

Building Vehicle Autonomy: Sensors, Semiconductors, Software and U.S. Competitiveness

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Abstract

This paper describes the current state of driving automation, the components that go into autonomous vehicles, and U.S. firm participation in the sector. There are three main components that enable autonomous driving: sensors, semiconductors, and software. Sensors, including cameras, Light Detection and Ranging (LiDAR), and radar are used together to help vehicles see road conditions at various distances, and in different weather and lighting conditions. Semiconductors facilitate the processing of data gathered by sensors in order to make real time driving decisions. Machine learning and mapping software provide the tools to improve the operation and decision making of vehicles. U.S. firms, including vehicle manufacturers, parts suppliers, and tech companies are competing across all of the components of driving automation. As a new area of competition, there are opportunities for startups and for firms to move into new areas (e.g., vehicle manufacturers developing chips, and technology companies supplying automotive parts).

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Introduction

The development of driving automation, including automated driving, has been discussed in the news regularly, and in many U.S. cities, including San Francisco, Las Vegas, Phoenix, and Pittsburgh, there are on-road driving automation tests taking place. Major vehicle manufacturers, suppliers, and tech companies have invested billions of dollars in driving automation. These different competitors are working to develop driving automation all over the world, and it is unclear who the leading suppliers will be, where driving automation will be most heavily concentrated, or even who will own vehicles that drive autonomously. Rather than attempt to predict trends in the automation of driving (such as fully autonomous vehicles), this paper seeks to outline the specific inputs to vehicles needed for automated driving, their sources, and their interaction with other inputs.¹

The remainder of this introduction describes the current status of driving automation and the types of companies involved in developing driving automation in the U.S. market. The rest of the paper then outlines the three major inputs that are used much more heavily in a vehicle capable of driving automation from a traditional vehicle: sensors, semiconductors, and software. Based on data availability and overall development of each component, these sections will describe the technology, explain how it fits into driving automation, the market for each input, and U.S. production and trade.

