil-eye**	**C7 Aptiv**	**C8 Bosch**	**C9 BMW**	**C10 Daim-ler**	**C11 FCA**	**C12 VW Audi AID**
ADS sourcing: invest / acq.				Argo AI	Cruise	Mobileye	nu-Tonomy			TORC		Argo AI
Potential drivers (ADS sourcing: investments / acquisitions, see section 9.1.1)												
I1 ach. lead. pos. in industry				✓	✓	✓	✓					
I10 get HR w/ expertise AD tech				✓	✓	✓	✓					
I2 acq. add. AD tech. res.				✓	✓	✓	✓					
I4 AD as revenue opportunity				✓	✓	✓	✓					
I7 compl. res. for dev. AD tech					✓	✓	✓					✓
I12 inv. get acc. strategic. important AD tech						✓						✓
I13 provide missing res. to acq. firm impr. AD tech						✓	✓					
I6 compl. res. to acc. TTM					✓		✓					
I9 get acc. to partnersh. comm. relationships						✓	✓					
I11 impr. product portfolio						✓						
I15 red. dev. costs / uncertainty												✓
I17 technology standardization												✓
I3 acquire MaaS capabilities							✓					
I18 aligned interests of investors dev. and commerc.												✓
I8 geo. proximity companies				✓								
HD-Maps (see section 8.1.3)												
Sourcing: doing-it-alone	✓	✓	✓		✓	✓						
Sourcing: invest / acquisition				✓		✓		✓	✓	✓		✓
Sourcing: R&D partnership				✓								

Table 13.: Characteristics of investigated cases (continued)

Characteristics	**C1 Aurora**	**C2 Waymo (Alphabet)**	**C3 Zoox**	**C4 Ford Argo AI**	**C5 GM Cruise**	**C6 Intel Mobileye**	**C7 Aptiv**	**C8 Bosch**	**C9 BMW**	**C10 Daimler**	**C11 FCA**	**C12 VW Audi AID**
Road data crowdsourcing partnership						✓		✓	✓			✓
LIDAR (see section 8.1.2)												
Sourcing: procurement			✓						✓	✓		✓
Sourcing: doing-it-alone		✓						✓				
Sourcing: invest / acquisition	✓			✓	✓	†	✓	†	†			
Potential drivers (LIDAR: doing-it-alone / acquisition)												
In-house to reduce sensor costs	✓	✓		✓	✓		✓	✓				
In-house to improve functionality		✓		✓								
Transportation-as-a-Service (see section 8.2)												
Development / operation of driverless TaaS		✓	✓	✓	✓	✓	θ	✓	✓	✓	✓	✓
Development of ADS for TaaS	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
ADS sourcing: procurement											✓	
TaaS joint venture						✓			✓	✓		✓
TaaS through partner platform		✓		✓			θ					
Purpose-built shared AV			✓	✓	✓			Δ				Δ
Legend: †venture capital invest identified, ? unclear, θ for testing purposes only, Δ concept car, ✓identified, 0 not identified in this case												
Sources: see Table 23 on page 107 in the appendix.												

to operators of driverless TaaS instead (Aurora Team, 2019*c*). However, the firm would provide supporting activities and interfaces that are required to operate vehicles equipped with their ADS in a product-service system environment (Aurora, n.d.*a*). Aurora primarily focused on simulated testing rather than testing on public roads, but the company already used modified Lincoln MKZ (that shares the platform with Ford Fusion, cases C4 -Ford Argo AI and C6 - Intel-Mobileye) and would deploy modified Chrysler Pacifica (C2 - Waymo, C7 - Aptiv) with Aurora's software and hardware (e.g., lidar) in the future as test vehicles to increasingly test specific scenarios on public roads (Urmson, 2020; Rudgard, 2019; Diether, 2017).

9.2.1.2. Case C2 Waymo (Alphabet)

Like other software companies, the US-based Alphabet subsidiary Waymo focused its R&D efforts exclusively towards the development of L4 ADS for the use in driverless transportation-as-a-service offerings. Like C1 - Aurora, Waymo argued that the former drivers would be inattentive when the system works well and would not be able to intervene within seconds as required by the SAE specification for L3 ADS (Google, 2015*a*). Like other software companies, Waymo developed the ADS following the doing-it-alone approach. This could be due to Alphabet's vast financial and technological resources (e.g., data science, AI, software) (PTOLEMUS, 2019). The amount of hired employees is about average compared to other cases. With regards to HD-maps and lidar sensors, the company followed the doing-it-alone approach based on obtained data. It was argued that bringing the development of lidar sensors in-house would enable to company to improve the functionality and reduce the sensor costs compared to existing solutions on the market (Waymo Team, 2017). Concerns about lidar sensor costs led to the decision to offer them to non-competitors to achieve economies of scale (Verghese, 2019). Like C1 - Aurora, Waymo intended to sell/license the ADS to operators of driverless mobility services (Wester, 2018). However, the company also started offering use-oriented product-service systems (transportation of passengers and goods) via its platform (like C3 - Zoox, C4 - Ford Argo AI, C5 - GM Cruise, C6 - Intel-Mobileye, C8 - Bosch, C9 - BMW, C10 - Daimler, C12 - VW) and established partner platforms (C4 - Ford Argo AI, C7 - Aptiv) (Waymo, n.d.*b*; Krafcik, 2019; Fiegerman, 2017). The company used modified Chrysler Pacifica (like C1 - Aurora, C7 - Aptiv) and Jaguar E-Pace as well as larger trucks as vehicles to test and operate its ADS in mobility services in the US (Waymo, 2019*a*, n.d.*b*). Although the company started with an autonomous ride-hailing service, Waymo argued that autonomous goods delivery with autonomous trucks would be more likely to be successfully commercialized due to their often repeated, more predictable routes (like C10 - Daimler) (Naughton, 2019).

9.2.1.3. Case C3 Zoox

The US-based software company Zoox developed L4 ADS that would be used for its driverless transportation-as-a-service offerings (Korosec, 2019). This means that Zoox would not have use for L3 ADS. With regard to the development of the ADS, the company followed the doing-it-alone approach based on obtained data. This is in line with the other software company cases. It was founded in 2014 with expertise in computer science and product design (Crunchbase, n.d.*d*; Kentley-Klay, n.d.) and hired a significant amount of skilled employees. The number of employees is about average compared to the other cases. The company was, furthermore, supported by $ 950 M in funding (Crunchbase, n.d.*f*). Like other software companies, Zoox developed its HD-maps in-house (Zoox, 2018*b*). Unlike other software companies, lidar sensors were purchased from suppliers (Schubarth, 2018). Zoox would operate a driverless ride-hailing service with a purpose-built shared autonomous vehicle (Zoox, 2018*b*), while other software companies did not show intentions of developing a purpose-built shared AV. Furthermore, in contrast to most other cases, it was not identified that Zoox would license the ADS to other firms. Hence, this could explain why Zoox would source lidar sensors from the market. It could be argued that not being required to deliver the ADS "as a system" comprising of the software and hardware to customers would allow more flexibility with regards to sourcing options. Furthermore, Zoox might not benefit from cost savings per unit using economies of scale, considering the companies' comparatively small size. Besides, cost reductions in recent years reached customers in the lidar market (Schubarth, 2018). Another important consideration is that a lidar technology acquisition would tie-up capital.

9.2.1.4. Case C4 Ford Argo AI

The American OEM Ford acquired the US-based software company Argo AI in 2017 with the aim of getting resources in technologies for autonomous driving (e.g., software capabilities, AI), especially human resources, into the company. With approximately 500 employees (Salesky, 2019*a*), Argo AI was among the smaller AV units that were investigated. However, the company would expand by 200 employees by integrating Audi's "AID" AV unit following VW's investment in Argo AI in 2019 (Salesky, 2019*a*). Ford welcomed VW's investment due to the ability to share R&D costs. Ford first argued against the use of L3 ADS due to security reasons. However, the company later argued that it could introduce L3 ADS-equipped vehicles in the meantime until L4 ADS are ready (Ford Motor Company, 2016; Martinez, 2019). Offering L3 ADS is similar to most incumbent firms in the automotive BE in this analysis. Argo AI developed SAE L4 ADS for its investors Ford and VW. Both companies would integrate the ADS into the vehicles and use them on their mobility platforms and established partner platforms in use-oriented product-service systems (Larkin et al., 2019*a*). Ford tested Argo's ADS in modified Ford Fusion vehicles (like C1 - Aurora and C6 - Intel-Mobileye) in a self-driving delivery service on public roads in the US (Korosec, 2018; Rander, 2019). Besides, Ford would use a purpose-built shared AV in the future (Farley, 2017) (like software company C3 - Zoox, and the OEM that acquired a software company C5 - GM Cruise). Argo AI argued that L4 ADS-equipped vehicles would be too expensive for private customers (Argo AI, n.d.*b*). Therefore, they would be used in a product-service environment. Furthermore, Ford argued that the company could license the ADS to interested customers in the future (Ford, 2017*b*). With regards to HD-maps, the company both entered into a partnership and invested in a company to get the resources. Like most companies that are software companies or acquired software companies that developed the ADS, Ford Argo AI acquired a firm specialized in the development of lidar sensors with the aim to reduce the costs per unit and to improve the functionality (Salesky, 2017).

9.2.1.5. Case C5 GM Cruise

The American OEM GM acquired the US-based software company Cruise in 2016 and, henceforth, used it to develop the ADS and the autonomous mobility service (General Motors Company, 2018). The primary objective of acquiring Cruise was to get the technology to be able to transform the business model from selling vehicles to providing mobility-as-a-service (THOMSON REUTERS, 2017). With Cruise, GM acquired human resources with expertise in technologies for autonomous driving, as well as complementary resources to accelerate time-to-market. In 2018, Honda invested and acquired a 5.7 % share of Cruise and provided $ 2 B long-term (General Motors, 2018*a*). Like most software companies, Cruise followed the doing-it-alone approach for the development of HD-maps (Bergen, 2018) and acquired a lidar company intending to reduce sensor costs (General Motors, 2018*b*). The motive to reduce costs per unit is in line with most cases where non-procurement sourcing initiatives were identified. Furthermore, it was argued that cheaper lidar sensors should help to accelerate time-to-market (Vogt, 2017*a*). Cruise also developed the autonomous mobility service platform where its purpose-built shared AVs would be used (Suryadevara et al., 2018). In the meantime, Cruise tested its ADS with modified Chevrolet Bolt test vehicles in the US on its own "Cruise Anywhere" ride-hailing platform, and it also tested autonomous deliveries (Davies, 2017).

