Chapter 3

Auto and tech companies – the drive for autonomous vehicles

In 2004, the United States (U.S.) Defense Department staged a novel off-road race in the Mojave Desert. The novelty lay in it being open only to driverless or self-drive cars. First prize for winning the "Grand Challenge" over the 240km course was $1 million. Nobody lifted the prize, because nobody finished the race.[1]

But a year later, the Department's Defense Advanced Research Projects Agency (DARPA) staged the competition again and doubled the prize. It attracted dozens of entrants and this time a number completed the course. The desert race was won by "Stanley," an autonomous vehicle (AV) entered by Stanford University, with vehicles from Carnegie Mellon University (CMU) taking second and third places.

The automobile industry has been envisioning self-driving[2] or autonomous vehicles at least since General Motors presented its "Futurama" concept at the 1939 World's Fair. Even in those early days, GM was not the only one dreaming of a self-driving future, and several attempts toward realization of AVs were made in subsequent years. But it is since the mid-2000s that huge advances in robotics and, particularly, artificial intelligence (AI)[3] have begun to turn a long-held aspiration into something closer to reality.

The AV industry is still in its infancy and fully autonomous vehicles (Level 5) are years from reaching the market. Nevertheless, robotics and AI are already reshaping the car industry – so much so that new technologies are posing a significant existential threat to the incumbent automakers. AI, data analytics and a slew of connected devices and components are reformulating the industry's business model toward services and the so-called "platform economy."

Traditional automakers fear being supplanted and reduced to bit-players in their core competency – the making and marketing of cars. To tackle these challenges a menu of options is available to them – from investing in internal knowledge development, recruiting human capital and strategic alliances, to acquisitions of new entrants, or a combination of these.[4] It is not clear which single or combination of the above strategies will yield the most successful results. What is clear though is that neither the incumbents nor the new entrants, on their own, currently have all the required competencies for producing AVs. They either need to join forces or else develop internally the respective skills they now lack.

Against this background, this chapter seeks to analyze current innovation clusters in the automotive industry and understand how AV is affecting the geographical spread and concentration of innovation (see Chapter 1). Understanding the relationship between the new entrants and the incumbents can offer pointers to the evolution of current innovation clusters. How firms react to AV technology will determine which firms will be the market leaders and which regions will be the AV technological hubs.

In the following sections the chapter looks into the contemporary evolution of AV technology and its key players. It also briefly discusses two other related technologies: mobility and connectivity. Next, it explores the impact of AV technology on the automotive industry from two perspectives. First, whether AV technology is changing the nature of innovative collaborations between and within incumbents and entrants. Second, whether it is changing the geography of innovation. It concludes with a discussion on potential positive and negative impacts.

3.1 Definitions

Basic components of a driving automation system

There are three basic functional components of any computer-automated system: monitoring, agency, and action – as depicted in Figure 3.1. Monitoring can be understood as sensing and paying attention, while agency consists of decision-making, and action involves implementing decisions. Furthermore, automated systems can also include various feedback loops, possibly including machine learning.

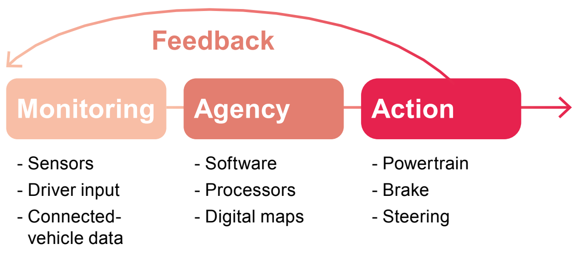
Levels of driving automation

The established Society of Automotive Engineers (SEA) industry standard for terms relating to automated vehicles is *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* (SAE J3016). It was initially published in 2014 and substantially revised in 2018.

The SAE standard introduced and defined six levels of driving automation (Figure 3.2), including level 0 for systems that perform no sustained dynamic driving tasks. Levels 1 and 2 are termed driver assistance and partial driving automation, respectively. The lower levels of automation require the driver to at least actively supervise the driving automation system. Driving automation systems that assume the entire dynamic driving task are classified as SAE levels 3, 4 and 5 and are collectively described as automated driving systems (ADS). While the main focus of this chapter is on level 3+ technologies, in the empirical analysis we do not exclude the historical innovations of the 1980s, 1990s and early 2000s that were the building blocks of modern AV technology.

Core aspects of computer-backed driving

Figure 3.1 Three basic functional components of any computer-automated system



Source: Center for Automotive Research (CAR).

3.2 Technological evolution of the automotive industry

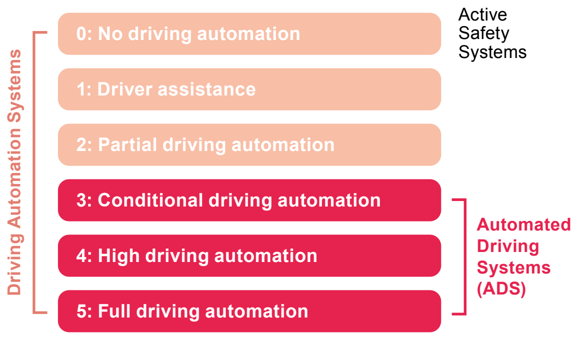
Industry evolution literature[5] divides the life cycle of any given industry into five stages: the introductory embryonic stage, growth, shakeout, maturing and decline. The early stages are ripe with high uncertainty and numerous entries and exits. Later on, the emergence of a dominant design will leave only a handful of firms standing. Names like Sprite, Unito, Wolfe, Angus, Empire do not exactly ring a bell and that is because these early car companies were some of the thousands that exited the industry more than a century ago when the first automobiles started mesmerizing the world.

Until a few years ago, the automotive sector was considered a mature industry with well-established players and for which the key technological questions had been answered in the 1930s.[6] The initial innovations were fundamental as they defined the basic structure of the automobile. These included the development of water-cooled engines placed in the front of the car, shaft-driven transmissions, streamlined bodies and pressed steel frames.[7] The remaining product and process innovation in the years after the Second World War, and particularly after the 1970s, was attributed to rising oil prices, cost pressure arising from intensifying international competition and changes in consumer demands.

At the turn of the millennium this picture changed; the increasing processing power of computers in

From manual to fully automated

Figure 3.2 Six levels of driving automation



Source: Center for Automotive Research (CAR) based on SAE 2016.

conjunction with the widespread adoption of the Internet and, consequently, smartphones, opened several avenues for innovation. Many established old-line industries – like newspapers, the music business, TV and retail – woke up to the waves of technological disruption that advances in software and the hardware side of computer technology had triggered. These affected not only their core competencies, but also their complementary assets – those needed to commercialize and market products – and their distribution channels. Many of these industries were rattled and reshuffled by the digital era. The automotive industry – although with some lag – has not been untouched by the waves. For instance, in 2018, the global electric vehicle fleet exceeded 5.1 million,[8] achieving almost 2.1 percent of market share. This number is expected to increase to around 30 percent by 2030.

Industry life-cycle literature discusses how industries, as they reach maturity, are subject to new technological shocks which can be the seeds for the beginning of a new cycle. Whether the new cycle is actually realized or not depends on the existence of various technological and non-technological competencies. The participants in the new cycle may be from within the same industry or from previously non-competing industries whose competencies meet the technological requirements for entering the new cycle.

Competencies required for the development of AVs have allowed players from the tech industry to enter the automotive sector, with the ultimate goal of creating fully autonomous vehicles that require no driver. The main ingredients for the realization of AVs are both the “V” and the “A.” An AV unit is basically chassis and engine, plus an intelligence that brings full autonomy to the physical aspect. The incumbent automakers’ core competency[9] lies with the “V.” Creating all the software (e.g., artificial intelligence) and hardware elements (e.g., sensors and cameras) required for autonomy – the “A” – is within the core competencies of the tech companies.

The incumbent automakers’ core competencies are mass manufacturing, mechanical engineering and jumping through the thousands of regulatory hoops that lead to the final car being on the road. They are the result of decades of accumulated tacit knowledge – knowledge that is not easily replicable – and know-how. Mastering these competencies is not immediate and straightforward.

New entrants’ technological competencies are in hardware and software, especially the deep-learning and real-time control algorithms needed for vehicle autonomy. They are beyond the spectrum of expertise of most automakers and their suppliers, which have little prior knowledge of them.

Core competencies of the automakers are more or less familiar to most people, but not so the technological waves that are transforming the industry. The following sections will briefly discuss three technological waves that are somewhat related. A fourth wave, electric vehicles, although equally affecting the industry, is not within the focus and scope of this chapter.