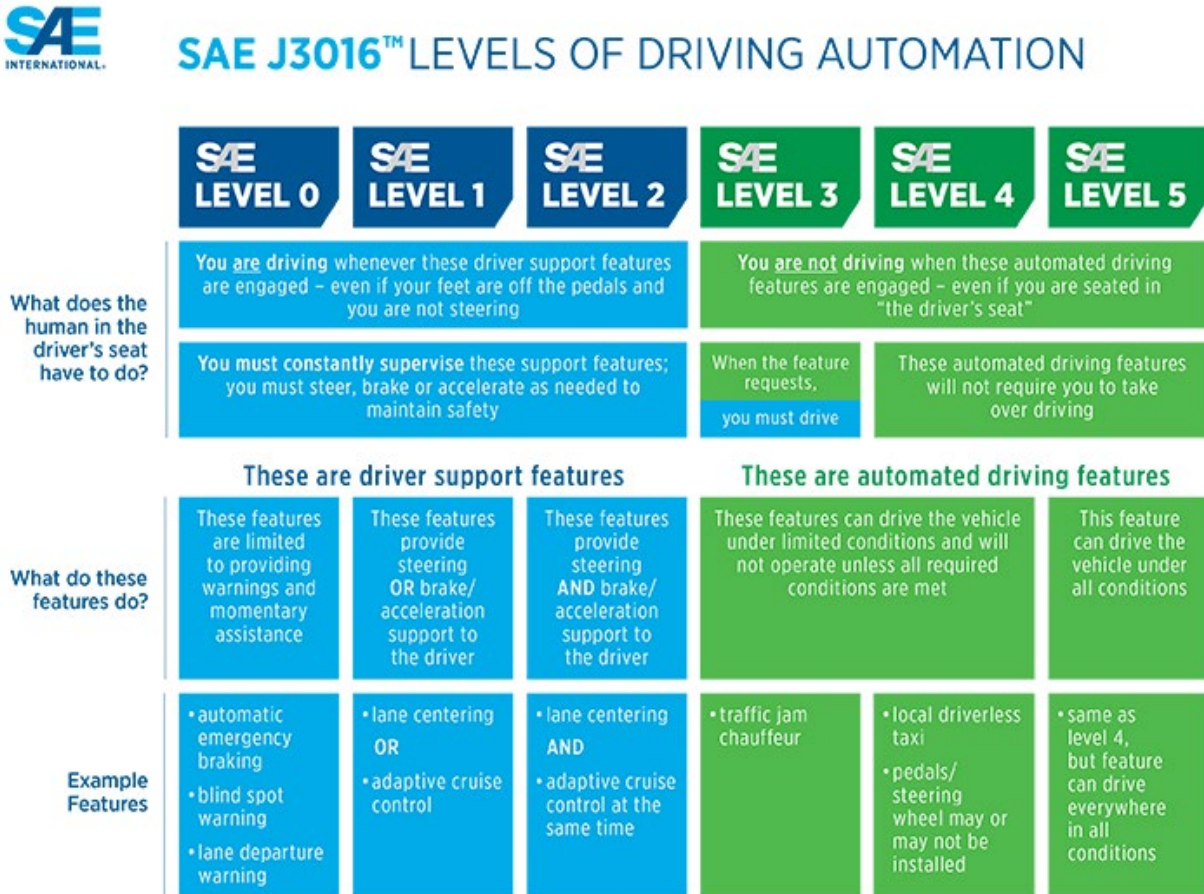
Before describing how companies compete, it is important to define driving automation. One of the most widely accepted definitions comes from the Society of Automotive Engineers (SAE), which defines five levels of driving automation based on the level of human driver involvement (figure 1). In the first two levels of driving automation, the driver has support features such as lane centering or adaptive cruise control, but should be constantly engaged in the task of driving the vehicle. Many vehicles produced in 2019 have these features. Beginning with level three, the driver can be disengaged, but may be prompted to take over driving. Level four has full automation in limited conditions (e.g., within a geographically-defined area, or on a certain type of road), and level five has fully automated driving under all conditions.² Much of the testing occurring today is level 4, with many focused on driverless taxis in specific areas. Level 5 continues to be relatively far off, and some argue may ultimately prove impossible, due to the scale of computing power required to support a level 5 vehicle.³

¹ Many also believe that additional infrastructure, such as smart stoplights, will be needed, but this paper is focused on the parts attached to vehicles.

² SAE, "SAE International Releases Updated Visual Chart," December 11, 2018.

³ Truett, "The cost of full autonomy could prove unrealistic," August 6, 2019.

Figure 1 Society of Automotive Engineers levels of driving automation



Source: SAE, “SAE International Releases Updated Visual Chart,” December 11, 2018.

Vehicle manufacturers, parts suppliers, hardware companies, software companies, and semiconductor companies are all involved in autonomous vehicle (AV) development. These participants include start-ups, as well as many of the largest vehicle manufacturers, automotive suppliers, and tech companies in the world. Table 1 (on the next page) gives a sample of U.S. companies involved, as well as the breadth of their involvement. Mergers, acquisitions, and joint ventures have also played a large role in AV development. For example, GM purchased Cruise Automation, which is now its AV development arm.⁴ Intel purchased a company with expertise in vision-safety technology to pair with its chips.⁵ Startups are also competing in AV development, and the development of specific software and tools needed for AV development. There are numerous software companies working to provide different software services for AV development, including the actual decision-making software, software for real-time updates to maps, and simulation software to train AV artificial intelligence. Some companies, such as Velodyne or Caramera, are focused on a specific product or service, while others (e.g., Waymo, GM, Tesla, etc.) participate in multiple areas for driving automation.

⁴ Primack and Korosec. “GM Buying Self-Driving Tech Startup for More Than \$1 Billion,” March 11, 2016.

⁵ Krzanich, “Safety is Why Intel Bought Mobileye,” June 19, 2018.

Table 1 Examples of U.S. Firm participation in the AV ecosystem

Company	Vehicles	Sensors			Chips	Software	
		Radar	Cameras	LiDAR		AV Machine Learning	AV Mapping
GM	X			X		X	
Ford	X					X	
Tesla	X				X	X	
Luminar				X			
Intel			X		X		
Nvidia					X		
Waymo				X		X	X
Uber ATG						X	
Carmera							X

Source: Assembled by the authors.