9.2.1.6. Case C6 Intel-Mobileye

The US-based technology company Intel used the acquisition of the Israeli-based technology company and supplier of ADAS Mobileye in 2017 to enter into the automotive segment and transform into a data-centric company (Krzanich et al., 2017). The acquisition would complement Intel's computing and AI resources with Mobileye's computer vision capabilities in order to be able to offer a turnkey solution (Swan et al., 2017). Moreover, Mobileye argued that a firm of its size (650 employees at the time) could not successfully manage to develop self-driving systems due to the complexity of the task, ranging from computer vision, computing hardware, HD-maps, cloud computing and data centers, connectivity, testing, vehicle integration, over to regulatory issues (Galves and Lache, 2018). Intel and Mobileye entered into a buyer-supplier relationship with BMW (Scheib et al., 2016) and FCA to develop the ADS for the OEMs in 2016 (Aviram et al., 2016; Intel, 2017*b*). Mobileye would contribute resources ranging from vehicle intelligence, computer vision capabilities, driving policies, and HD-maps, whereas Intel would offer the compute platform (Aviram et al., 2016). Intel and Mobileye identified a potential revenue opportunity and the chance to establish a common technology standard due to the reduction of system fragmentation. Besides, Mobileye and the automotive supplier Aptiv entered into an R&D partnership to develop an SAE L4 turnkey solution for robotaxi providers in 2016 (Clark et al., 2016). The qualitative content analysis revealed that the potential drivers were the reduction of risk, costs, and uncertainty, being able to leverage complementary resources to accelerate time-to-market to address the revenue potential, and shared interests of both partners. Mobileye, thus, entered into multiple partnerships and argued that the development would benefit from multiple attempts to develop a solution due to the complexity of the entire ecosystem (Clark et al., 2016). Prior to the development of automated driving systems, Mobileye already developed ADAS for OEM customers (Mobileye, 2020). Mobileye developed both L3 and L4 ADS. L4 ADS would be used in driverless mobility services, whereas L3-L5 ADS were expected in consumer-oriented passenger vehicles in the middle of the decade (Mobileye, 2020). In contrast to most other cases, Intel-Mobileye was cautious about lidar. It was argued that Mobileye, having its background in computer-vision-aided perception, would develop a vision-based system first, and a second separate system for redundancy that would be lidar or radar-based (McCourt et al., 2016). This is in line with what has been suggested in theory on the redundancy of systems (Lipson and Kurman, 2017; Becker et al., 2017). The company, thus, only recently announced the formation of a lidar unit (Ben-Gedalyahu, 2019). With regards to HD-maps, however, Intel acquired a minority stake in HERE (Intel, 2017*d*), and Mobileye developed HD-maps in-house (Mobileye, n.d.*c*). It is noteworthy that Mobileye leveraged its existing ADAS that were integrated into conventional vehicles (see cases C8 - Bosch, C9 - BMW, C12 - VW) to generate and update HD-maps (HERE, 2016). Mobileye would license the ADS to OEMs (like its current ADAS) and mobility service providers. However, it would also operate an Israeli-based driverless ride-hailing service in a joint venture by 2022 (see case C12 - VW) (Intel, 2018*c*). Meanwhile, Mobileye tested its L4 ADS with modified Ford Fusion (like C1 - Aurora, C4 - Ford Argo AI) as test vehicles in Israel (Scheer, 2018).

9.2.1.7. Case C7 Aptiv

The Irish automotive supplier Aptiv acquired the US-based software company nuTonomy in 2017 (Aptiv, 2018*a*). The acquired company would provide complementary resources in software for AD, AD test vehicles in a TaaS environment in Asia, intellectual property, as well as additional human resources (scientists, engineers, PhDs) to accelerate the time-to-market. Moreover, Aptiv entered into a partnership with the supplier Mobileye (see case C6 - Intel-Mobileye, L4 ADS turnkey solution for TaaS) in 2016 (Clark et al., 2016). Aptiv and Mobileye had mainly the same motives in order to collaborate (see section 9.2.1.6). In 2019, Aptiv additionally entered into a non-exclusive joint venture with the South Korean OEM Hyundai to develop SAE L4 ADS for ride-hailing services by 2022 (Fox et al., 2019). Aptiv contributed its L4 AD technology, and employees specialized in AD technology, whereas Hyundai contributed $ 1.6 B of cash and additional engineering resources (Fox et al., 2019). That would fund the joint venture *"for a* *number of years"* (Fox et al., 2019, par. 193). Typical of R&D partnerships (see section 6.1.3 on technology sourcing), it was identified that this would reduce the risk, costs, and uncertainty and provide additional resources for the development of ADS. With regards to HD-maps, the archival analysis did not reveal any information. Aptiv, however, invested in two companies specialized in the development of lidar sensors. Like C4 - Ford Argo AI and C5 - GM Cruise this happened in late 2017 (Delphi Automotive PLC, 2017; Aptiv, 2017). Furthermore, like most other cases, the investment aimed at reducing unit costs while guaranteeing usability in the automotive segment (Delphi Automotive PLC, 2017). In contrast to most other cases, Aptiv did not want to develop and operate a driverless transportation-as-a-service platform (Lache et al., 2018). The company deployed a limited amount of AVs (modified BMW 5 series that would be replaced with Chrysler Pacificas (like C1 - Aurora and C2 - Waymo), and Hyundai vehicles following the Aptiv-Hyundai joint venture) via an established partner platform in the US, and a fleet of Renault Zoes in Singapore to test the ADS in a commercial environment that is similar to that of Aptiv's customers (Zhaki, 2019; Cardinal, 2020).

9.2.1.8. Case C8 Bosch

The German automotive supplier Bosch developed the L4 ADS together with the OEM Daimler (case C10) to enable driverless TaaS offerings (Daimler, 2017*c*). Bosch provided sensors, computing units, actuators, and the software for the hardware (Daimler, 2019*d*). The potential drivers that led to the partnership could not be identified. In addition, Bosch developed L3 ADS for private passenger vehicles (Ebberg, 2018). Bosch acquired a minority stake in "HERE" HD-maps and would like to participate with its radar sensors and cameras that were integrated into conventional vehicles to create and update HD-maps (like case C6 - Intel-Mobileye) (Etheridge, 2018; Bonte and Hodgson, 2018). Bosch and Daimler used HERE HD-maps for their ADS (BoschGlobal, 2018), and Bosch developed its own lidar sensors and, similar to C2 - Waymo, counted on economies of scale to reduce unit costs (Ebberg, 2020). Bosch announced the transformation into a mobility service provider (Bosch, 2018*d*) (like C5 - GM Cruise), and developed and tested together with Daimler its L4 ADS in an autonomous ride-hailing service in the US (Daimler, 2019*e*; Abuelsamid, 2019*a*). Bosch, furthermore, showed a concept car of a purpose-built shared AV that could be used in driverless TaaS (Fischer, 2018).

9.2.1.9. Case C9 BMW

The German OEM BMW developed, together with an OEM (C11 - FCA), technology companies (C6 - Intel-Mobileye), and automotive suppliers an L3-L4 ADS. In contrast to most other cases, the motivation to reduce risk, costs, and uncertainty was not identified in the BMW-Intel-Mobileye partnership in 2016. BMW required the resources of the technology companies and automotive suppliers (e.g., compute platform, vehicle intelligence, computer vision, driving policy, HD-maps)

(Aviram et al., 2016). It is noteworthy that Mobileye's HD-maps were required as a resource although BMW and Intel also invested in HERE HD-maps. Daimler, in contrast, also invested in HERE but used HERE HD-maps in the ADS (see C10 - Daimler). It could be argued that this is the difference between a buyer-suppliers relationship (BMW-Intel-Mobileye) and a partnership concentrated on single partners (Bosch-Daimler). BMW's partnership also required T1 suppliers for the integration of the system (Clark et al., 2016). Working together in a partnership should accelerate the time-to-market. The OEM FCA joined the open partnership in 2017 and supported the development with financial and engineering resources (case C11 - FCA) (Intel, 2017*b*). The output would be an L3 ADS (highway pilot) for private passenger vehicles and a test fleet of L4 ADS (urban) for driverless TaaS offerings in 2021 (BMW Group, 2019*b*). Besides, BMW entered into a partnership with Daimler in 2019 (see case C10 - Daimler). The goal would be to develop the second generation of the L3 highway pilot by 2025 (Daimler, 2019*c*). Like most other cases, a potential driver to enter into the partnership was the reduction of risk, costs, and uncertainty as well as the use of complementary resources to accelerate the time-to-market. BMW, Daimler, and Audi acquired the provider of HD-maps HERE in 2015, and BMW and VW participated in Mobileye's road data crowdsourcing initiative because both firms had conventional vehicles on public roads with Mobileye's L2+ ADAS that would enable the joint data collection (Audi, 2016; Continental, 2018; Bosch, 2018*e*; HERE, 2016; Mobileye, 2020). With regard to lidar sensors, BMW's venture capital unit invested in a lidar developer (BMW, 2018*d*). However, Aurora (C1) acquired the company. Thus, BMW would buy lidar sensors on the market (Magna, 2018). BMW and Daimler merged their mobility services intending to achieve a significant amount of users to be able to compete against bigger established competitors (BMW, 2019*a*). They would use their driverless vehicles on those mobility platforms (BMW, 2019*a*). The SAE L4 ADS that was expected to be tested in 2021 would be required to operate driverless vehicles in the mobility service joint venture.

9.2.1.10. Case C10 Daimler

The German OEM Daimler developed both L3 and L4 ADS (Mercedes-Benz, 2019; Ebberg, 2018). The L4 ADS was developed together with Bosch (Daimler, 2019*d*). In this partnership that started in 2017, Daimler worked on the system integration and helped with its vehicle expertise (Daimler, 2019*d*). The firms would develop sensor algorithms and sensor fusion, motion control, path planning, and IT for the operation of autonomous vehicles together (Daimler, 2019*d*). The potential drivers that led to this partnership could not be identified. Besides, Daimler entered into a partnership with BMW to develop the second-generation L3 highway pilot for the use in private vehicles (Daimler, 2019*c*). In line with most partnership cases in this analysis, both firms argued that potential cost savings (50 %) for each partner were the key benefit of this partnership (Daimler, 2019*c*). Daimler, furthermore, acquired the US-based software and robotics firm TORC, a developer of ADS for trucks, in 2019 (TORC, 2019). This is in line with initiatives of other OEMs (Ford, GM, and VW) that also invested in software companies. The potential drivers that led to this acquisition, as well as the anticipated integration into the Daimler group, could not be identified. However, Daimler announced a shift of resources from driverless ride-hailing services in urban areas to driverless hub-to-hub truck services due to technical difficulties and uncertainties concerning the autonomous ride-hailing business model (Daimler, 2019*b*). This conclusion about autonomous trucks was also mentioned in C2 - Waymo. This means that Daimler would focus on the use of ADS on highways (L3 in private vehicles and L4 in trucks). Nonetheless, Daimler and Bosch started testing their L4 ADS in a ride-hailing service for employees with modified Mercedes S-Class vehicles in California (Daimler, 2019*d*). With regards to HD-maps, Daimler would use HERE maps in the Daimler-Bosch partnership as both firms have invested in HERE (BoschGlobal, 2018). It is noteworthy that the data analysis did not reveal a road data crowdsourcing partnership. In contrast, other firms that invested in HERE would leverage their existing fleet of vehicles on public roads. Daimler would acquire lidar sensors on the market (BusinessWire, 2017*b*) and did not show intentions of in-house lidar sensor development. However, Daimler developed the ADS together with a T1 supplier that announced the development of lidar sensors. Thus, Daimler would not need in-house capabilities for lidar sensors. TORC, the ADS company that Daimler recently acquired argued that economies of scale and increased competition would make more capable lidar sensors available at lower costs in the future (TORC, 2017).

9.2.1.11. Case C11 FCA

The Italian-American OEM FCA joined the BMW-Intel-Mobileye partnership in 2017 to develop L3 ADS for private passenger vehicles (Intel, 2017*b*). The identified potential drivers behind the collaboration were the reduction of risk, costs, and uncertainty as well as the complementary resources in the partnership between OEMs, technology companies, and automotive T1 suppliers. Furthermore, FCA argued that a great number of individual solutions would destroy value, and BMW's excellent reputation was a motivation to enter into the partnership (Veltri et al., 2017). While BMW also developed L4 ADS, FCA would integrate Aurora's and potentially Waymo's L4 ADS for the driverless use of FCA vehicles in logistics (Wester, 2018; Aurora Team, 2019*a*). FCA was the only case where no L4 ADS development could be identified. It was argued that L3 ADS would be needed quickly to be competitive in the private vehicle market (Wester, 2018). The analysis of secondary data did not reveal initiatives towards HD-maps or lidar technology. It could be argued that FCA would not require those resources because the firm sources L3 ADS together with BMW and license Aurora's L4 ADS that comes with the entire array of sensors.