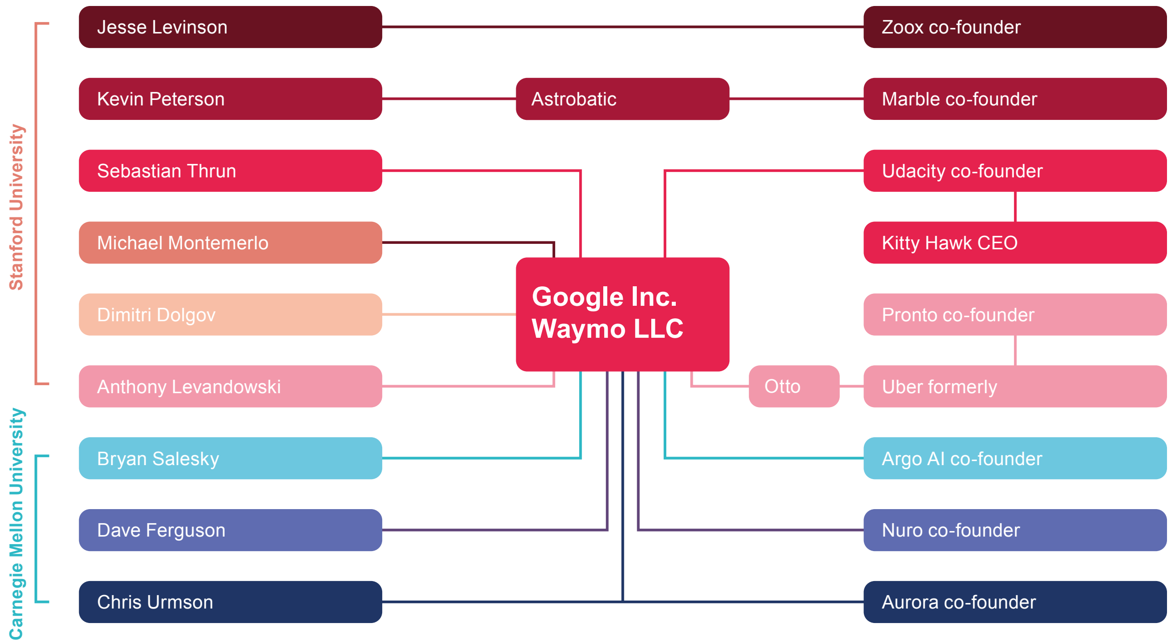
Autonomous vehicles: scientists behind their contemporary rise

The genesis of a set of AV-related startups and tech firms stems from the Massachusetts Institute of Technology (MIT). MIT has been a global leader in robotics technology for decades and has contributed to an agglomeration of firms specializing in AV-related robotics technology in the Cambridge and Boston area. MIT graduates have also produced several robotics-related spin-offs, including a few specifically interested in deploying autonomous vehicles.

In 2007, DARPA held a follow-up competition to its “Grand Challenge,” this time providing a 60-mile course through a simulated urban traffic environment, including interaction with other vehicles and compliance with traffic laws. CMU and Stanford again led the pack,

Grand challenge scientists and their spin-offs

Figure 3.3 Many leading players in today's AV industry started in the DARPA grand challenges



Source: Stanford and Carnegie Mellon University

with CMU's "Boss" taking first place. In all, six teams completed the 2007 course – demonstrating the rapid development of self-driving technology within several universities. Silicon Valley tech giants, notably Google, later recruited many Stanford and CMU participants of the DARPA challenges. (Waymo originated as a self-driving project of Google before it became a standalone subsidiary.) Most of the scientists involved subsequently have founded their own spin-offs, including such tech startups as Aurora, Udacity, Nuro and Argo AI, all of which are at the forefront of the AV industry (see Figure 3.3).

The DARPA challenges have been a milestone in the history of modern AV technology. Although there's no evidence of their causal effect, we observe an increasing trend in innovative activity in AV technology (measured by patents, see Box 3.1) in the mid-2000s that coincides with the DARPA initiatives, with a major innovative spike after 2010. Despite this upward trend, AV technology is still very niche and comprised less than 0.1 percent of total patent filings globally even at the height of that spike in 2016 (see Figure 3.4).

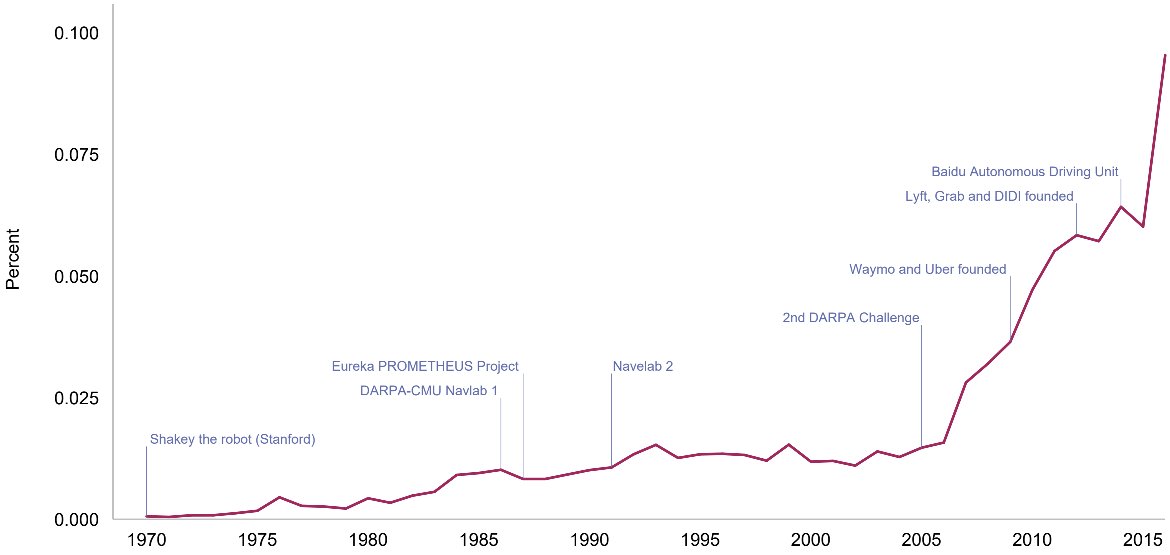
Box 3.1 The AV patent mapping strategy and its limitations[10]

The AV industry is a combination of various technologies applied to a specific use – automating the operation of ground-based vehicles. Thus, search strategies to identify AV-related technologies and scholarship are inherently imprecise and require creativity and several iterations. Defining clear-cut boundaries is very difficult.

Against these limitations, this chapter makes use of technological codes of the Cooperative Patent Classification (CPC), an international system for classifying patent documents. A list of CPC classes that corresponds to the technologies used in AV was compiled. The list was divided into two groups. First, the smaller number of niche classes where it is relatively safe to say the entirety were relevant to AV. Second, the classes that were broader and had patents that may not be relevant to AV. For this second group, a list of keywords was added to the search. These keywords were some permutation

AV technology has taken off since the mid-2000s

Figure 3.4 AV share of all patent first filings and key milestones over time



Source: WIPO based on PATSTAT and PCT data (see Technical Notes).

of autonomous vehicle, car, taxi, truck, etc. These keywords were used to identify the patents that belonged to the selected CPCs and had one of these keywords mentioned either in their patent abstract or title.

The same list of keywords was used to search for scientific publications that had mentioned some permutation of the keywords in their abstracts or titles. From these selected sets of papers a new list of keywords was compiled, for example, predictive cruise control. As publications only have broad categories, with no level of granularity similar to CPCs, the subject-level category was used to eliminate those false positive articles that belonged to areas that are intuitively far from AV technology – microbiology, zoology, etc.

Mobility as a service

Parallel to these efforts, Mobility-as-a-Service (MaaS), which integrates various transport services into a single service available on demand, became a popular concept. Companies like Uber (founded in 2009) and Lyft (founded in 2012) in the U.S. came to fruition. Soon, others with similar business models started popping up all around the globe: Ola Cabs in India (founded in 2010), Grab (founded in 2012) in Singapore and DiDi Chuxing (founded in 2012) in China. These companies provided services like ride-hailing and/or car-sharing. Many of them have expanded their businesses to other services, including deliveries, logistics and bike-sharing.

Uber's former CEO, Travis Kalanick, described the development of "robotaxis" (self-driving taxis) as "existential" to the company. If the future of automobiles is driverless, mobility companies have a vested interest in AV technology for multiple reasons. First, removing the driver from the equation will reduce their costs.

Second, their business model has the potential to change the economics of the automotive industry. The MaaS business model can lead to a reduction of private car ownership and a shift to a more fleet-oriented system, where the revenue model would be based on mileage instead of the number of cars sold. AV technology can enable a system where people buy access to transportation as opposed to owning vehicles. A rough calculation based on the number of cars on the road and their average annual mileage, compared to what mobility companies charge per mile, shows that if all existing cars were to convert to AVs, automakers could make a profit and charge far less than mobility companies.