Note: This table is intended to illustrate the types of U.S. companies participating in autonomous vehicle development, and does not provide an exhaustive list of all U.S. firms in the market.

Autonomous Vehicle Inputs

For an autonomous vehicle to “see,” it requires a variety of different sensors, and hardware and software to interpret the inputs from those sensors. Autonomous vehicles also need software to make driving decisions based on current road conditions. Developing each of these areas is important for achieving full autonomy for vehicles, and vehicle manufacturers are collaborating with suppliers and software developers to achieve level 3 through 5 autonomy. Vehicles with higher levels of automation tend to need more sensors, better chips, and better software, as a more automated vehicle must be able to drive safely in a wide range of situations and at a variety of speeds and types of traffic.

This section will provide a brief description of the relatively unique inputs of an autonomous vehicle compared to other vehicles on the road today, which companies make these inputs, and U.S. competitiveness in this area. To the extent such data is available, it will also examine U.S. trade in these inputs as well. There will be separate sections for sensors, chips, and software.

Sensors: LiDAR, Radar, and Cameras

Most autonomous vehicles use at least three different types of sensors to “see”: LiDAR, radar, and cameras.⁶ These three types of sensors often have overlapping responsibilities. AVs use these sensors to insure clear “automotive vision” in a range of weather, distances, and lighting scenarios (figure 2).⁷ For example, GM’s Cruise AV uses at least two types of sensors for many tasks: radar and LiDAR measure the speed of moving objects; LiDAR and cameras classify and track objects.⁸

⁶ Some autonomous vehicles also use ultrasonic sensors, but these sensors tend to be used more for parking, not on-road use.

⁷ Bosch, “Automated Driving, (accessed March 14, 2019).

⁸ GM, “2018 Self-Driving Safety Report,” 2019, 8.

Figure 2 Overlapping layers of sensors



Source: American Planning Association “Autonomous Vehicles” <https://www.planning.org/knowledgebase/autonomousvehicles/>.

Vehicles operating in 2019 use cameras for level one and level two autonomous features, such as lane detection and other advanced driver assistance tasks, but autonomous vehicles at level three or higher will use cameras for object and traffic sign recognition. One report predicted that the cost of cameras for levels 3 through 5 of driving automation would not be higher than current prices.⁹ In clear weather, cameras provide the most detailed picture of the vehicle’s surroundings, which helps an AV identify vehicles, pedestrians, cyclists, etc. Key camera producers include major automotive suppliers such as Continental (Germany), Denso (Japan), and Magna (Canada), and specialized suppliers like Mobileye (Israel, owned by Intel).

Autonomous vehicles use a suite of cameras pointing in all directions. Waymo uses several sets of high-resolution cameras to provide a 360-degree view of the vehicle that is designed to work well at long range, in daylight and low-light conditions.¹⁰ GM’s Cruise AV uses 16 cameras to detect and track pedestrians/cyclists, traffic lights, and free space.¹¹ Uber uses a system of cameras mounted to its sensor pod on top of the vehicle for 360-degree coverage.¹² Auto X— a San Jose, California-based startup with \$43 million in funding as of August 2018¹³— vehicles have six cameras mounted to its sensor pod on top of the vehicle and two additional cameras on their sideview mirrors. Auto X’s vehicle uses cameras for mapping, lane detection, traffic light and sign recognition, and other tasks.¹⁴ Ford’s AV uses top-mounted cameras and a rear-facing camera.¹⁵ Mercedes Benz Drive Pilot uses two cameras, one front facing and one rear facing as well as a “Surround View System”.¹⁶

Automotive radar is the second largest part of the automotive sensor segment. It is used in passenger vehicles for a range of advanced driver assistance systems (ADAS), such as adaptive cruise control, and

⁹ Goldman Sachs, “Monetizing the rise of Autonomous Vehicles,” September 17, 2015, 19.