9.2.1.12. Case C12 VW Audi AID

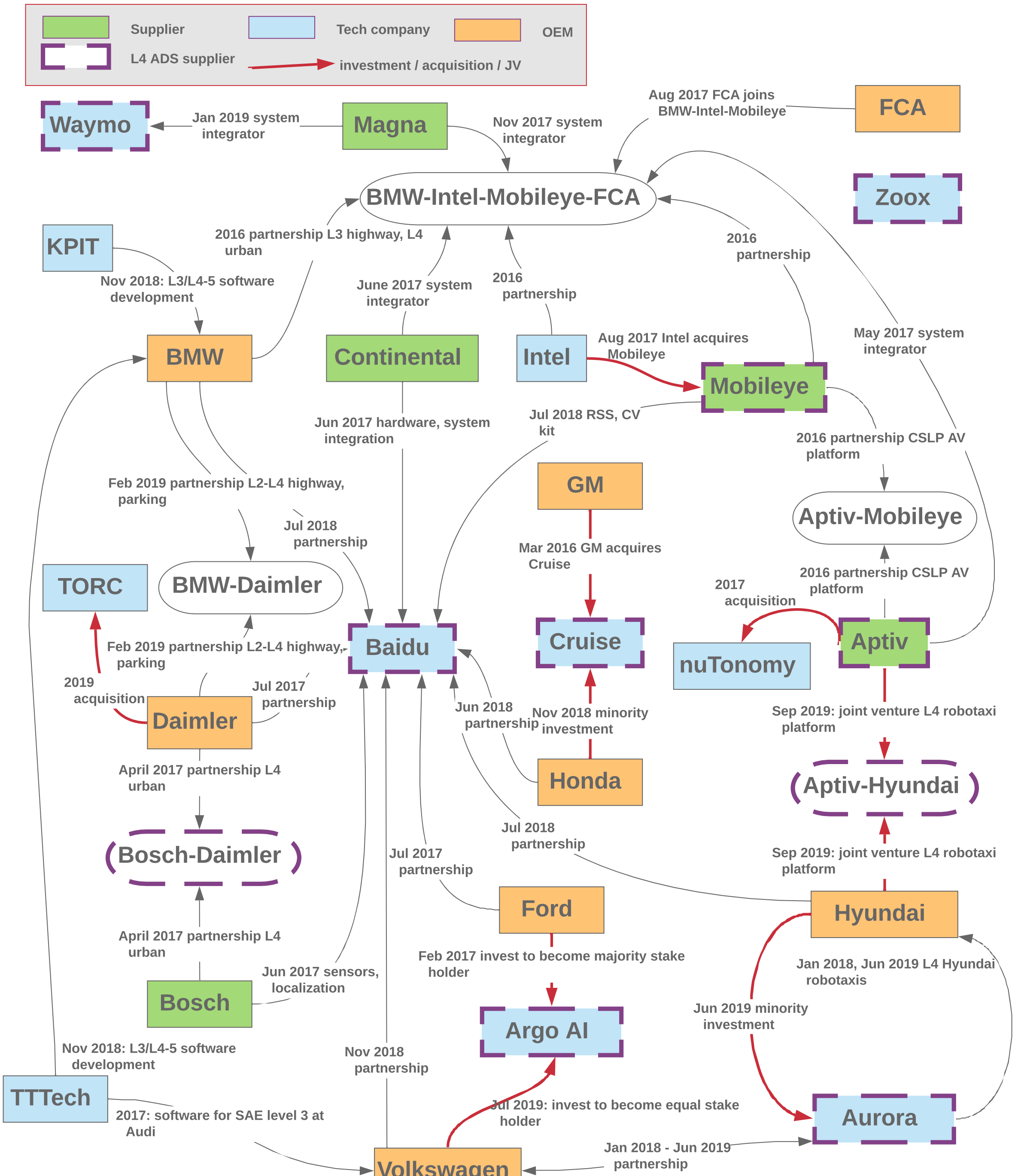
The German OEM Volkswagen founded its AID unit that developed L4 ADS in 2017 (Audi, 2018). AID had comparatively few employees in relation to the other cases, especially considering VW's size. However, the AD unit would be integrated into Argo AI following VW's investment in 2019 (Salesky, 2019*a*). The analysis of potential drivers that led to the investment showed that they were mostly different compared to the other investment/acquisition cases. Before the investment in Argo AI, VW wanted to acquire another software company (C1 - Aurora). However, the offer was declined and, therefore, VW invested in Argo AI primarily to get access to strategically crucial autonomous driving technology. VW thus followed the OEMs Ford, Cruise, and Daimler by investing in a software company that developed L4 ADS. Furthermore, Ford and VW would benefit from sharing R&D costs. This potential driver, however, was primarily identified with partnership cases. VW's Audi division invested in HERE (Becker, 2015) (like C6 - Intel-Mobileye, C8 - Bosch, C9 - BMW, C10 - Daimler) and participated in Mobileye's road data crowdsourcing partnership with its existing fleet of vehicles on the road (Mobileye, 2020). VW would like to establish its own autonomous ride-hailing service (Volkswagen, 2017) that would most likely depend on Argo AI for the availability of the ADS as a key resource. Moreover, VW entered into a joint venture with Intel-Mobileye to develop and operate an autonomous ride-hailing network in Israel. In this JV, Mobileye would contribute the ADS, whereas VW would contribute the vehicles (Intel, 2018*c*).

9.2.2. Cross-Case Synthesis

Following the analysis of each case in section 9.2.1, in this section, the cases are analyzed to find similarities and discrepancies, and an attempt was made to explain them.

All investigated new entrants in the automotive BE which are essentially the software companies argued against the development of L3 ADS. The companies argued that the use of L3 ADS-equipped vehicles would be unsafe due to the possible but unexpected und sudden interventions human drivers have to make in case of a system failure or when leaving the operational design domain. In addition to the safety concerns, those systems would not enable the execution of driverless transportation-as-a-service business models. This is because L3 ADS still require a human driver that must be able to intervene within seconds; only L4/5 ADS can be used without a human driver (SAE International, 2018). Thus, the author argues that software companies would not even have a use case for L3 ADS despite selling/licensing the system to OEMs.

Incumbent firms in the automotive BE, in contrast, required L3 ADS that would resemble the further development of current L2+ driver assistance systems (ADAS). This would appeal to the firm's existing customer base and serve as an optional feature in the industries' current business model. Among all cases, no incumbent firm finally argued against the use of L3 ADS-equipped vehicles. Most incumbent firms, additionally, developed L4 ADS. There was only one case where the development of L4 ADS could not be identified (C11 - FCA). In that case, the OEM required L3 ADS quickly for its private vehicle customers and therefore entered into an R&D partnership that would accelerate time-to-market compared to turnkey solutions of automotive suppliers (Clark et al., 2016). The same company considered licensing the L4 ADS of the "leading" software companies Waymo and Aurora for transportation services (Wester, 2018; Aurora Team, 2019*a*).



Sources: Magna - Waymo: Waymo Team (2019); FCA - BMW-Intel-Mobileye-FCA: Intel (2017b); KPIT - BMW: BMW (2018c); BMW - BMW-Intel-Mobileye-FCA: Intel (2016a); Continental - BMW-Intel-Mobileye-FCA: Continental (2016); Intel - BMW-Intel-Mobileye-FCA: Intel (2016a); Intel - Mobileye: Intel (2018a); Mobileye - BMW-Intel-Mobileye-FCA: Intel (2016a); GM - Cruise: General Motors Company (2018); Mobileye - Aptiv-Mobileye: Clark et al. (2016); BMW - BMW-Daimler: Daimler (2019c); BMW - Baidu: BMW (2018b); Continental - Baidu: Continental (2017); Mobileye - Baidu: Intel (2018b); Daimler - BMW-Daimler: Daimler (2019c); Daimler - Baidu: Daimler (2018a); Daimler - TORC: TORC (2019); Honda - Cruise: General Motors (2018a); Honda - Baidu: Furukawa (2018); Aptiv - Aptiv-Mobileye: Clark et al. (2016); Aptiv - BMW-Intel-Mobileye-FCA: Intel (2017a); Aptiv - Aptiv-Hyundai: Fox et al. (2019); Aptiv - nuTonomy: Aptiv (2018a); Daimler - Bosch: Daimler (2017c) Bosch - Baidu: Bosch (2017c); Ford - Baidu: Ford (2018a); Ford - Argo AI: Ford (2017a); Hyundai - Aurora: Aurora Team (2019d) TTTech - BMW: BMW (2018c); TTTech - VW: TTTech (2019); VW - Argo AI: Volkswagen (2019a); VW - Aurora: Volkswagen (2018a); VW - Baidu: Volkswagen (2018b);

Figure 13.: ADS-related relationships (consists of findings that were identified as relevant by the author, own creation)

Figure 13 depicts the sourcing strategies with regards to the development of automated driving systems. It shows the major partnerships and investments that were identified during the data analysis. It visualizes the high degree of interconnectedness among suppliers and OEMs. Furthermore, it is observable that software companies did not require R&D partnerships for the core of their ADS, whereas OEMs and suppliers entered into partnerships and acquired software companies. Nonetheless, companies in all cases hired a significant amount of skilled employees. Thus, following our definition in section 6.1.3, there was no case where the company followed a make-related technology sourcing approach. Furthermore, as Figure 13 shows, multiple attempts (partnerships) to develop the ADS were commonly identified. For example, it was argued that *"[...] creating multiple attempts to make this technology is a good thing, it reduces risk and enables to accelerate this type of innovation [...]"* (Clark et al., 2016, par. 55) and referred to the complexity of the AD BE that would require partnerships between firms of different types.

The case analysis showed partnerships of different types for the development of ADS between OEMs and suppliers in any combination. Apart from the BMW-Intel-Mobileye partnership, the desire to reduce risk, costs and uncertainty was identified as the potential main driver that led to partnerships. Furthermore, leveraging complementary resources of partners with the desire to accelerate time-to-market was commonly found as potential drivers in the investigated cases. The roles of BE actors in the partnerships did not reveal meaningful patterns, other than automotive suppliers that contribute with their sensors. Besides, partnerships between developers of ADS did not prevent firms from acquiring software companies that developed ADS, as Daimler's acquisition of TORC showed. However, this move was accompanied by a change of company strategy with regard to ADS applications.

The case analysis showed that most OEMs invested in US-based software companies. The companies that acquired software companies wanted to achieve a leading position in the autonomous driving BE to be able to participate in the driverless mobility service market. They acquired the technological resources (mostly digital and human resources) that enable the execution of the new business model. C12 with VW's investment in Argo AI was an outlier as the identified potential drivers were mostly different. However, the investment differed significantly in the acquired stake compared to the other acquisitions. All of those initiatives mean that no OEM had the resources available to the firm that were required to develop the ADS alone. Thus, the aim was to acquire the resources to get access to the automated driving system as a key resource.