Third, mobility companies are sitting on abundant data and information about customer behavior and preferences, which would give them a significant advantage in a sales environment that is increasingly about customized and bespoke experience.

Connected vehicles

Another branch of technology that has intertwined with autonomous driving is "connected vehicle technology." A vehicle can be connected without being autonomous, therefore the two terms are not interchangeable and should not be confused. The connected vehicle technologies allow vehicles to communicate with each other and the world around them. They aim to increase efficiency and road safety for both drivers and pedestrians. Popular use cases for connected vehicles are sharing braking data, real-time high-definition maps, road hazards, closure updates, fleet tracking and infotainment. All of these require minimum latency (delay in implementation of commands) and maximum precision in the transmission of data. That is why 5G cellular network technology is becoming the future of autonomous and "connected" vehicles.[11] Several tech companies, notably Huawei, Intel and Ericsson, are exploring this field.

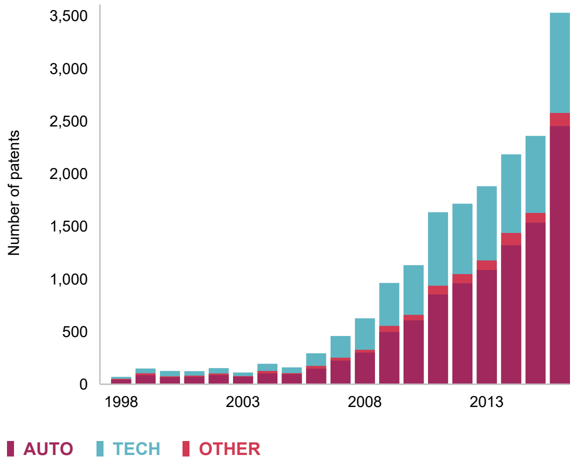
3.3 Technological shift

The sectoral breakdown of AV patenting over time supports the idea that the rise of AI, robotics and mobility services is the main driver of the technological shift. In the years immediately after 2005 almost half of the patents seem to be from the tech sector.[12] However, the traditional auto sector later regained dominance (see Figures 3.5 and 3.6). Not surprisingly, the majority of the patent applicants are companies, roughly 20 percent are individuals and only 10 percent are universities or other public entities.

A quick look at the list of the top applicants[13] in the 1990s shows manufacturing and auto companies. Later lists tell a different story. Google, Qualcomm, Mobileye, Uber, Baidu are not among the usual suspects of the auto industry, but from the mid-2010s they appear in the top 100 AV patent applicants. These top 100 applicants, led by names such as Ford (357 patents), Toyota (320) and Bosch (277) have generated around half of the total patents. Non-automakers also feature in the list of top patent applicants. Google and its AV subsidiary Waymo lie in eighth position, with 156 patents, ahead of automakers like Nissan, BMW and Hyundai. They are followed by other companies like Uber and Delphi, which each have 62 AV patents and are ranked joint 31st.

The rise of AI, robotics and mobility services is the main driver of the technological shift in the mid-2000s

Figure 3.5 Sectoral breakdown of AV-related patents by frequency



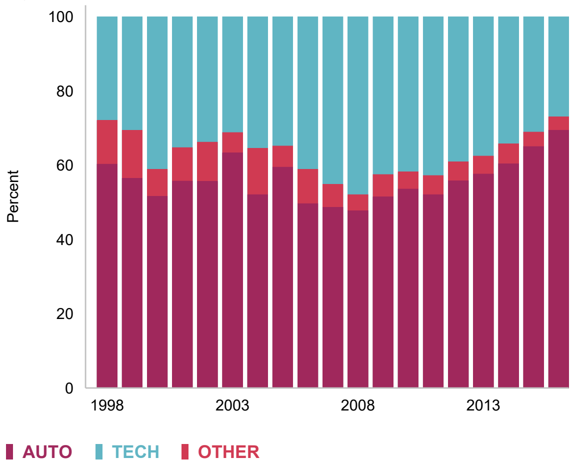
Source: WIPO based on PATSTAT and PCT data (see Technical Notes).

3.4 Competition and cooperation in AV

Thus far it is established that the auto sector is in the early phases of a period of technological disruption, with several new entrants, both from the auto and the tech side, joining this bandwagon. Standardization and regulatory issues are not yet being deeply discussed and there is still no consensus on basic definitions and terminologies. AV technology is an extremely costly endeavor not only in terms of capital but also time. Therefore, players in this industry have high incentives to collaborate with each other to share the risks and costs. But who collaborates with whom? And why? Theoretically speaking, three types of collaboration can form: incumbent automakers with each other, tech firms with each other, or automakers with tech firms.

In the years immediately after 2005, the tech sector comprised almost half of the patents in AV

Figure 3.6 Sectoral breakdown of AV-related patents by share



Source: WIPO based on PATSTAT and PCT data (see Technical Notes).

Collaboration among auto companies

In the face of the AV technological shock, auto companies have an incentive to join forces to share the costs and risks but also defend their market position, which is being threatened by outsiders. The common threat they are facing is "commoditization" of their core competency; that is, becoming simply a supplier of a commodity good, which in this case is a car. The tech companies would be the ones generating the value added and therefore reaping the largest benefits. Global automakers Daimler and BMW announced they would partner in a new long-term partnership to co-develop automated driving technologies.

The joint effort will involve 1,200 technicians from both companies. The technicians will be based at BMW's autonomous driving campus in Unterschleissheim, near Munich, its Mercedes subsidiary's technology center in Sindelfingen, near Stuttgart, and Daimler's testing and technology center in Immendingen in southern Germany. The two companies aim to launch their next-generation, self-driving passenger cars by 2024.[14] Audi, another German automaker, has announced that it is to join forces with them.[15]

While some may be surprised to see long-time foes becoming friends, it is not rare in AV development. The enormous costs of designing and building computer-powered vehicles has already prompted Honda to pool its efforts with General Motors, while Volkswagen is pursuing talks with Ford about an alliance on autonomous cars.

Collaboration among tech companies

Tech firms also would need to collaborate with each other to share the technology's large risks and costs. Most tech firms, especially the smaller startups, occupy niches, focusing on hardware, software, mobility services, connectivity, communications and many more (see Figure 3.7 below). With the exception of Waymo – which develops all its hardware and software stack[16] in-house – no single tech company has the necessary expertise in all these areas. So, collaboration among tech companies is not uncommon. Taiwan-based VIA Technologies Inc. announced in 2018 that it is partnering with AI vision startup Lucid to deliver AI-based depth sensing in dual- and multi-camera devices for use in security, retail, robotics and autonomous vehicles.[17] This is just one of a long list of examples of collaboration between tech companies.

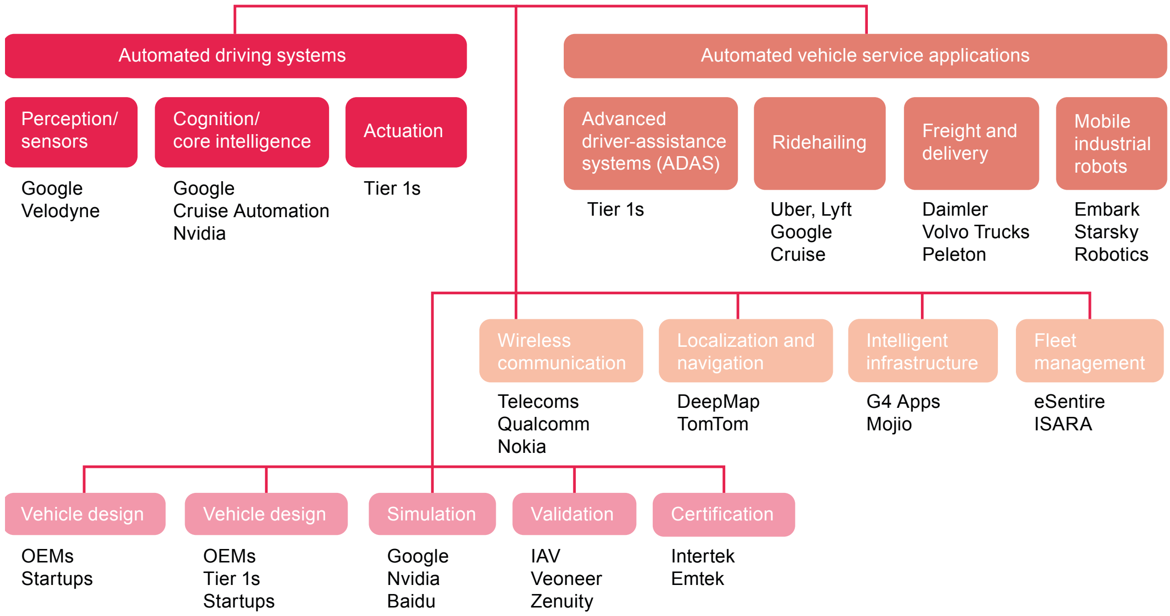
Some tech companies have also decided to give open access – free of cost or other access barriers – to their closely guarded data and technologies. For instance, Waymo has decide to sell one of its three LIDAR sensors – called Laser Bear Honeycomb, which uses a laser to measure distances – to third parties interested in using the technology for purposes other than self-driving cars. Some believe the LIDAR sensor development curve is similar to Moore's Law in computer chips – every 18 months, resolution will double and the price drop by half[18] – so granting open access offers the chance to scale up with reduced costs.