¹⁰ Waymo, “Waymo Safety Report 2017, October 2017, 14.

¹¹ GM, “2018 Self-Driving Safety Report,” 2019, 7.

¹² Uber, “Uber ATG Safety Report,” 2018, 20.

¹³ Korosec, “AutoX Is Using Its Self-Driving Vehicles To Deliver Groceries,” August 27, 2018.

¹⁴ Auto X, “The Auto X Safety Factor,” 2018, 10.

¹⁵ Ford, “A Matter of Trust,” 2018, 19.

¹⁶ Mercedes-Benz, “Introducing Drive Pilot,” February 20, 2019, 20.

blind spot detection, which are considered lower-levels of driving automation functions (levels 0-2), but demand from level 3 and up could drive further growth. Traditional auto parts suppliers including Continental, Bosch (German), and Denso supply original equipment manufacturers (OEMs) with automotive radar.¹⁷

The number of radar in autonomous vehicles being tested in 2019 varies significantly, but tends to be more than LiDAR but less than cameras. Waymo uses a 360-degree radar system that tracks the speed of road users around the vehicle.¹⁸ GM's Cruise AV uses three types of radar (and a total of 21 radar). Its radar are a complement to LiDAR because it detects objects with low-light reflectivity.¹⁹ Uber ATG has eight radar, two below-each headlamp in the front, four on the corners facing the side, and two near each end of the rear bumper beam.²⁰ Auto X uses six radar to detect the position and speed of objects.²¹ Ford uses four radar: front, rear, and side-facing.²² The Mercedes Benz Drive Pilot uses front-facing long-range radar, and front and rear facing multimode radar.²³

LiDAR is the smallest segment of the automotive sensor market, but has seen significant investment, as many developers of autonomous vehicles believe it is a key component in automotive vision. LiDAR is a detection system that works on the principles of radar, but uses light from a laser. For the most common form of LiDAR being developed for vehicles, the lasers shoot out in all directions, and the bounce back provides the vehicle with an image of its surroundings (figure 3). LiDAR for autonomous vehicles is still mostly in the development stage, and per unit costs are quite high, but have dropped from nearly \$80,000 in the early 2010s to \$8,000 in 2017, and now \$3,500 in 2019.²⁴ Unit costs will need to decline further for mass produced vehicles, but economies of scale may provide some of the necessary unit cost reduction.

¹⁷ Prescient & Strategic Intelligence, "Automotive Radar Market," April 2018.

¹⁸ Waymo, "Waymo Safety Report 2017, October 2017, 14.

¹⁹ The three types of radar are: articulating radars to detect moving vehicles at long range over a wide field of view; long-range radars to detect vehicles and measure velocity; and short-range radars to detect objects around the vehicle. GM, GM Safety Report, 2019, 7.

²⁰ Uber, "Uber ATG Safety Report, 2018, 20.

²¹ Auto X, "The Auto X Safety Factor," 2018, 10.

²² Ford, "A Matter of Trust," 2018, 19.

²³ Mercedes-Benz, "Introducing Drive Pilot," February 20, 2019, 20.

²⁴ Automotive LiDAR is not yet used in many vehicles, so costs may go down as it is installed in more vehicles. Zoia, "Velodyne Says Nearing Mass Production of Forward-Facing Lidar," June 11, 2019; Lampinen, Megan. "LiDAR emerges as the star of the AV sensor line-up," Automotive World, January 24, 2019; Lee, "How the Lidar-On-A-Chip Technology GM Just Bought Probably Works," October 11, 2017.

Figure 3 Roof mounted LiDAR



Source: Plougmann, "Top LiDAR Scanner and a Peek Inside the Cabin" <https://www.flickr.com/photos/criminalintent/20823743810> under a creative commons license.

Note: Photo was modified to focus on the LiDAR.