Among the OEMs in the investigated cases, only BMW and FCA as members of the BMW-Intel-FCA partnership did not invest in a (US-based) ADS developer. As the autonomous driving timeline in Figure 14 shows, BMW committed to the partnership at a time when potential acquisition candidates (software company competitors that got investments from OEMs, e.g., C1 - Aurora, C4 - Argo AI) were not even founded. This means that there could have been a lack of suitable companies. Ford, for example, acquired Argo AI only three months after its foundation. Furthermore, it was argued that BMW made substantial financial commitments in this buyer-supplier partnership, which is atypical of the potential drivers identified in most other partnership cases that

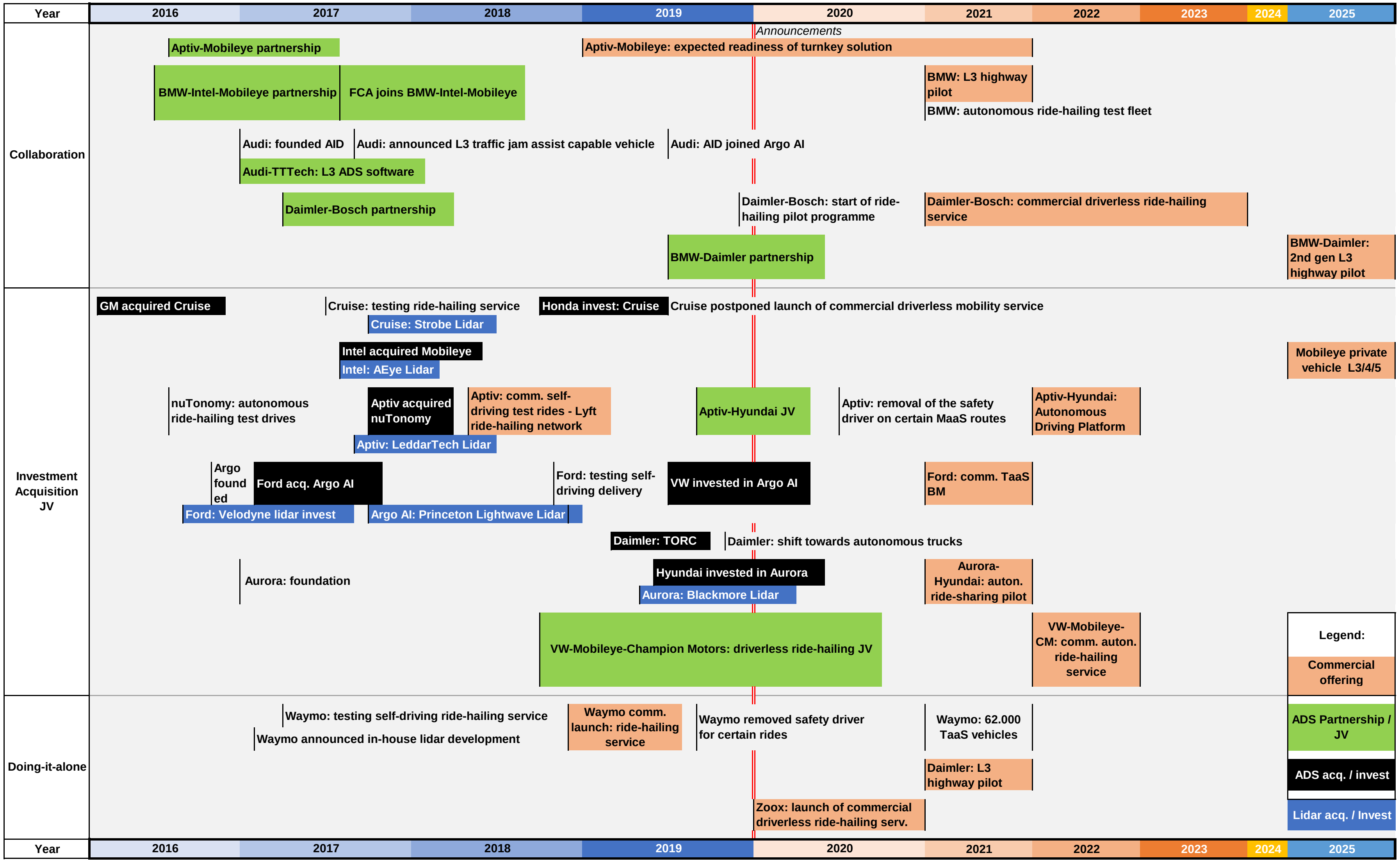


Figure 14.: Autonomous Driving Timeline (includes major AD-related events as identified as relevant by the author) Sources: see Table 24 on page 110 (own creation)

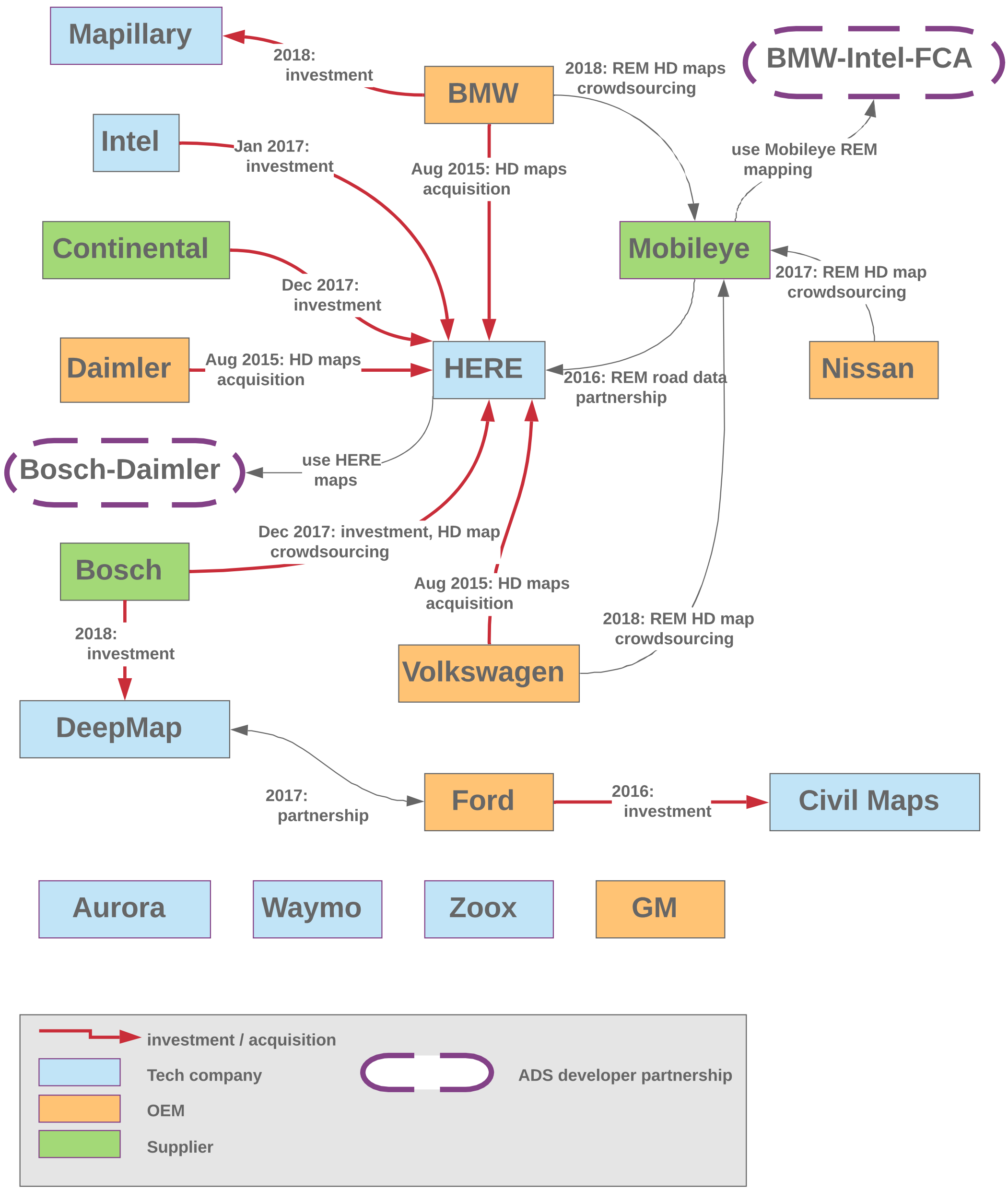
were mainly about the reduction of risk, costs, and uncertainty. Nonetheless, it remains an open question of whether BMW wanted to acquire a software company specialized in ADS development. FCA, as discussed before, did not want to develop L4 ADS and would license the system from software companies.

A higher degree of interconnectedness between firms could also be identified with regards to HD-maps, as Figure 15 shows. However, only the incumbent firms in the automotive BE used the joint approach. Most noticeably, the incumbent and predominantly European firms that were affiliated with HERE HD-maps and also used Mobileye's L2+ ADAS collaborated and leveraged their existing fleet of production vehicles on the street. They used the sensors that were required for their L2+ driver assistance systems to (automatically) generate and update HD-maps (crowdsourcing). A noteworthy exception is GM that did not participate in HD-map crowdsourcing, even though the company used Mobileye's L2+ ADAS (Mobileye, 2020). However, GM did not invest in HERE and did not use Mobileye's maps in its L2+ ADAS-equipped vehicles (Abuelsamid, 2019*b*). The case analysis showed that technology firms, in general, developed their own HD-maps. Moreover, the software companies that were not affiliated with OEMs did not have the existing resources (a large number of L2+ ADAS-equipped vehicles on public roads) to participate in crowdsourcing initiatives.

The importance of lidar sensors as a component of automated driving systems was identified in every case. However, the pace and initiatives towards this sensor technology differed between cases. Software companies and suppliers tend to focus on in-house development of lidar sensors. OEMs that developed the ADS in partnerships, on the other hand, did not develop lidar sensors. This could be due to the presence of automotive T1 suppliers in their partnerships that developed lidar sensors. As visualized in the autonomous driving timeline in Figure 14, there was a spike of lidar-related investments and in-house development announcements in 2017. Mobileye, in contrast, only recently announced the formation of an in-house group that focused on lidar technology, as the company wanted to use its key resources in computer vision to develop a camera-centric ADS first, and a second radar- and lidar-centric ADS for redundancy later (Ben-Gedalyahu, 2019). The major concerns within cases were mostly about the sensor costs, but also about the sensor functionality. The software companies C1 - Aurora, C2 - Waymo, the software companies of OEMs C4 - Argo AI, C5 - Cruise, and the suppliers C7 - Aptiv, C8 - Bosch, tried to address the sensor cost issue with in-house development. In contrast, OEMs that developed the ADS in a partnership did not begin with in-house development of lidar. Other cases argued that the increased capacity and the increased competition on the market would eventually reduce the costs per unit and improve the sensor's capabilities.