Waymo is making some of the high-resolution sensor data gathered by its fleet of autonomous vehicles available to researchers for free. It is not the first company to release an open dataset. In March 2019, global technology company Aptiv was one of the first large AV operators to publicly release a set of its sensor data. Uber and Cruise, the autonomous division of General Motors, have also released their AV visualization tools to the public.[19]

These decisions are in line with the "open innovation"[20] strategies that firms adopt as a response to highly complex innovative ideas.

Mapping the involvement of AV companies

Figure 3.7 Examples of companies working in various AV technologies



Source: Center for Automotive Research (CAR).

Collaboration between tech and auto companies

AV technology is not rendering the upstream core knowledge of automakers completely obsolete. In fact – at least for now – AV is a type of technological discontinuity that needs the incumbent's core competency to achieve its goal. Research shows[21] that – historically – incumbents can survive the discontinuity if they cooperate with the entrants challenging their core knowledge. In presence of strong "appropriability regimes," the new entrants have the incentive to license out their technologies. The literature[22] defines strong appropriability regimes as environmental factors – legal protection (e.g., patents) or the needed knowledge is difficult to pass on (tacit) or codified – that allow the tech company to recuperate its investment.

AV technology shows characteristics of strong appropriability. This allows the new entrants to cooperate with incumbents while securing their benefits without fear of imitation.[23] By partnering with tech companies, automakers gain a better understanding of the key technologies that are transforming the industry and accelerate the learning process that can keep them competitive in a rapidly changing environment.

While it seems logical for auto companies to collaborate with tech companies, the reverse is not so straightforward. Some might even argue that tech giants do not need auto companies and that they can, and will eventually, directly enter the auto sector.[24] Their argument focuses on the costs. Since IT giants like Alphabet, Amazon and Apple in the U.S. and Alibaba, Baidu and Tencent in China have deep pockets they can easily afford the costs of designing and manufacturing a car. Others do not agree.[25] Excelling at complex mass manufacturing, organizing quality value chains, dealing with complex regulatory issues is neither trivial nor negligible. U.S. energy and automotive company Tesla's financial losses and struggles to keep up with delivery schedules of its Model 3 electric sedan car attest to this issue. The ecosystem in which automakers operate and lobby is their stronghold. Even if the tech companies had the technological capacity to produce cars, they would still have difficulties challenging the current socio-technical regime unless they collaborate with the incumbent automakers.

Therefore, tech companies also have an incentive to collaborate and see where their strengths complement those of the automakers. This division of labor, at least at this stage of the industry, allows each side to focus on what they do best and is the shortest and safest route to AV success.

The types of collaboration outlined are not mutually exclusive and they coexist. The high uncertainty makes firms simultaneously bet on multiple combinations of the three options – “build,” “borrow” and “buy.”[26]

By default, much of the above collaboration may not be captured by patent or scientific publication data. The main reason is that most are formal partnerships and alliances, joint ventures, investments or acquisitions. Out of more than 100 formal collaborations identified,[27] in terms of frequency, the largest share belongs to auto–tech, followed by tech–tech and auto–auto. Finally, a small portion of the collaboration is between tech companies and national or regional government entities. For instance, Detroit-based Quadrobot and the Chinese Postal Service are partnering to produce autonomous delivery vans.

3.5 Role of geography in AV technology

Spread over time

Until a few years ago, no one would have associated places like Boston, San Francisco and Pittsburg, Singapore or Jerusalem with the automotive industry. The more familiar names were Detroit, Toyota City in Japan and Stuttgart in Germany. But advances in robotics and AI as general-purpose technologies,[28] with multi-faceted applications in various fields, have created avenues for new entrants. Naturally, these entrants reside in the main tech hubs, such as the U.S. Silicon Valley and others around the world. However, places like Singapore or Jerusalem, with no history in the automotive sector but with booming and vibrant tech and startup scenes, have become highly active in AV technology.

A historical look at innovative activity in AV shows its geographical evolution and global spread. Figure 3.8 displays the regions involved in patenting[29] and publishing scientific articles concerning AV-related technologies, before and after 2005. Not surprisingly, in the earlier period, regions that traditionally led the auto market also show high patenting activity. But even then, there was significant patenting activity from Silicon Valley and Singapore. The focus in the earlier period was still on areas like advanced driver assistance systems (ADAS) and automated highway systems (AHS), technologies that are not directly related to AI/robotics approaches. These patents were closer to the operations of the traditional automobile and mainly related to level 1 or 2 of driving automation (See Figure 3.2).

In the later years, we observe some developing countries that are not traditional automaking countries also engaging in this technology. The most noticeable change is the emergence of China and India. As discussed earlier, the changing nature of technology can be one explanation of this expansion. The new sets of technologies – AI and robotics – allow for “leapfrogging” of countries/regions with no longstanding ties to the auto-manufacturing sector.[30] Despite this, the top countries involved are still the U.S., Japan, Germany, the Republic of Korea and Sweden, with the U.S. and China latterly being the most active.

When looking at scientific publication we observe that more developing countries in the Middle East, Latin America and Africa – that are not captured in the patenting data – are highly active in generating basic research and scientific articles. Iran would be an example of a country highly active in scientific publication but with almost no patenting presence in this field. Scientific publication data complements patents in giving a better picture of the innovation landscape in AV technology.

3.6 AV innovation, countries and cities

North America

Boston, Massachusetts

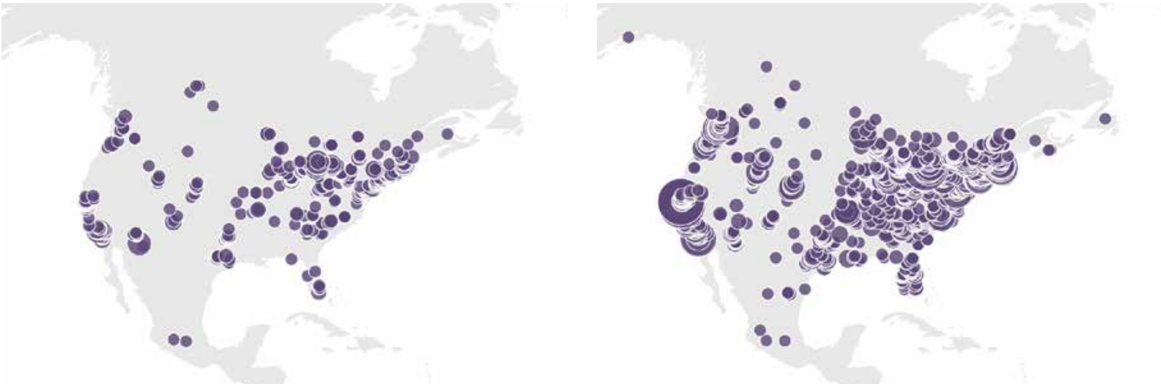
Boston is not a traditional automotive industry cluster. However, the Massachusetts Institute of Technology (MIT) has been a global leader in robotics technology for decades and has contributed to an agglomeration of firms specializing in AV-related robotics technology. One major company that has taken advantage of the Boston robotics cluster for AV development is the Toyota Research Institute (TRI), which located one of its three offices in Cambridge (the other two offices are in Michigan and California). TRI sponsors MIT’s Computer Science and Artificial Intelligence Laboratory (CSAIL), where researchers study various aspects of AI and machine learning applied to vehicle automation.[31]

MIT has produced several robotics-related spinoffs, including a few specifically interested in deploying