LiDAR is used with other sensors to identify objects both short and long-range. Unlike cameras and radar, LiDAR is not used for lower levels of driving automation, but is one of the more expensive components that is expected to be used on level three and level four autonomous vehicles.²⁵ Due to its cost, many AVs currently being tested only have one top-mounted LiDAR, but GM's Cruise AV actually uses five LiDARs to detect fixed and moving objects.²⁶ Waymo uses three types of LiDAR developed inhouse: Short-range LiDAR with an uninterrupted view of area directly around vehicle; High-resolution mid-range; and Long-range that can see nearly 300 yards away.²⁷ At least one company with ambitions to sell vehicles with level 4 or higher automation capabilities (Tesla) does not believe LiDAR are necessary.²⁸

Market

The automotive camera is the sensor with the largest market, while LiDAR is the smallest. Estimates of the global market for automotive cameras range from \$831 million to in 2017 to \$14 billion.²⁹ Much of that market is in backup cameras, which are standard in new vehicles in many countries, including the United States. The automotive radar market has grown significantly in new vehicles in recent years due to increased use in safety features for light vehicles. P&S Intelligence estimated that automotive radar had a \$3 billion global market in 2017 and that Europe was the largest market for automotive radar.³⁰ BIS Research estimated that LiDAR had a \$353 million global market in 2017.³¹ Despite having little to no

²⁵ Goldman Sachs, "Monetizing the rise of Autonomous Vehicles," September 17, 2015, 19.

²⁶ Tesla reportedly does not have plans to use LiDAR at all. GM, "2018 Self-Driving Safety Report," 2019, 7; Uber, "Uber ATG Safety Report," 2018, 20; Auto X, "The Auto X Safety Factor," 2018, 10; Ford, "A Matter of Trust," 2018, 19; Fosse, Paul. "Deep Dive Into Tesla's Autopilot," November 4th, 2018.

²⁷ Waymo, "Waymo Safety Report 2017, October 2017.

²⁸ In an April 2019 event, one Tesla employee claimed LiDAR was a "crutch," for vision recognition. Tesla reportedly believes better vision recognition systems forego the need for LiDAR. Lee, "Elon Musk: "Anyone relying on lidar is doomed." Experts: Maybe not," August 6, 2019.

²⁹ Business Wire, "Global Automotive Camera Market Overview & Outlook (2017-2023)," December 27, 2018.; Statista, "Global Automotive camera sales in 2015 and 2020," October 2015.

³⁰ Prescient & Strategic Intelligence, "Automotive Radar Market," April 2018.

³¹ BIS Research, "Global Automotive LiDAR market to Reach \$8.32 Billion by 2028," November 29, 2018.

automotive market in 2015, equity research by Goldman Sachs predicted that it could be the largest sensor segment by 2035.³²

U.S. Production

Information on sensor production in the United States is relatively limited, but there appears to be U.S. production of each sensor type, as well as R&D. At least two companies, ZF (German) and Magna (Canadian), produce automotive cameras in the United States. ZF produces automotive cameras at its plant in Marshall, IL.³³ Magna produces rearview cameras in Holly, MI.³⁴ At least two companies produce radar or radar components in the United States, another U.S. company produces integrated circuits for radar, while a fourth has a radar-related R&D center in the United States. The United States is one of four places where Continental (German) produces automotive radar.³⁵ Continental has a three million-unit capacity for producing short-range units in Seguin, Texas.³⁶ Denso (Japan) produces radar components in Maryville, TN.³⁷ Valeo (French) has a R&D center for radar systems in Hudson, New Hampshire.³⁸ There are at least two U.S. producers of LiDAR, Velodyne (U.S.) and Luminar (U.S.). However, neither currently produces at a large scale: Luminar's factory has a 5,000-unit capacity, and Velodyne is contracting with Veoneer to produce an automotive-grade LiDAR.³⁹ Velodyne's forward-facing radar will reportedly be used on a mass produced vehicle in 2020.⁴⁰ GM purchased Strobe, a California-based LiDAR startup in 2018 that claims to have found a way to reduce LiDAR costs by 99 percent.⁴¹ In May 2019, Aurora Innovation (a U.S.-based self-driving startup) purchased Blackmore, another U.S.-based LiDAR manufacturer.⁴² Magna also opened a new factory in Michigan in 2019 for producing cameras and combining them with other technologies for ADAS purposes.⁴³