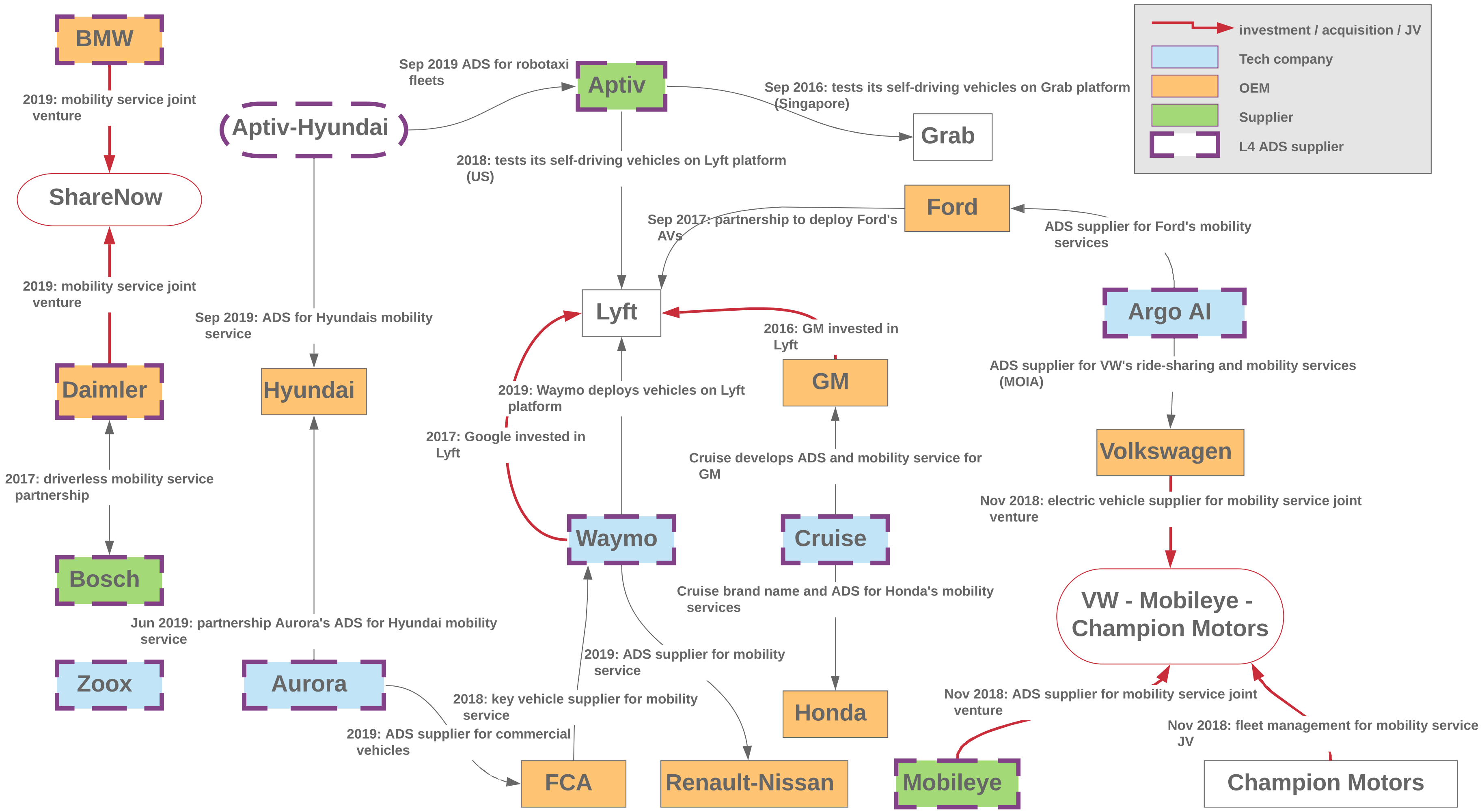
There is a strong tendency that companies that acquired a developer of ADS early on also developed HD-maps and lidar sensors in-house.

For testing of ADS on public roads, all developers integrated their ADS in conventional vehicles. OEMs and software companies with OEM investments used the vehicles supplied by the OEM.



Sources: BMW - Mapillary: BMW (2018e); BMW - Mobileye: Mobileye (2018); BMW - HERE: Becker (2015); Mobileye - HERE: HERE (2016); Mobileye - BMW-Intel-FCA: Aviram et al. (2016); Intel - HERE: Intel (2017d); Continental - HERE: Etheridge (2018); Daimler - HERE: Becker (2015); HERE - Bosch-Daimler: BoschGlobal (2018) Nissan - Mobileye: Mobileye (2018); Bosch - HERE: Etheridge (2018); Nissan - Mobileye: Mobileye (2018); Bosch - DeepMap: Bosch (2018c); VW - HERE: Becker (2015); VW - Mobileye: Mobileye (2018); Ford - DeepMap: Luo (2017); Ford - CivilMaps: BusinessWire (2016); Aurora: Aurora Team (2019e); Waymo: Weddeling (2018); Zoox: Zoox (2018b); GM: Bergen (2018);

Figure 15.: HD-maps relationships (consists of findings that were identified as relevant by the author, own creation)



Sources: ShareNow: BMW (2019a); Daimler-Bosch: Daimler (2019e); Zoox: Korosec (2019); Aptiv-Hyundai: Aptiv (2019c); Aurora-Hyundai: Aurora Team (2019d); Aurora-FCA: Aurora Team (2019a); Aptiv-Lyft: Aptiv (2018b); Waymo-Lyft: Krafcik (2019), Fiegerman (2017); FCA-Waymo: Wester (2018); Waymo-Renault-Nissan: Renault Nissan Mitsubishi (2019); Aptiv-Grab: Grab (2016); GM-Lyft: GM (2016); GM-Cruise: General Motors (2018a); Cruise-Honda: General Motors (2018a); Ford-Lyft: Campbell (2017); Argo AI: Larkin et al. (2019a); VW-Mobileye-Champion Motors: Intel (2018c);

Figure 16.: Mobility service relationships (consists of findings that were identified as relevant by the author, own creation)

Interestingly, the other companies mainly used or switched to using two vehicle models, either Chrysler Pacifica or Ford Fusion. It was commonly identified that SAE Level 4 ADS-equipped vehicles were used to test the ADS with its software and hardware and to explore the use of self-driving vehicles in mobility services at the same time. This included the test of autonomous ride-hailing and delivery services (C2 - Waymo, C4 - Ford Argo AI, C7 - Aptiv, C8 - Bosch, C10 - Daimler).

Across all cases, driverless mobility services would be the only way to commercialize L4 ADS in the near future. Despite the common goal of using the ADS in product-service systems, the cases differed in the resources, activities, and partnerships the companies would offer and use. Two companies, which would be suppliers of L4 ADS (Aurora and Aptiv), specialized in digital services that would be required for the use of their ADS in L4 ADS-equipped vehicles. The other companies planned to operate their L4 ADS-equipped vehicles at scale in driverless mobility services. Commercializing ADS in a product-service system requires a number of key resources, ranging from L4 ADS-equipped vehicles to the digital platform to connect the passengers, goods, and vehicles. This would also lead to platform-related key activities in future business models. As shown in Table 13 and Figure 16 and discussed before, the ADS as a key resource was either developed in-house, together with partners, or licensed from other companies. Figure 16 furthermore shows that companies developed and consequently operated the (digital) mobility platform either in-house, together with the ADS development partners or as a joint venture. It is noteworthy that two operators of smaller mobility services, Daimler and BMW, merged their services to achieve scale as digitally-enabled services tend to follow the winner-takes-most paradigm (Amit and Zott, 2001). At the same time, at least two companies (Waymo, Ford) would also use established mobility platforms to deploy their ADS-equipped vehicles in a product-service system environment. Despite the agreement among cases that L4 ADS would be embedded in a use-oriented product-service system environment, the case analysis showed that the exact procedure to develop and use those product-service systems differed significantly across cases. This could be due to the early phase of the business ecosystem.

10. Discussion and Outlook

Based on the results of three studies on the leading companies with regards to the development and commercialization of autonomous vehicles (see section 7.1), the automotive suppliers Aptiv and Bosch, the OEMs BMW, Daimler, FCA, Ford (Argo AI), GM (Cruise), and Volkswagen, and the technology companies Aurora, Intel (Mobileye), Waymo, and Zoox were investigated as cases in this multiple-case study.

The cross-case synthesis identified that most long-established actors developed SAE level 3 ADS that enable conditional driving automation for the use in private vehicles (e.g., highway pilot). None of the new entrants (Aurora, Waymo, Zoox), in contrast, signaled an interest in L3 ADS development and exclusively developed L4 ADS that enable high driving automation for the use of mobility services. Among the analyzed cases, most incumbent firms in the automotive business ecosystem developed L4 ADS for mobility services, too. The development of different levels of driving automation by firms of different types shows the two-way correlation between technological development and the business model (Baden-Fuller and Haefliger, 2013). The incumbent firms in the automotive BE had the legacy of the existing vehicle sales business and thus required improved features for high-end customers. However, as discussed in section 6.2.2, system costs would not justify the integration of L4 ADS in vehicles for private customers yet. New entrants in the business ecosystem, in contrast, would not have a significant use case for L3 ADS and thus developed L4 ADS that enable the use of driverless vehicles according to SAE International (2018). The BE actors in all cases would use L4 ADS in product-service systems such as driverless transportation-as-a-service offerings first. However, this conclusion that almost all BE actors in the investigated cases developed L4 ADS could be skewed due to the case study case selection and the underlying studies.

The findings that incumbent firms in the automotive industry develop systems that are improvements of current L2+ ADAS for their existing high-end customers would concur with the principles of sustaining innovation, as discussed by Christensen (2016). This was described as the evolutionary route that leads from current ADAS to ADS in private vehicles (Zetsche, 2015). The case analysis showed that smaller firms were about to challenge the established businesses in higher levels of driving automation. Nonetheless, both incumbent and new entrants were identified at developing L4/5 systems. However, the categorization of driverless vehicles as disruptive innovation would be beyond the scope of this thesis. Besides, the identification of disruptive innovation is only possible ex-post (Christensen, 2006).

Among the cases, different initiatives were identified for the development of the automated driving system: *buy*, and *hybrid* approaches as well as *doing-it-alone*, *concentration on single partners*, and *open strategic partnering*. It was commonly identified among cases that all leading actors in the field of autonomous driving hired a significant amount of skilled employees. Veugelers and Cassiman (1999, p. 77) argued that hiring of skilled employees embodies a buy-strategy. Thus, no firm followed a clear make-strategy. It also means that none of the companies in the analyzed cases already had all the required resources to develop the ADS available to the firm (Cruz-Cázares et al., 2013).

It is noteworthy that the software companies (Aurora, Waymo, Zoox) followed the *doing-it-alone* approach. Based on obtained data, they neither entered into R&D partnerships to develop the ADS nor acquired major ADS developers. Furthermore, those companies were relatively new, especially compared to the established OEMs and suppliers. As shown in Table 13 on page 71, those companies were typically smaller in size compared to their long-established competitors with different origins in the automotive industry. Thus, smaller and newer firms were able to execute technological innovation strategies more easily compared to their older and bigger rivals. Previous studies showed that a smaller firm size puts companies not necessarily at a disadvantage. It was argued that smaller companies could excel in the early phase of a high-tech business ecosystem where in-depth knowledge of skilled employees could outrank great financial resources of large firms, especially if the industry was dominated by large firms (Acs and Audretsch, 1987) such as the automotive business ecosystem (Iansiti and Levien, 2004*b*).

It could be argued that the autonomous driving BE is in an early phase. There were still no autonomous vehicles deployed at scale, and publicly available information on autonomous vehicle testing was scarce and unreliable as described in section 7.2. Moore (1996*a*) described that the initial phase of a BE is about creating a value proposition around innovation and getting the most important customers, suppliers, and channels. Johnson et al. (2008) argued that the value creation elements must be in place to be able to deliver the value proposition. While the firm's intentions on offering a value proposition could be identified in this thesis (e.g., highway pilots, or TaaS at lower costs), the value creation elements on which the value proposition depended were not ready. Most noticeably, none of the identified actors announced the completion and commercial readiness of their ADS. However, one sign that would indicate the upcoming transition into the second phase (expansion) of the BE was identified. Moore (1996*a*) described the expansion phase as the competition between the "old" and the "new" ecosystem, and scaling requires a significant amount of financial resources. Waymo announced the acquisition of up to 62.000 vehicles for its autonomous ride-hailing service by 2021 (Wester, 2018) as shown in the autonomous driving timeline in Figure 14 on page 84. This step would require a significant amount of financial resources, and it would also mean that the company was about to scale up its operations and thus about to enter the second phase of the BE.

In essence, the new firms had technological key resources of AD (AI, software, robotics) at their core in an environment that was dominated by large firms. This could explain the relative success of new entrants in the field of autonomous driving. However, the development of automated driving systems requires a significant amount of financial resources (Clifford, 2020). For example, it was identified that the reduction of R&D costs was one of the main drivers that led to partnerships. The companies that followed the *doing-it-alone* approach, therefore, had financial support from its owners or investors. Studies and competitors considered Google's Waymo to be the leading company in the field of autonomous driving (PTOLEMUS, 2019; Wester, 2018; Reuters, 2018*b*). The company would profit from the combination of Google's highly-specialized resources in AD-related key technologies (AI, software engineering, digital platforms) as well as Google's vast financial resources (PTOLEMUS, 2019). In addition, Waymo was leading in the metrics on public road testing in California, as described in section 7.2.