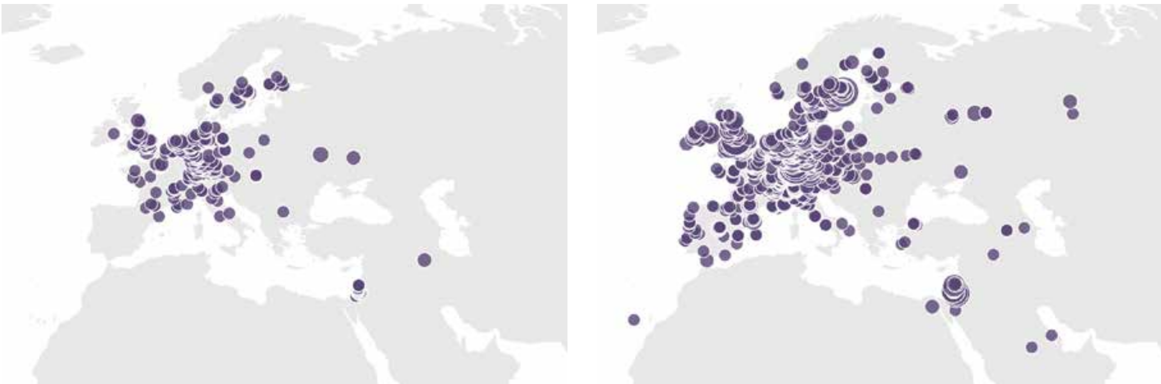
East Asia has become very active in AV technology in recent years

Figure 3.8 Geographical distribution of AV-related patents (this page) and publication (next page) in selected regions, pre- (left) and post-2005 (right)

North America



Europe and the Middle East

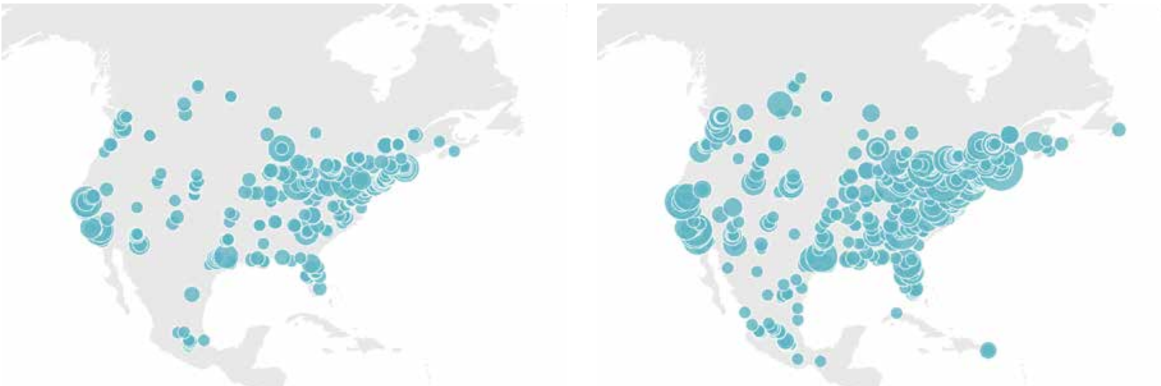


East Asia

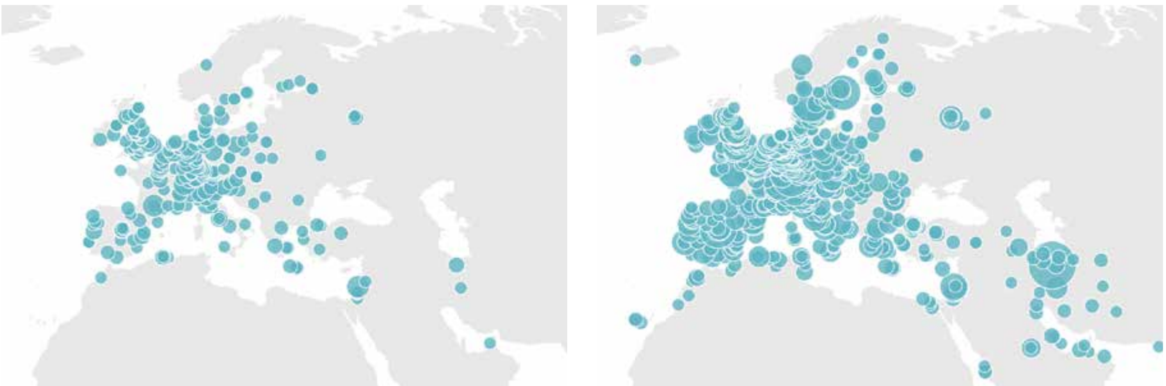
PATENTS SCIENTIFIC PUBLICATIONS

Source: WIPO based on PATSTAT, PCT and Web of Science data (see Technical Notes).

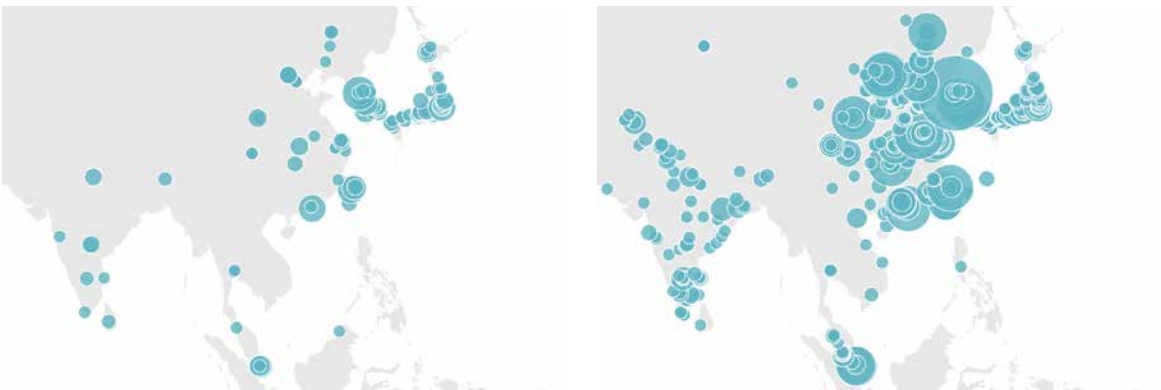
North America



Europe and the Middle East



East Asia



autonomous vehicles. One of these, nuTonomy, was purchased in 2017 by Aptiv – a global tier-1[32] automotive supplier historically tied to Detroit and General Motors.[33] Aptiv maintains a technology center in Boston, along with centers in Pittsburgh and California.[34] nuTonomy is running trials in Boston and Singapore, where the state Economic Development Board has taken a stake in the company.[35] Another MIT spinoff, Optimus Ride, has partnered with multiple Silicon Valley and automotive firms to deploy low-speed, self-driving shuttles in defined geo-fenced routes.[36]

Detroit, Michigan

Detroit is the historical center of the North American automotive industry. General Motors and Ford maintain headquarters and multiple research centers in the Detroit metropolitan area, as do several international automakers (Fiat Chrysler Automobiles (FCA), Hyundai/Kia and Toyota) and dozens of large automotive suppliers. Nearly all automakers involved in the North American market have some presence in the Detroit area.

Michigan is not a historical locus for robotics. However, it is among the top areas worldwide for research, development, design and manufacturing of advanced automotive systems. While Detroit-based firms have opened regional offices in robotics hubs, such as Pittsburgh, Boston and Silicon Valley, AV-focused startups have opened offices near Detroit to leverage the local expertise in engineering and validating robust automotive-grade systems. The automotive focus of the technology is also leading to increased investment in software development facilities in the Detroit area, including significant investments by Ford, GM and Toyota.

Waymo – perhaps the most advanced autonomous vehicle developer in the industry – plans to renovate a historic Detroit facility to fit vehicles with its proprietary automotive technology.[37] Waymo is partnering with Magna International – a tier-1 automotive supplier based in Aurora, Canada, with multiple facilities in the Detroit area.[38] Previous to the partnership with Magna, Waymo contracted with another major Detroit-area engineering firm – Roush.[39] Roush, meanwhile, has expanded its involvement in automated-vehicle engineering, opening a new research center focused on AV software and systems integration.[40]

Ontario, Canada

The interest in automated vehicle systems has brought additional attention to centers of software development and artificial intelligence. One research cluster that has benefited is the Canadian province of Ontario, including Toronto, Waterloo and Ottawa.