Trade

While the U.S. market for automotive cameras is estimated to be the largest of the sensor categories, it is not the most imported sensor, which appears to be automotive radar. U.S. imports of color transmission apparatus, including automotive cameras, totaled \$2.1 billion in 2017, a significant increase from \$1.3 billion in 2013.⁴⁴ According to estimates based on U.S. Customs data, nearly 24 percent (\$600 million) of those imports were for automotive uses.⁴⁵ U.S. imports of radar for other uses grew from \$440 million in 2013 to \$842 million in 2017.⁴⁶ According to author estimates based off U.S.

³² Goldman Sachs, "Monetizing the rise of Autonomous Vehicles," September 17, 2015.

³³ Taylor, "Marshall Auto Parts Plant Struggling To Find Workers," September 17, 2018.

³⁴ Magna International, "Magna Produces Ten Millionth Rearview Camera in Holly, Michigan," September 2, 2014.

³⁵ Continental, "Fifth Radar Generation Meets Future Requirements for Automated Driving," November 28, 2017.

³⁶ Continental, "Continental to Launch Production of Short Range Radar Sensors in the USA," March 26, 2014.

³⁷ McGavin, "Why Denso Is Spending Big in East Tennessee," June 11, 2018.

³⁸ Valeo. "Locations," (accessed May 28, 2019).

³⁹ Niedermeyer, Edward. "Velodyne-Veoneer Deal Shows Lidar Is Getting Serious." The Drive, January 16, 2019;

Lampinen, "LiDAR Emerges as the Star of the AV Sensor Line-up," January 24, 2019.

⁴⁰ Zoia, "Velodyne Says Nearing Mass Production of Forward-Facing Lidar," June 11, 2019.

⁴¹ Davies, "GM Buys a LIDAR Startup that could Deliver Its Self-Driving Future," October 9, 2017.

⁴² Davies, "Self-Driving Startup Aurora Buys Speed-Sensing LiDAR Company," May 23, 2019.

⁴³ Winter, "Magna Opens New Factory for Advanced Tech," August 15, 2019.

⁴⁴ HTS 8525.80.3010 IHS Markit, Global Trade Database (accessed February 18, 2019).

⁴⁵ Author estimates from proprietary Customs records.

⁴⁶ HTS 8526.10.0040 IHS Markit, Global Trade Atlas Database (accessed January 28, 2019).

Customs data, nearly \$655 million (64 percent) of those imports in 2017 were for automotive use. The top three suppliers were Japan, Canada, and Germany, making up over 60 percent of U.S. imports. U.S. optical instrument imports, which include LiDAR, grew from \$31.8 million in 2013 to \$69.2 million in 2017.⁴⁷ However, according to USITC estimates, automotive LiDAR only makes up a small share of these imports.⁴⁸

Semiconductors

Autonomous vehicles rely on semiconductors for all electronic functions. Also known as integrated circuits or “chips,” semiconductors are the enabling hardware for all information technology and are essential for both the aforementioned sensors, LiDAR, and cameras, as well as software functions, which will be discussed in the following section of this working paper.

Automotive semiconductors fall in to five general categories: analog, optoelectronics, discrettes, logic and memory (Table 2). Within the automotive end use market for semiconductors, there are multiple sub-markets including:

- Automated driver assistance systems (ADAS) and autonomous driving (ex. gathering and interpreting information, electronic control of vehicle)
- Control, monitoring, and safety (ex. power steering)
- Powertrain (ex. battery and motor system of an electronic vehicle, transmission)
- Vision (ex. cameras that assist with parking)
- Infotainment (ex. radio and entertainment systems, integrated cellular connectivity)
- Body (ex. tire pressure monitors, wireless activated door locks).⁴⁹

Automobiles increasingly consume semiconductors associated with on-board navigation systems, infotainment systems and ADAS and other safety features.⁵⁰ As levels of automation increase, industry forecasts suggest that the average semiconductor content per car could increase from \$160 (level 2) to \$630 (level 3) to \$970 (level 4 and 5) and total 3,500 semiconductors per vehicle.⁵¹

⁴⁷ HTS 9015802000 IHS Markit, Global Trade Atlas Database (accessed January 28, 2019).