It was identified that technology companies (mostly software companies) that developed self-driving systems were the target of acquisitions and investments by OEMs, suppliers, and technology companies. They were then used as a working base to develop the ADS for the investors. The qualitative content analysis in section 9.1.1 on the potential drivers for investments and acquisitions identified that firms primarily wanted to achieve a leading position in the BE. They wanted key resources in autonomous driving technologies, most noticeably engineers and scientists with expertise in artificial intelligence, teams with previous experience in automotive safety systems, as well as experienced management. In addition, firms argued that they acquired resources that would complement their existing capabilities. The results are mainly in line with previous findings that firms favor technology acquisitions when the target technology fundamentally differed from the firm's core competencies (Kurokawa, 1997), as most acquisitions were performed by OEMs that entered into the technology sphere, and Intel's acquisition to enter into the automotive segment. Furthermore, as the number of actors in the AD BE in section 7.2 showed, rivalry among firms was intense, with more than 60 companies testing their AVs in California. This is consistent with what has been found in previous studies described by Kurokawa (1997) that an increasing number of competitors favors external technology acquisitions. In addition to the presented drivers that typically lead to technology acquisitions, this thesis identified the potential revenue opportunities that come with the technology in use as a potential driver to pursue a buy-strategy with the aim to accelerate time-to-market.

R&D partnerships as hybrid approaches to develop the ADS were identified between OEMs, suppliers, and technology companies. The qualitative content analysis in section 9.1.2 identified that the two most common potential drivers were the reduction of risks, costs, and uncertainty as well as leveraging complementary resources to develop the ADS. This is in line with previous findings that the firm's awareness about costs and the associated risks and the combination of being in high-tech industries is in favor of entering into an R&D partnership (Veugelers and Cassiman, 1999). Leveraging complementary resources is in accordance with the literature on R&D partnerships that partnerships result from the need for resources and *"firms must have resources to get resources"* (Eisenhardt and Schoonhoven, 1996, p. 137). Furthermore, in a majority of analyzed cases, the joint initiatives should accelerate time-to-market, and companies argued that they found the right partner for this project of high complexity. Often, companies already had partnerships with target firms in the past. This is in line with previous studies that partnerships are a way to speed up the development (Veugelers and Cassiman, 1999; Kurokawa, 1997) and firms that worked with R&D partnerships in the past are more likely to enter into new partnerships (Eisenhardt and Schoonhoven, 1996).

Both investments and partnerships as external technology sourcing initiatives are in line with previous studies that firms favor external technology sourcing initiatives when the target technology fundamentally differs from the firm's core competencies (Kurokawa, 1997). In this analysis, the initiatives of software companies were mainly limited to hiring skilled employees, whereas especially OEMs but also automotive suppliers additionally acquired software companies that developed ADS or entered into R&D partnerships.

An increased willingness to enter into partnerships was identified with regards to HD-maps. Incumbent firms in the automotive business ecosystem used their existing fleet of vehicles on public streets to participate in road data crowdsourcing partnerships to automatically generate and update HD-maps. Again, this means that firms already had certain resources to get resources (Eisenhardt and Schoonhoven, 1996, p. 137). Therefore, the new entrants in the automotive business ecosystem did not participate in those partnerships. It furthermore concurs with previous studies that the use of AVs on public roads would be a noteworthy source of data that provides insights into society (Loebbecke and Picot, 2015). Besides data collection activities, it was argued that the operation of self-driving vehicles requires highly accurate road information (HD-maps) (Zhao et al., 2018). This means that developers of ADS should offer digital key activities such as map updates throughout the lifetime of the vehicles.

Previous studies argued that the costs and functionality of lidar sensors would be limiting factors with regards to autonomous vehicles and that economies of scale and future research would enable the commercial use of lidar technology (Zhao et al., 2018). These findings were supported in this study. It was identified that both costs and functionality of lidar sensors were a significant concern of ADS developers. For example, it was argued that the lidar sensors acquired from suppliers were more expensive than the car itself (Waymo Team, 2017). Most technology companies and suppliers, therefore, moved to in-house development to overcome these issues. This was mainly done by acquiring a developer of lidar sensors. Furthermore, it was identified that mass production and economies of scale would be used to reduce the unit costs.

The case analysis identified an agreement among the investigated BE actors that higher levels of driving automation (SAE level 4/5) would be used for driverless mobility services. This study, therefore, supports previous findings that mobility platforms would be required to commercialize systems capable of higher levels of driving automation (Skeete, 2018). Considering the opportunities that highly automated vehicles enable on the one hand, and the costs of those systems on the other hand, the findings are in line with previous studies that the business model influences the development (Baden-Fuller and Haefliger, 2013) and determines the economic output of technology (Chesbrough and Rosenbloom, 2002; Christensen, 2016). Furthermore, this development of use-oriented product-service systems would follow the trend towards a service-dominated economy (Godlevskaja et al., 2011) and that manufacturing companies go downstream the value chain and combine services and product offerings (Oliva and Kallenberg, 2003, p. 160). The key-enabler of those use-oriented product service systems would be the automated driving system that must be available to the firm. The case analysis did not reveal a characteristic pattern towards the development and use of mobility platforms for autonomous vehicles. Mixed approaches were identified, ranging from developing the mobility service in-house, leveraging established partner platforms, developing the mobility service in a partnership or joint venture, or multiple attempts at the same time. This could be the balancing act between being in control of the commercialization platform, reaching customers, and influencing the amount of captured value. This balancing act would be typical of a new business model (Chesbrough, 2010; Teece, 2010), especially given the circumstances that the autonomous driving business ecosystem is in an early phase. Especially the development of the ADS and the service platform would be a type of vertical integration that represents the role of physical dominators in a business ecosystem. This means that providers could dominate value creation and value capture (Iansiti and Levien, 2004*b*). This is of particular interest in a market where digitally-enabled services tend to follow the winner-takes-most paradigm (Amit and Zott, 2001)

With the ADS and the mobility service platform as key resources in the business model, this would lead to new key partnerships and key activities. Key partnerships could be required for the operation of autonomous vehicles (e.g., fleet management in the Mobileye-VW-Champion Motors joint venture, or Aptiv using its autonomous vehicles on the Lyft ride-hailing platform), as well as for the sourcing of the ADS (e.g., FCA would license Aurora's ADS, or key partnerships like the Daimler-Bosch cooperation to develop and operate autonomous vehicles).

In essence, companies mainly required the digital resources to develop the automated driving system, and partially performed in-house sourcing of specific components like lidar to further accelerate and optimize the development. The entire system would then be required as a key resource in future business models to offer driverless transportation-as-a-service. Incumbent firms in the automotive business ecosystem additionally required more affordable solutions (L3 ADS) as a key resource for their existing customers that would be served using their existing and established business model.

One limitation of this thesis is that the selection of cases was mainly based on the results of studies that did not separate between actors that develop SAE level 3 and SAE level 4/5 ADS. Both systems would enable and require different use cases. Furthermore, as illustrated in the autonomous driving timeline in Figure 14 on page 84, the introduction of L3 and L4 ADS to different market segments differs significantly in time. The studies mainly focused on SAE level 4 ADS that would be used in driverless mobility services. Thus, developers of ADS for the private vehicle market were neglected. Another limitation of this thesis is that Chinese developers were not investigated due to limited insights into the Chinese market. However, Chinese developers were described as contenders for the leading role in the autonomous driving business ecosystem

(PTOLEMUS, 2019). They, therefore, could be investigated in future studies. Future studies could also investigate the specific roles of actors in the autonomous driving business ecosystem. This was not possible in this study due to the early phase of the investigated business ecosystem, as roles within a BE are determined in the leadership phase (Moore, 1996*a*). Furthermore, only a fraction of the key components of autonomous vehicles were covered in this thesis. The focus on the ADS as a digital system, as well as HD-maps, transportation-as-a-service platforms, and lidar sensors, could skew the results in favor of the more digitized value creation aspects of firms. These issues could be addressed in future studies. In addition, further research could perform expert interviews to get a more holistic and in-depth perspective. Furthermore, this study showed that the autonomous driving business ecosystem is dynamic and in an early phase. This means that changes in initiatives in the near future are likely.

Part IV.

Appendix

A. Testing of Autonomous Vehicles in California, Report Year 2015

Table 14.: Testing of autonomous vehicles in California, report year 2015

Organization	**km 2015**	**disengagements 2015**	**km / disengagement 2015**	**Sources**
Waymo	682 895	341	2002,62	(Google, 2015*b*)
Volkswagen	24 051	260	92,50	(Herzfeld & Rubin, 2015)
Aptiv	26 814	405	66,21	(Delphi, 2016*b*)
Nissan	2 209	99	22,31	(Nissan, 2015)
GM	384	103	3,73	(Cruise, 2016)
Daimler (Mercedes-Benz)	2 798	1031	2,71	(Mercedes-Benz, 2015)
Bosch	1 504	625	2,41	(Bosch, 2015)

B. Testing of Autonomous Vehicles in California, Report Year 2016

Table 15.: Testing of autonomous vehicles in California, report year 2016

Organization	**km 2016**	**disengagements 2016**	**km / disengagement 2016**	**Sources**
Waymo	1 023 330	124	8252,66	(Waymo, 2017*b*)
BMW	1 026	1	1026,00	(BMW, 2016*c*)
Ford	949	3	316,33	(Ford, 2016*b*)
Nissan	6 596	28	235,57	(Nissan, 2016)
GM	15 732	181	86,92	(Cruise, 2016)
Aptiv	5 029	178	28,25	(Delphi, 2017)
Daimler (Mercedes-Benz)	1 083	336	3,22	(Mercedes-Benz, 2016)
Bosch	1 581	1442	1,10	(Bosch, 2017*b*)

C. Testing of Autonomous Vehicles in California, Report Year 2017

Table 16.: Testing of autonomous vehicles in California, report year 2017

Organization	**km 2017**	**disengagements 2017**	**km / disengagement 2017**	**Sources**
Waymo	567 365	63	9005,79	Waymo (2017*c*)
GM	211 911	105	2018,20	(Cruise, 2017)
Nissan	8 057	24	335,71	(Nissan, 2017)
Zoox	3 612	14	258,00	(Zoox, 2017)
Drive.ai	9 861	93	106,03	(Drive.ai, 2017)
plus.ai	7 354	97	75,81	(Plus.ai, 2018)
Baidu	3 173	48	66,10	(Baidu, 2017)
Aptiv	2 914	81	35,97	(Aptiv, 2018*d*)
WeRide	5 458	162	33,69	(WeRide, 2018)
Autox	7 615	954	7,98	(AutoX, 2018)
NVIDIA	817	109	7,50	(NVIDIA, 2017)
Bosch	2 339	598	3,91	(Bosch, 2017*a*)
Daimler (Mercedes-Benz)	1 750	842	2,08	(Mercedes-Benz, 2017)
Apple	1 348	7074	0,19	(Apple, 2018*a*)
AIMotive	764	0	0,00	(AImotive, 2018)