Ontario is an established automotive industry cluster, owing mainly to its proximity to Detroit. Ontario is also strong in the computer software industry. The University of Waterloo, for example, has outstanding math and computer programs. The Waterloo Centre for Automotive Research (WatCAR) has several distinct groups researching advanced vehicle and mobility technology.[41] The University of Toronto also has programs focused on vehicle automation, connectivity and cyber-security.[42]

Pittsburgh, Pennsylvania

Carnegie Mellon University (CMU) in Pittsburg has been a center of autonomous driving technology for decades. CMU researchers tested the very first prototype on-road hands-free driving automation system in 1986, the Navlab 1 project,[43] which was followed by Navlab 2 in 1990. CMU teams also were among the most successful in the DARPA grand challenges that helped usher in the current era of AV research.[44] To some extent, the CMU robotics program has been a victim of its success, as dozens of established researchers have been hired away by AV startups. The most notable example of this is Uber, which first began a strategic partnership with CMU and opened a nearby research center. However, eventually, it hired over 50 CMU researchers away from the university.[45]

CMU has also spawned some AV startups, such as Argo.AI, of which Ford has purchased an ownership stake and announced it will deploy a robotaxi service in 2021.[46] Boston-based nuTonomy, now owned by tier-1 auto supplier Aptiv, has facilities in Pittsburgh and is actively expanding. Many other CMU robotics alumni are now scattered throughout the AV diaspora, including some of the most significant names in the industry, as shown earlier. CMU's Robotics Institute carries on, though with less emphasis on driving automation than in previous decades.[47] Meanwhile, Pittsburgh has become one of the world's most popular cities for on-road testing and development of prototype autonomous vehicles.[48]

Silicon Valley, California

It now feels as though Silicon Valley (the area surrounding San Francisco, California), has always been the center of the AV industry. However, it began with Google (now Waymo) taking an interest in on-road autonomous vehicles following the DARPA grand challenges. Google started to hire grand challenge participants in 2009, including CMU team leader Chris Urmson, who became chief technology officer (CTO) of the project. Other researchers were available locally. Stanford University had an established robotics and automated-driving research program on the same level as CMU and otherwise unparalleled in the world.

Google announced its self-driving project in 2010 with a compelling video of a blind man taking a self-driving car to a Taco Bell restaurant. The video did not convey the extent of preparation required for the demonstration, but it did show a level of driving automation capability that surprised the automotive industry and sparked a movement of industry stalwarts and startups to catch up and get in on the self-driving action.

Google's self-driving car project, combined with the pre-existing pool of AI and software engineers, catalyzed the development of Silicon Valley as a global leader in AV development.

It would be difficult to tabulate the number of firms pursuing automated driving in the Valley. But as of early 2019, 62 entities have received a permit from the California Department of Motor Vehicles to test prototype ADS on public roads in the state.[49]

China

The three waves of technological disruption discussed earlier (AV, MaaS and connected cars), have created a window of opportunity for Chinese auto firms as they have no legacy disadvantage vis-à-vis foreign multinationals.[50] Even in China, however, local tech giants have the upper hand over the auto sector. Chinese tech giants, such as search engine company Baidu, e-commerce concern Alibaba and ride-hailing firms Didi Chuxing, Dida and Ucar are more or less on par with their foreign counterparts. With regard to connectivity, Baidu's CarLife – a system that allows mobile phones to control the infotainment in a car – has been up and running since 2015. Baidu's voice assistant technology is called DuerOS. Alibaba has also rolled out an embedded control system, AliOS, and a smart assistant called Tmall Genie. Tencent, another tech giant, has its own system called "AI in Car."

Moreover, the Government's New Generation Artificial Intelligence Development Plan,[51] announced in 2017, shows China's determination to become a global leader in artificial intelligence, including autonomous driving technology. China also heavily invests in infrastructure and building roads and streets that are compatible with connected and autonomous vehicles. Roads in Beijing's E-Town[52] are among 44 roads (total 123 km) marked out for testing AVs. Besides Beijing, extensive testing is also taking place in 15 other cities around China, including Shanghai, Shenzhen and Guangzhou in Guangdong province, Hangzhou in Zhejiang province, Wuhan in Hubei province and Chongqing.[53]

Baidu, Pony.ai and WeRide are the leaders in self-driving technology in China.[54] However, even Baidu is not yet considered to be among the top 10 globally. In California, Baidu's test vehicles required human intervention every 41 miles driven, compared with every 5,596 miles driven by Waymo's vehicles.[55] The Baidu Apollo Automated Vehicle Platform has, however, attracted more than 100 global partners. Apollo has an AV simulation system, vehicle test data and high-definition maps.[56] Both CarLife and DuerOS are incorporated in Apollo. Further, Baidu has pledged to deploy self-driving taxis in geo-fenced areas of Changsha, Hunan Province, in 2019.[57] Baidu is attracting the majority of investment and attention in the Chinese market for autonomous driving. However, the city government of Beijing, which has begun requiring reporting for testing of automated vehicles on city streets, has received reports from seven other companies in addition to Baidu.[58] Many Chinese companies also maintain research facilities in Silicon Valley, including Baidu.[59] Chinese companies, including Baidu, NIO, Tencent, Alibaba, FAW, SAIC, ChangAn, BAIC, Great Wall, GAC, Dongfeng, Geely, BYD and Lifan have started testing their vehicles in China. Waymo has also opened a subsidiary in Shanghai, although the filing says the subsidiary will focus on logistics consulting, supply chain and AV parts and product design and not AVs.[60]

Japan

Japan's AV work was slow to start due to particularly restrictive laws on self-driving. However, with the 2020 Olympics approaching, there has been an explosion in the AV industry in order to show off the country's cutting-edge technology. Japan has introduced legislation to ease restrictions on self-driving cars and it intends to use Toyota autonomous self-driving shuttles at the 2020 Olympics to transfer competitors around the athletes' village. Evidently, Toyota has become a large part of Japan's foray into AV tech, but Toyota and other Japanese companies are doing much more than just the Olympics push.

Within Japan, Toyota has partnered with Japanese tech investment firm Softbank, most known for its USD 100 billion Vision Fund to buy stakes in fast-growing technology companies, to create a joint venture – MONET – that will focus on development of driverless technology and MaaS solutions in Tokyo. Additionally, MONET has investment from Japanese automakers Honda and Hino. Waymo has partnered with Renault and Nissan, a Franco-Japanese alliance, to bring its AV mobility services to France and Japan. Also, ZMP, a Japanese AV company, and Hinomaru Kotsu, a Japanese taxi company, have paired to develop an autonomous taxi, which they are hoping will be ready for the 2020 Olympics. However, the Japanese AV space isn't just populated by private companies. Both the University of Tokyo and Keio University have smart/advanced mobility projects developing AV technology.

Internationally, the main player is Toyota, again. It has partnered and invested internationally for AV advancements with a myriad of companies, including Uber, May Mobility, Hui, Grab, Getaround, Nvidia and AT&T. Furthermore, on the international front, Softbank has invested USD 2.25 billion in GM's Cruise Automation, a robotaxi firm, and was involved in providing USD 1 billion in funding for Uber to use on its AV division. Chinese company SenseTime is one of the world's highest-valued AI startups, and they have opened a self-driving facility in Joso, just outside of Tokyo.

United Kingdom (U.K.)

The U.K. is an established hub of automotive and engineering talent. The Government has taken a keen interest in autonomous vehicles and has worked to leverage existing capabilities to remain a significant contributor to an emerging AV industry. For example, the U.K. Autodrive project funded trials of prototype automated vehicles made by several manufacturers.[61] The UK CITE Consortium is an industry-led group focused on connected vehicle technology but with an eye toward automation.[62] The U.K. has also published an advisory document to guide testing automated-driving technologies on public roads.[63]

The U.K. has also benefited from EU-funded research programs, such as the EU GATEway project. That project funded U.K.-based Oxbotica – an Oxford University spin-off – to deploy a low-speed autonomous shuttle on a mixed-use pathway.[64] Another U.K. project supported the development of an automated podcar,[65] which operates on purpose-built guideways, to be developed by the U.K.-based RDM group, an automotive supplier. That project resulted in RDM spinning-off an independent company, Aurrigo, which now has facilities in the U.S., Canada and Australia.[66]

Cambridge is a global center of innovation for AI – dating back to 1936 when Alan Turing invented the "universal computing machine" at Kings College.[67] Cambridge is also the home of ARM – a global leader in high-performance processors – which has taken an interest in automated driving.[68]

Other U.K. universities are heavily invested in developing an AV cluster. The universities of Warwick, Birmingham and others contribute to the AI talent pipeline supporting clusters. Oxford University boasts an exceptionally strong robotics program and, as previously mentioned, gave birth to Oxbotica.

France

France's automobile industry is doing its part to remain engaged in the development of next-generation automated vehicles. Renault has pledged "eyes-off/hands-off" functionality in production vehicles as soon as 2021.[69] The Groupe PSA (whose brands include Peugeot, Citroen and DS) is pursuing its Autonomous Vehicle for All (AVA) program.[70] PSA is testing AV technology on roads in Europe and China.[71] The global automotive tier-1 supplier Valeo is also investing heavily in driving automation.[72] Valeo is building a research center for AI in Paris and has secured multiple research partnerships. Such efforts have been buoyed by a national effort to make France an AI leader.[73]

Europe has seen dozens of low-speed autonomous shuttle trials deployed by several firms. France is a center of R&D for autonomous shuttles. One of the largest and best-known companies, Navya, was founded in France in 2014. It has pilot deployments of shuttles around the globe and has a facility in Michigan. Well over 100 shuttles have been produced.[74] Keolis, a France-based private operator of public transit systems, operates many of these deployments.[75]

Another of the world's largest autonomous shuttle companies is EasyMile. It was founded in Toulouse in 2014 following the EU-funded CityMobile2 Project. Over 100 EasyMile shuttles have been produced and used in test deployments around the globe.[76] TransDev, another France-based private operator of public transit systems, manages many of these deployments.[77] TransDev has also partnered with U.S.-based Torc Robotics to test autonomous shuttles in France.[78]

Many French companies are making efforts to expand in the North American market.[79] While many of the French AV-focused companies remain small, many are actively partnering with other companies and institutions, which demonstrates their global ambitions.

Germany

Germany may be second only to the U.S. as a wellspring of innovation and development of AV technology. The EU-sponsored PROMETHEUS research program in the 1980s paralleled DARPA-sponsored research and established German institutions, such as Universität der Bundeswehr München (UBM), as sources of AI and AV expertise.[80] The very first consumer-available level 2 driving automation system, which provides such things as steering, braking and acceleration support to the driver, was introduced by Mercedes Benz and was a legacy of the PROMETHEUS program.[81]

The German auto industry, including Daimler, BMW and Volkswagen, has created numerous partnerships inside and outside of Germany in efforts to bring about a new era of autonomous shared mobility. These activities include not only minor research partnerships and investment tie-ins, but also large consortia.[82] The German automakers have been among the most aggressive in communicating goals for public deployment of automated driving. VW's Audi brand announced that the 2018 Audi A8 would have an option for the world's first consumer-available level 3 ADS, called "Traffic Jam Pilot,"[83] which would allow for highly automated driving. But it later cited regulatory barriers as delaying its appearance.[84] Mercedes has announced its flagship S-Class sedan will include level 3 automation in 2020[85] and BMW is targeting deployment of consumer-available autonomy in 2021.[86]

German tier-1 suppliers are also very active in this space. Tire company Continental has long manufactured components of vehicle automation and has even constructed its own autonomous shuttle.[87] Conti also aspires to provide an ADS platform as a supplier to automakers.[88] German firm ZF has been partnering and maneuvering for years to become integrated into a global supply chain for AVs and is also developing a prototype vehicle.[89] Bosch is another major tier-1 with ambitions to provide AV technology and is working with Daimler among others to deploy the technology in future consumer vehicles.[90] The maturity of this cluster has supported dozens of autonomy and mobility-related startups.[91]

Israel

The agglomeration of technology companies in this small country is remarkable. By one count, as of mid-2018, nearly 1,000 Israeli startups were using or developing AI technology, and well over a dozen new firms were being established every month.[92]

Global AI and software firms have maintained facilities in Israel for some time to take advantage of this ecosystem, and the auto industry has followed. For example, General Motors was once notable for having no significant presence in Silicon Valley (this is no longer the case after GM acquired Cruise Automation), but it established a research center for automated vehicle technology in Israel in 2008 and expanded it in 2016.[93] Several other automakers have expanded or opened research centers in Israel since 2016.[94]

Perhaps the best-known Israeli firm contributing to the global AV ecosystem is Mobileye – a supplier of vision systems for multiple automakers. Mobileye started in 1999. It had its initial public offering (IPO) in 2014 and was acquired by Intel in 2017 for USD 15 billion. As an established supplier, Mobileye claims that its technology has been embedded in over 27 million vehicles across 25 different brands.[95] Mobileye is now the face of Intel's foray into the automotive supply chain and is pursuing fully autonomous driving in earnest. Intel has announced a partnership with Israel's Champion Motors and Volkswagen to deploy driverless taxis in Israel with commercialization scheduled for 2022.[96] Beyond its supplier role, Intel/Mobileye's activity in strategic R&D partnering has become increasingly extensive and global.[97]

3.7 Is AV technology changing the geography of innovation in the automotive industry?

Innovation has a geographical dimension.[98] Research has shown that industries tend to co-locate in the vicinity of each other (see Chapters 1 and 2). The two types of players in the auto industry, the incumbents and the new entrants, have their own geographical clusters. The new entrants belong to the tech clusters of the world (e.g., Silicon Valley), whereas the incumbent automakers are well established in their manufacturing clusters (e.g., Detroit). The key question is whether the emergence of AV has made the automakers and tech companies seek greater geographical proximity. If the answer is yes, in which direction? The automakers are appearing in the tech clusters or vice versa.

While it is too early to give a definitive answer to the above questions, evidence based on patent data can shed some light. This section looks at the top global auto industry companies' patents, selected from three geographical areas: the U.S. (Ford and GM), Germany (Daimler, BMW, Audi, Volkswagen and Bosch) and Japan (Toyota, Honda and Nissan). These companies' total patent portfolio was examined, and a subset of patents related to AV technology identified and flagged. Based on this data the share of each company's total patenting for different clusters is calculated together with that of AV patents. For instance, 72.6 percent of Daimler's total patents are in Stuttgart, with 76.9 percent of its AV patents also being there.

The major chunk of automakers' AV patents is still generated in the same main clusters where most of their patenting happens. Nevertheless, there are also important variations. More than 82 percent of Japanese automakers' total and AV patents belong to their primary, Japan-based clusters, a far higher percentage than that of the two U.S. companies, as can be seen from Table 3.1 below.

A quick look at the list below of second-line clusters reveals some interesting differences. A number of clusters, such as San Jose, Berlin, Los Angeles and Osaka, have strong AV specialization (in the sense that their AV share is large relative to their total patent share). For Volkswagen, for example, San Jose and Berlin each have 16.1 and 9.7 percent of AV patents but only 1 and 4.8 percent, respectively, of general patents.[99]

In order to test whether tech companies have moved physically closer to automakers, the same exercise was repeated[100]. The selected companies were Google, Waymo, Delphi, Mobileye, DeepMap, Magna Electronics, Qualcomm, Uber and Apple. No systematic trend toward auto clusters was observed. As with automakers, the lion's share of both total and AV patenting happens in the same top cluster.

The geography of Uber's AV patents is interesting. While 39.6 percent of its patents are in San Francisco, Silicon Valley is not its top cluster when it comes to AV. Around 48.5 percent of Uber's AV patents are in Pittsburgh, where it has been hiring and collaborating with CMU researchers. Uber has also been testing AVs in Pittsburg since late 2018.

These results indicate that, while there is some shifting geography at the margin, auto and tech companies' innovation is still largely home based. However, the evidence available, although interesting, should be treated with caution. The numbers, particularly for AV patents, are very limited and the weight of this limited set of patents may distort the overall picture. Moreover, patent data is made public with at least 18 months' delay after being first filed. And the actual innovation may have been developed months, if not years, before the patent request was made. Finally, applicants' name disambiguation issues may have impacted the results for some companies.

3.8 Potential positive and negative impacts of AVs

Despite the high anticipation that surrounds them, fully autonomous vehicles are, if not decades, definitely years away.[101] Multiple intertwined technological advances are creating new rules for an industry that had not changed its way of doing business for almost a century. Key players from the tech and traditional automobile sectors – although with different incentives – are pooling resources to realize the goal of self-driving cars. However, the obstacles are not simply technical. Every technological shock at the early stages faces some level of socio-technical inertia in the sense that new technology requires organizational changes that also affect the interaction of people and technology. Oftentimes, change is not easily welcomed.