D. Testing of Autonomous Vehicles in California, Report Year 2018

Table 17.: Testing of autonomous vehicles in California, report year 2018

Organization	**km 2018**	**disengagements 2018**	**km / disengagement 2018**	**Sources**
Waymo	2 021 331	114	17730,98	(Waymo, 2018*a*)
GM	720 376	86	8376,47	(Boniske, 2018)
Zoox	49 509	16	3094,31	(Zoox, 2018*a*)
Pony.AI	26 322	16	1645,13	(Pony.ai, 2018)
Nuro	13 009	17	765,24	(Nuro, 2018)
Nissan	8 807	26	338,73	(Nissan, 2018)
Baidu	29 117	88	330,88	(Baidu, 2018)
AIMotive	5 516	17	324,47	(AImotive, 2018)
Autox	36 548	119	307,13	(AutoX, 2018)
WeRide	25 226	89	283,44	(WeRide, 2018)
Roadstar	12 132	43	282,14	(Roadstar, 2018)
Aurora	52 879	379	139,52	(Aurora, 2018)
Drive.ai	7 428	54	137,56	(Drive.ai, 2018)
plus.ai	17 406	199	87,47	(Plus.ai, 2018)
Phantom AI	6 677	200	33,39	(Phantom AI, 2018)
NVIDIA	6 665	206	32,35	(NVIDIA, 2018)
BMW	66	9	7,33	(BMW, 2018*a*)
Daimler (Mercedes-Benz)	2 815	1194	2,36	(Mercedes-Benz, 2018)
Apple	128 337	69510	1,85	(Apple, 2018*b*)
Uber	43 289	70165	0,62	(Uber, 2018)
Aptiv	462	0	0,00	(Aptiv, 2019*a*)

E. Description of BE Actor Origins

Table 18.: Description of BE actor origins (see Figure 9 on page 44

BE Actor	Origin	Description
Aptiv	Automotive supplier / technology	Automotive supply chain: *"Electrical & wiring products, body controls, infotainment, safety & autonomous driving technologies "* (Automotive News, 2018, p. 9). Aptiv acquired the technology company nuTonomy, a developer of ADS (Aptiv, 2018*a*).
Bosch	Automotive supplier / technology	Automotive supply chain: *"Powertrain solutions; chassis systems controls; electrical drives, car multimedia, electronics & steering systems, battery technolog"* (Automotive News, 2018, p. 11).
Mobileye-Intel	Automotive supplier / technology	The technology company Intel acquired Mobileye, the automotive supplier of ADAS with strengths in computer vision (Intel, 2017*c*).
BMW	OEM	Vehicle manufacturer (BMW Group, 2019*a*)
Daimler	OEM	Vehicle manufacturer that only recently acquired an ADS developer and did not reveal information about the firm's integration (TORC, 2019)
FCA	OEM	Fiat Chrysler Automobiles is a vehicle manufacturer (FCA, n.d.)
VW	OEM	Volkswagen is a vehicle manufacturer that only recently (July 2019) invested in a developer of ADS (Argo AI) and had its dedicated ADS development unit prior to the investment (Volkswagen, 2019*a*).

Table 18.: Description of BE actor origins (continued)

BE Actor	Origin	Description
Aurora	Technology	Aurora was categorized as a technology company due to its origins in capabilities such as robotics, computer vision, and machine learning (Aurora, n.d.*b*), although the firm aimed at being a supplier of ADS in the future (Aurora, n.d.*a*)
Waymo	Technology	Waymo originated from Google's self-driving car project and was established with expertise in artificial intelligence, machine learning, and deep learning (Dolgov, 2018).
Zoox	Technology	Zoox was founded *"with expertise in vehicle and aerospace engineering, safety, robotics, artificial intelligence, machine learning, and product design"* (Zoox, 2018*b*, p. 7).
Ford Argo AI	Technology / OEM	Argo AI was founded with resources in robotics and AI (Argo AI, 2017) and developed the ADS for its majority investors Ford and VW and therefore acted as supplier (Larkin et al., 2019*a*). To show the business background and the origins of the company, Argo AI was not categorized as an automotive supplier.
GM Cruise	Technology / OEM	Cruise was acquired by the OEM GM and acted as a supplier of ADS (General Motors Company, 2018) but the firm's background was categorized as technology company due to its capabilities in software engineering and expertise in AI (Perry, 2019). Due to the strong affiliation with the OEM, GM-Cruise was categorized as being both a technology firm and OEM.

F. Investments in Control Platform Technology Companies

Table 19.: Investments in control platform related technology providers

Year	Investor	Company	Type	Investment	Scope	Source
2014	Google	DeepMind	acquisition	approx $ 400 M	AI	Chowdhry (2014)
2015	Aptiv	Ottomatika	acquisition	$ 16 M	ADS developer	Aptiv (2018*a*)
2015	Bosch	TrunkTech	investment		CV and AI for AVs	GLP (2019)
2015	Bosch	AImotive	investment		ADS developer	Vancura (2016)
2015	Bosch	Prophesee	investment		CV and AI for AVs	Vancura (2016)
2016	Intel	Prophesee	investment		CV and AI for AVs	Prophesee (2016)
2016	Intel	Movidius	acquisition		CV and DL	Intel (2016*b*)
2016	Ford	SAIPS	acquisition		ML and CV for ADS	Ford (2016*a*)
2017	GM	Nauto	investment		AI in vehicles	Kharpal (2017)
2017	BMW	Nauto	investment		AI in vehicles	Kharpal (2017)
2017	Bosch	Graphcore	investment		AI chip and software	Toon (2017)
2017	Daimler	Momenta	investment		ADS developer	Lin (2017)
2018	GM	Algolux	investment		perception and CV for AVs	Algolux (2018)
2018	Daimler	ThinCi	investment		automotive DL and CV chip	DENSO (2018)
2019	BMW	Recogni	investment		AI for sensing in AVs	DiIanni (2019)

Table 19.: Investments in control platform related technology providers

Year	**Investor**	**Company**	**Type**	**Investment**	**Scope**	**Source**
2019	BMW	Cartica AI	investment		AI for sensing in AVs	Save et al. (2019)

G. Investments in Lidar Technology

Table 20.: Investments in lidar technology

Year	Investor	Company	Type	Investment	Source
2015	Delphi (Aptiv)	Quanergy	investment	$ 3 M	(Delphi, 2016*a*)
2016	Ford	Velodyne	investment	$ 75 M, 9.2 %	(Ford Motor Company, 2017)
2017	Intel	AEye	investment		(BusinessWire, 2017*a*)
2017	Aptiv	Innoviz	investment	$ 15 M	(Aptiv, 2018*a*, 2017)
2017	Aptiv	LeddarTech	investment	$ 10 M	(Aptiv, 2018*a*)
2017	Ford Argo AI	Princeton Lightwave	acquisition		(Salesky, 2017)
2017	GM	Strobe	acquisition		(General Motors, 2018*b*)
2018	BMW	Blackmore	investment		(BMW, 2018*d*)
2018	Bosch	ABAX Sensing	investment		(Bosch, 2018*b*)
2019	Aurora	Blackmore	acquisition		(Aurora Team, 2019*b*)

H. Investments in HD Map Technology

Table 21.: Investments in high definition maps technology

Year	Investor	Company	Type	Investment	Source
2015	Audi, BMW, Daimler	HERE	acquisition	€ 2.8 B	(Becker, 2015)
2016	Ford	Civil Maps	investment		(BusinessWire, 2016)
2017	Intel	HERE	investment	15 %	(Intel, 2017*d*)
2018	Bosch	HERE	investment	5 %	(Etheridge, 2018)
2018	BMW	Mapillary	investment		(BMW, 2018*e*)
2018	Bosch	DeepMap	investment		(Bosch, 2018*c*)

I. Investments in Digital Mobility Platforms

Table 22.: Investments in digital platforms

Year	Investor	Company	Type	Capital	Info	Source
2011	GM	RelayRides	investment		car sharing platform	(GM, 2011)
2012	Daimler	mytaxi	investment		taxi app	(Daimler, n.d.)

Table 22.: Investments in digital platforms (continued)

Year	Investor	Company	Type	Capital	Info	Source
2013	Google	Uber	investment	$ 258 M	mobility as a service platform	(Geron, 2013)
2013	Daimler	Flixbus	investment		bus transport platform	(Trimborn, 2013)
2013	Daimler	Blacklane	investment		chauffeur portal	(Daimler, 2013*b*)
2014	Daimler	Ridescout	acquisition		mobility platform provider	(Daimler, 2014)
2014	Daimler	mytaxi	acquisition		taxi app	(Daimler, n.d.)
2015	Daimler	GlobeSherpa	acquisition		mobile payments and ticketing	(Rogoway, 2015)
2015	BMW	Moovit	investment		real time timetable platform	(BMW, 2015*b*)
2015	BMW	ZIRX	investment		on-demand parking and car services	(BMW, 2015*a*)
2016	GM	Lyft	investment	$ 500 M, 9 %	mobility as a service platform	(GM, 2016)
2016	BMW	RideCell	investment		software for mobility as a service	(BMW, 2016*a*)
2016	BMW	Scoop	investment		mobility as a service platform	(BMW, 2016*b*)
2016	VW	Gett	investment	$ 300 M	mobility as a service platform	(Volkswagen, 2017)
2016	Daimler	Hailo	acquisition		taxi app	(Daimler, n.d.)
2016	Daimler	Taxibeat	acquisition		taxi app	(Daimler, n.d.)

Table 22.: Investments in digital platforms (continued)

Year	Investor	Company	Type	Capital	Info	Source
2017	Aptiv	nuTonomy	acquisition	$ 454 M	automated mobility on demand solutions for automakers	(Aptiv, 2018*a*)
2017	BMW	bus.com	investment		bus rental platform	(BMW, 2017)
2017	Daimler	Clevertaxi	acquisition		taxi app	(Posirca, 2017)
2017	Daimler	Careem	investment		mobility as a service platform	(Parasie and Boston, 2017)
2017	Daimler	Turo	investment		car sharing	(Daimler, 2017*b*)
2017	Daimler	Via	joint venture		mobility as a service platform	(Daimler, 2017*d*)
2017	Daimler	Chauffeur Prive	acquisition		mobility as a service platform provider	(Daimler, 2017*a*)
2017	Google	Lyft	investment		mobility as a service platform	(Fiegerman, 2017)
2018	Daimler	Taxify	investment		mobility as a service platform	(Steuer, 2018)
2018	Ford	Autonomic	acquisition		architecture for mobility services	(Ford, 2018*b*)
2018	Ford	Transloc	acquisition		technology for mobile services	(Ford, 2018*b*)
2018	Intel	Moovit	investment		mobility as a service platform	(Intel Capital, 2018)

Table 22.: Investments in digital platforms (continued)

Year	Investor	Company	Type	Capital	Info	Source
2018	Bosch	SPLT	acquisition		mobility as a service platform	(Bosch, 2018*a*)
2018	BMW	DriveNow	acquisition	€ 209 M, 50 %	acquisition of remaining shares, car sharing platform	(Reuters, 2018*a*)

J. Characteristics of Investigated Cases (Sources)

Table 23.: Sources of Table 13 on page 71 (Characteristics of Investigated Cases)