While there is some shifting geography at the margin, auto and tech companies' innovation is still largely home-based

Table 3.1 Comparison of the total share of patents with the AV patents of selected automakers in different clusters

Cluster name	Total share (%)	AV share (%)
Audi		
Ingolstadt	60.1	60
Munich	10.7	18.8
Frankfurt	3.9	6.2
San Jose–San Francisco	0.4	6.2
BMW		
Munich	72.5	84.1
Nürnberg	1.3	6.1
Würzburg	0.4	3.7
San Jose–San Francisco	0.4	3.7
Bosch		
Stuttgart	69.1	77.6
Munich	2.6	5.0
San Jose–San Francisco	1.0	4.6
Braunschweig	0.5	4.1
Daimler		
Stuttgart	72.6	76.9
Ulm	5.8	7.4
Frankfurt	5.1	4.1
Aachen	0.7	4.1
Ford		
Detroit-Ann Arbor	65.0	71.5
Cologne–Dusseldorf	8.8	6.6
San Jose–San Francisco	1.4	3.6
Aachen	4.8	2.9

Cluster name	Total share (%)	AV share (%)
GM		
Detroit–Ann Arbor	45.3	54.7
Waterford	5.1	11.3
Los Angeles	4.5	8.5
Frankfurt	16.6	7.5
Honda		
Tokyo	90.8	82.3
Los Angeles	0.2	3.7
Osaka	2.6	2.4
Nagoya	3.1	1.8
Nissan		
Tokyo	97.0	87.7
Osaka	1.5	8.6
San Jose–San Francisco	0.0	3.1
Nagoya	1.2	2.5
Toyota		
Nagoya	95.4	93.7
Tokyo	5.4	5.2
Osaka	2.3	3.0
Shizuoka	0.2	1.1
Volkswagen		
Wolfsburg	47.9	46.8
Braunschweig	37.1	40.3
San Jose–San Francisco	1.0	16.1
Berlin	4.8	9.7

Note: The sum of the percentages may be more than 100 percent, due to the fact that a single patent can be assigned to more than one cluster so there is double counting.

The current ecosystem of the automotive industry – its market power and its social and political position, for example – has been in place for decades and is very strong. This ecosystem is not so likely to change easily unless the key players in the industry change (i.e. existing automakers exit the market or the market is totally taken over by the tech companies), there is a drastic transformation of policy and regulatory issues or customer demand and preferences shift considerably. At the same time, public opinion is still split over AV.

Advocates of AV technology see it solving several grave urban problems. For example, it could reduce traffic jams and air pollution and improve road safety. Increased precision in the movement of vehicles and the elimination of human error can reduce traffic fatalities. Connected "smart" vehicles can safely travel much closer together – a technique known as "platooning." This, together with automated highway systems, should increase road capacity and lead to other efficiency gains, such as lower fuel consumption and better energy efficiency, which will also have a positive impact on the environment.

Hours would no longer be wasted “behind the wheel” and those who would once have been driving could instead dedicate time to relaxing, working or even sleeping. Children, senior citizens and disabled people would have more independence and mobility. Land currently devoted to parking lots could be put to other uses.

Not everyone is so positive about self-drive cars, however. In 2018, the death of a pedestrian in Arizona in an accident involving a test vehicle operating in self-driving mode was a huge setback. Some companies temporarily halted road testing. Whatever the state of play technologically, the general public may not yet be ready for AVs to go mainstream. Some critics question whether AVs would really help solve urban issues such as traffic jams and pollution. The new technology could simply increase the number of vehicles on the road, and therefore congestion. And with cars being self-driving, commuters might be prepared to “drive” further to work rather than take a train, which is less polluting.

Privacy and cyber-security are also major concerns. Data about drivers collected through autonomous, connected vehicles and other “intelligent transport system” applications could potentially be used for purposes not related to driving. The ability of hackers to crack the system, and alter information or the identity of another vehicle is one of the many serious security worries. Legal and regulatory systems already have trouble keeping up with the fast pace of change in the automotive industry. It is still not clear, in the case of an accident, who would be legally liable – the company that runs the software system, the hardware or the mobility platform.

Moreover, countries and regions are at different levels of infrastructure readiness for AVs. Uneven degrees of preparedness may exacerbate inequality between richer and poorer areas within countries and between regions. All these changes will ripple through other industries – from insurance to repair, trucking to taxi driving. AV technology has an impact that goes beyond the boundaries of a single industry.

Until the auto and tech world can address all these technical, ethical, security and legal issues, the AV future will continue to be a dream.

Notes

1 This section draws on Dziczek *et al*. (2019).
2 In this chapter, terms like autonomous vehicle, self-driving, driverless, etc. are used interchangeably and are meant to refer to the same phenomenon.
3 See WIPO Technology Trends 2019 - Artificial Intelligence
4 See Tripsas (1997) on internal knowledge development strategies, Zucker and Darby (1997) on recruiting human capital, Rothaermel (2001) on strategic alliances, Higgins and Rodriguez (2006) on acquisitions of new entrants, and Rothaermel and Hess (2007) for combinations of these strategies.
5 See Klepper (1997), Audrestsch and Feldman (1996), Abernathy and Utterback (1978), Jovanovic and MacDonald (1994).
6 See Abernathy and Clark (1985) and Klepper (1997).
7 See Klepper (1997).
8 See IEA (2019).
9 See Prahalad and Hamel (1997).
10 See Zehtabchi (2019) for more detailed information about AV patent and scientific publication search strategy.
11 See Intel (n.d.).
12 Tech includes: electronics, ICTs, semiconductors and audio-visuals. Auto includes: instruments, material, machines, engines and transport, civil engineering. Others include: biopharma, chemicals and environment and consumer goods.
13 See Zehtabchi (2019).
14 See Hummel (2019).
15 See Reuters (2019).
16 A technology stack is the list of all the tools and technologies used to build and run a single product.
17 See VIA Technologies (2018).
18 See Randall (2019).
19 See Hawkins (2019).
20 See Chesbrough (2003)
21 See Arora and Gambardella (1990).
22 See Teece (1986).
23 See Gans and Stern (2003) and Cozzolino and Rothaermel (2018).
24 See Perkins and Murmann (2018).
25 See MacDuffie (2018), Jiang and Lu (2018), Teece (2018).
26 See Capron and Mitchell (2012).
27 The majority of the data was collected from the latest media and company announcements. However, at times this info may be misleading as other motivations like market signaling and gaining venture capitalist attention might be behind the announcements.
28 See Bresnahan and Tratjenberg (1995).
29 The patent and scientific publication data used in this section are a sub-sample of those explained in Chapter 2. For more information about detailed search strategy and data collection please check the respective working papers.
30 See Lee and Lim (2001).
31 See Toyota Research Institute-CSAIL (n.d.).
32 See Stone (2018).
33 See Abuelsamid (2017).
34 See nuTonomy (2017).
35 See Singapore Economic Development Board (2016).
36 See Engel (2017).
37 See Bigelow (2019a).
38 See Bigelow (2019b).
39 See Nicas (2017).
40 See Snavely (2017).
41 See University of Waterloo (n.d.) and McKenzie and McPhee (2017).
42 See University of Toronto (2019).
43 See Carnegie Mellon (1986).
44 See U.S. Defense Advanced Research Projects Agency (n.d.).
45 See Lowensohn (2015).
46 See Vasilash (2018).
47 See Carnegie Mellon University (n.d.).
48 Wiggers (2019).
49 See California Department of Motor Vehicles (n.d.).
50 See Teece (2019).
51 See full translation: FLIA (2017).
52 Economist (2019).
53 See Feifei (2019).
54 See Silver (2018).
55 See Teece (2019) and Jing (2018).
56 Visit apollo.auto.
57 See Xinhua (2019).
58 See Liao (2019).
59 Visit research.baidu.com.
60 See Korosec (2018).
61 Visit www.ukautodrive.com/the-uk-autodrive-project.
62 See Fleet News (2018).
63 See U.K. Department for Transport (2015).
64 See Dennis and Brugeman (2019).
65 Personal Rapid Transit (PRT), also referred to as podcars, is a public transport mode featuring small automated vehicles operating on a network of specially built guideways.
66 See Dennis and Brugeman (2019).
67 See Taylor (n.d.).
68 See ARM (n.d.).
69 See Poulanges (2017).
70 See PSA Groupe (n.d.).
71 See PSA Groupe (n.d.).
72 See Valeo (2015).
73 See Ministère de l'Enseignement supérieur, de la Recherche et de l'Innovation (2019).
74 See Dennis and Brugeman (2019).
75 Visit www.keolis.com/en.
76 See Dennis and Brugeman (2019).
77 Visit www.transdev.com/en.
78 See McQuilkin (2019).
79 See UBI Mobility-Connected Cars France (2018).
80 See Dickmanns (2002).

81 See Gregor *et al*. (2002), Daimler (2016), Oagana (2016).
82 See Taylor and Wissenbach (2019).
83 See Audi (2017).
84 See Ulrich (2019).
85 See Hetzner (2018).
86 See DeMattia (2018).
87 See Continental AG (n.d.).
88 See Continental AG (2018).
89 See Behrmann and Rauwald (2018).
90 See Daimler (n.d.).
91 See Initiative for Applied Artificial Intelligence (n.d.).
92 See Singer (2018).
93 See South Africa Israel Chamber of Commerce (2016).
94 See Leichman (2017).
95 See Scheer (2018).
96 See Intel (2018).
97 See Reichert (2019).
98 See Saxenian (1996) and (2007).
99 See Zehtabchi (2019).
100 See Zehtabchi (2019).
101 See Ghemawat (1991).

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