Table Row	Sources
Foundation (unit investigated)	Aurora (Crunchbase, n.d.*b*), Waymo (Waymo, n.d.*a*), Zoox (Crunchbase, n.d.*d*), Ford Argo AI (Argo AI, n.d.*a*), GM Cruise (Cruise, n.d.), Intel-Mobileye (Mobileye, n.d.*a*), VW Audi AID (Audi, 2018)
Headquartered	Aurora (Crunchbase, n.d.*b*), Waymo (Crunchbase, n.d.*e*), Zoox (Crunchbase, n.d.*f*), Ford Argo AI (Crunchbase, n.d.*a*), GM Cruise (Crunchbase, n.d.*c*), Intel-Mobileye (Intel, 2018*a*; Mobileye, n.d.*b*), Aptiv (Aptiv, 2018*a*), Bosch (Bosch, 2019), BMW (BMW Group, 2019*a*), Daimler (Daimler, 2019*a*), FCA (FCA, 2019), VW Audi AID (Audi, 2019)
Company origins	see section 7.3 and Table 18 on page 100 in the appendix.
Number of employees: Entire company	Aurora (Wolpin, 2019), Waymo (Alphabet) (Alphabet, 2019), Zoox (Zoox, 2019), Ford Argo AI (Ford, 2019*a*), GM Cruise (General Motors Company, 2019), Intel-Mobileye (Intel, 2018*a*), Aptiv (Aptiv, 2019*b*), Bosch (Bosch, 2019), BMW (BMW Group, 2019*a*), Daimler (Daimler, 2019*a*), FCA (FCA, n.d.), VW Audi AID (Volkswagen, 2019*b*)

Table 23.: Sources of Table 13 on page 71 (Characteristics of Investigated Cases) (continued)

Column	Sources
Number of employees: Unit investigated	Aurora (Wolpin, 2019), Waymo (Alphabet) (Efrati, 2019), Zoox (Zoox, 2019), Ford Argo AI (Salesky, 2019*a*), GM Cruise (Wiggers, 2020), Intel-Mobileye (Mobileye, n.d.*a*), Aptiv (Aptiv, 2019*c*), VW Audi AID (Salesky, 2019*a*)
Hired skilled employees	Aurora (Aurora, 2019; Wolpin, 2019), Waymo (Waymo, 2019*b*; Efrati, 2019), Zoox (Zoox, 2019), Ford Argo AI (Salesky, 2019*a*; Cannis et al., 2017), GM Cruise (Perry, 2019), Intel-Mobileye (Mobileye, 2019*a*), Aptiv (Aptiv, 2020), Bosch (Glassdoor, 2019), BMW (BMW, 2019*b*), Daimler (Daimler, 2019*g*), FCA (FCA, 2020), VW Audi AID (autonomous intelligent driving, 2019)
L3 ADS development	Aurora (Urmson et al., 2018), Waymo (Google, 2015*a*), Zoox (Zoox, 2018*b*), Ford Argo AI (Ford Motor Company, 2016; Martinez, 2019), GM Cruise: no information concerning GM's SAE level 3 intentions could be found, Intel-Mobileye (Mobileye, 2020), Aptiv (Aptiv, 2019*d*), Bosch (Ebberg, 2018), BMW (BMW Group, 2019*b*), Daimler (Mercedes-Benz, 2019), FCA (Wester, 2018), VW Audi AID (Audi, 2018)
L4 ADS development	Aurora (Urmson et al., 2018), Waymo (Google, 2015*a*), Zoox (Zoox, 2018*b*), Ford Argo AI (Ford Motor Company, 2016; Martinez, 2019), GM Cruise (GM, 2018), Intel-Mobileye (Mobileye, 2020), Aptiv (Aptiv, 2019*d*), Bosch (Ebberg, 2018), BMW (BMW Group, 2019*b*), Daimler (Ebberg, 2018), FCA (Wester, 2018), VW Audi AID (Audi, 2019)
ADS sourcing: doing-it-alone	see the findings of the data collection in section 8.1.6
ADS sourcing: partnership / JV	the identified R&D partnerships and joint ventures are described in section 8.1.5
Potential drivers (ADS sourcing: partnerships / joint ventures)	the potential drivers of identified partnerships and joint ventures are the result of the qualitative content analysis and are described in section 9.1.2
ADS sourcing: invest / acq.	see Table 5 on page 49
Potential drivers (ADS sourcing: investments / acquisitions)	the potential drivers of identified investments and acquisitions are the result of the qualitative content analysis and are described in section 9.1.1
HD-Maps Sourcing: doing-it-alone	Aurora (Aurora Team, 2019*e*), Waymo (Weddeling, 2018), Zoox (Zoox, 2018*b*), GM Cruise (Bergen, 2018), Intel-Mobileye (Mobileye, n.d.*c*)

Table 23.: Sources of Table 13 on page 71 (Characteristics of Investigated Cases) (continued)

Column	Sources
HD-Maps Sourcing: invest / acquisition	Ford Argo AI (BusinessWire, 2016), Intel (Intel, 2017*d*), Bosch (Etheridge, 2018), BMW (Becker, 2015), Daimler (Becker, 2015), VW Audi AID (Becker, 2015)
HD-Maps Sourcing: R&D partnership	Ford Argo AI (Luo, 2017)
Road data crowd-sourcing partnership	Intel-Mobileye (HERE, 2016), Bosch (Bonte and Hodgson, 2018), BMW (Mobileye, 2020), VW Audi AID (Mobileye, 2020)
LIDAR Sourcing: procurement	Zoox Schubarth (2018), BMW Magna (2018), Daimler: BusinessWire (2017*b*), VW: Lee (2020)
LIDAR Sourcing: doing-it-alone	Waymo (Waymo Team, 2017), Bosch (Ebberg, 2020)
LIDAR Sourcing: invest / acquisition	Aurora: Aurora Team (2019*b*), Ford Argo AI: Ford Motor Company (2017), GM Cruise: General Motors (2018*b*), Intel-Mobileye: BusinessWire (2017*a*), Aptiv: Delphi Automotive PLC (2017); Aptiv (2017), Bosch: Bosch (2018*b*), BMW: BMW (2018*d*)
LIDAR In-house to reduce sensor costs	Aurora (Aurora Team, 2019*b*), Waymo (Alphabet): Waymo Team (2017), Ford Argo AI (Salesky, 2017), Aptiv: Delphi Automotive PLC (2017), GM Cruise: General Motors (2018*b*), Bosch (Ebberg, 2020)
LIDAR In-house to improve functionality	Waymo: Waymo Team (2017), Ford Argo AI (Salesky, 2017)
Development / operation of driverless TaaS	Waymo (Krafcik, 2018), Zoox (Korosec, 2019), Ford Argo AI (Marakby, 2018), GM Cruise (Ammann, 2019), Intel-Mobileye (Intel, 2018*c*), Aptiv (Lache et al., 2018), Bosch (Bosch, 2018*d*; Daimler, 2019*e*; Abuelsamid, 2019*a*), BMW (BMW, 2019*a*), Daimler (BMW, 2019*a*), VW (Volkswagen, 2017)
Development of ADS for TaaS	Aurora (Aurora Team, 2019*c*), Waymo (Waymo, n.d.*b*), Zoox (Somerville, 2018; Welch, 2019; Korosec, 2019), Ford Argo AI (Larkin et al., 2019*a*), GM Cruise (Suryadevara et al., 2018), Intel-Mobileye (Intel, 2018*c*), Aptiv (Fox et al., 2019), Bosch (Daimler, 2017*c*), BMW (BMW Group, 2019*c*), Daimler (Daimler, 2017*c*), VW (Volkswagen, 2019*a*)
ADS sourcing: procurement	FCA (Aurora Team, 2019*a*)
TaaS joint venture	Intel-Mobileye (Intel, 2018*c*), BMW (BMW, 2019*a*), Daimler (BMW, 2019*a*), VW (Intel, 2018*c*)

Table 23.: Sources of Table 13 on page 71 (Characteristics of Investigated Cases) (continued)

Column	Sources
TaaS through partner platform	Waymo (Krafcik, 2019; Fiegerman, 2017), Ford Argo AI (Campbell, 2017), Aptiv (Aptiv, 2018*b*)
Purpose-built shared AV	Zoox (Zoox, 2018*b*), Ford Argo AI (Farley, 2017), GM Cruise (Ammann, 2020), Bosch (Fischer, 2018), VW (Volkswagen, n.d.)

K. Autonomous Driving Timeline (Sources)

Table 24.: Sources of Figure 14 on page 84 (Autonomous Driving Timeline)

Description	**Source**
Aptiv-Mobileye partnership	(Clark et al., 2016)
Aptiv-Mobileye: expected readiness of turnkey solution	(Clark et al., 2016)
BMW-Intel-Mobileye partnership	(Intel, 2016*a*)
FCA joins BMW-Intel-Mobileye	(Intel, 2017*b*)
BMW: L3 highway pilot, autonomous ridehailing test fleet	(BMW Group, 2019*b*)
Audi: founded AID	(Audi, 2018)
Audi: announced L3 traffic jam assist capable vehicle	(Audi, 2018)
Audi: AID joined Argo AI	(Salesky, 2019*a*)
Audi-TTTech: L3 ADS software	(TTTech, 2019)
Daimler-Bosch partnership	(Daimler, 2017*c*)
Daimler-Bosch: start of ridehailing pilot programme	(Daimler, 2019*d*)
Daimler-Bosch: commercial driverless ride-hailing service	(Daimler, 2019*f*)
BMW-Daimler partnership	(Daimler, 2019*c*)
BMW-Daimler: 2nd gen L3 highway pilot	(Daimler, 2019*c*)
GM acquired Cruise	(General Motors Company, 2018)
Cruise: testing ride-hailing service	(Davies, 2017)
Honda invests: Cruise	(General Motors, 2018*a*)
Cruise postponed launch of commercial driverless mobility service	(Ammann, 2019)
Cruise: Strobe Lidar	(General Motors, 2018*b*)
Intel acquired Mobileye	(Intel, 2018*a*)

Table 24.: Sources of Figure 14 on page 84 (Autonomous Driving Timeline) (continued)

Description	Source
Intel: AEye Lidar	(BusinessWire, 2017*a*)
Mobileye private vehicle L3/4/5	(Mobileye, 2020)
nuTonomy: autonomous ride-hailing test drives	(EDB, 2016)
Aptiv acquired nuTonomy	(Aptiv, 2018*a*)
Aptiv: commercial selfdriving rides on Lyft ride-hailing network	(Aptiv, 2018*b*)
Aptiv-Hyundai JV	(Fox et al., 2019)
Aptiv: removal of the safety driver on certain routes	(Sigal, 2019)
Aptiv-Hyundai: Autonomous Driving Platform	(Aptiv, 2019*c*)
Aptiv: LeddarTech Lidar	(Aptiv, 2018*a*)
Argo founded	(Argo AI, n.d.*c*)
Ford acquired Argo AI	(Ford, 2017*a*)
Ford: testing self-driving delivery service	(Korosec, 2018)
VW invested in Argo AI	(Volkswagen, 2019*a*)
Ford: commercial TaaS BM	(Marakby, 2018)
Ford: Velodyne lidar invest	(Ford Motor Company, 2017)
Argo AI: Princeton Lightwave Lidar	(Salesky, 2017)
Daimler acquired TORC	(TORC, 2019)
Daimler: shift of resources from ride-hailing towards autonomous trucks	(Daimler, 2019*b*)
Hyundai invested in Aurora	(Aurora Team, 2019*d*)
Aurora: Blackmore Lidar	(Aurora Team, 2019*b*)
Aurora-Hyundai: autonomous ridesharing pilot fleet	(Aurora Team, 2019*d*)
VW-Mobileye-Champion Motors: driverless ride-hailing JV	(Intel, 2018*c*)
VW-MobileyeChampion Motors: commercial autonomous ride-hailing service	(Intel, 2018*c*)
Waymo: testing self-driving ride-hailing service	(Waymo, 2018*c*)
Waymo announced in-house lidar development	(Waymo Team, 2017)
Waymo: commercial launch of ride-hailing service	(Krafcik, 2018)
Waymo removed safety driver for certain rides	(Chu, 2019)
Waymo ordered up to 62.000 vehicles for TaaS	(Wester, 2018)
Daimler: L3 highway pilot	(Mercedes-Benz, 2019)
Zoox: launch of commercial driverless ride-hailing service	(Korosec, 2019)

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