⁴⁸ Proprietary Customs records.

⁴⁹ Maxim, “Form 10K,” 2018; Nvidia, “Form 10K,” 2018; ON Semiconductor, “Form 10K,” 2018; TI, “Form 10K,” 2018.

⁵⁰ Wells Fargo Semiconductor Industry Primer 2017.

⁵¹ Infineon, “The Importance of Semiconductors for the Fast Changing World of Automotive” 2018. 17; Lawrence and VerWey, “The Automotive Semiconductor Market – Key Determinants of U.S. Firm Competitiveness,” May 2019. ON Semiconductor, “Analyst Day Presentation,” 2019. 25.

Table 2 Types of automotive semiconductors and applications

Types of Automotive Semiconductors	Function	Example of Automotive Use Case	Automotive Applications	Examples
Analog	Change real-world signals, such as sound, temperature, pressure or images, by conditioning them, amplifying them and converting them in to digital data that can be processed by other semiconductors	Engine temperature monitor	ADAS and Autonomous Driving; Vision; Body	A/D converters, D/A converters, amplifiers
Optoelectronics	Generate light (ex. for displays) or sense light (ex. in digital cameras).	Dashboard lighting	Body; Control, Monitoring and Safety	Sensors, actuators, image sensors, LEDs
Discretes	Single devices used in power management, voltage regulation, and to connect integrated circuits within a system (ex. PCB)	Airbags	Body; Control, Monitoring and Safety	Power transistors, rectifiers and diodes, radio frequency
Logic	General purpose thinking chips used for tasks that require low (MCUs) to high computing (MPUs) power or increased flexibility (FPGAs).	Anti-lock brakes	Powertrain; ADAS and Autonomous Driving; Vision; Control, Monitoring and Safety	Microprocessors (MPUs, CPUs), Digital signal processors, Microcontrollers, Programmable logic devices (FPGAs)
Memory	Provide temporary or permanent storage for data and instructions used to execute programs and software.	GPS navigation	Control, Monitoring and Safety; Body; ADAS and Safety	DRAM, SRAM, NAND, NOR

Source: Wells Fargo Semiconductor Industry Primer, Authors Compilation.

Market

The market for automotive semiconductors is large and growing. All of the aforementioned types of semiconductors have experienced growth in recent years and that growth is expected to continue in 2019, with the exception of memory chips (Table 3).

Table 3 Worldwide semiconductor sales by type, 2017–19

	Amounts in US\$M			Year on Year Growth in %		
	2017	2018	2019	2017	2018	2019
Discrete Semiconductors	21,651	24,102	24,776	11.5	11.3	2.8
Optoelectronics	34,813	38,032	38,611	8.8	9.2	1.5
Sensors	12,571	13,356	13,899	16.2	6.2	4.1
Integrated Circuits	343,186	393,288	377,261	24	14.6	-4.1
Analog	53,070	58,785	61,083	10.9	10.8	3.9
Micro	63,934	67,233	68,513	5.5	5.2	1.9
Logic	102,209	109,303	112,109	11.7	6.9	2.6
Memory	123,974	157,967	135,557	61.5	27.4	-14.2
Total Products - \$M	412,221	468,778	454,547	21.6	14	-3

Source: World Semiconductor Trade Statistics, August 2019.

The traditional markets for semiconductors are consumer, communications, and PC/computers, which collectively consumed roughly 75% of all semiconductors in 2017 (see Figure 2).⁵² However, industry analysts expect that the automotive semiconductor market will be the fastest growing end use market for chips from 2017 to 2021, with a 12.5 percent compound annual growth rate (CAGR).⁵³ The reason for the expected increase in the consumption of semiconductors by the automotive industry is due to the advent of autonomous, connected, and electric vehicles.⁵⁴ This increasing consumption of semiconductors represents an important growth market for the semiconductor industry and many firms are actively investing to serve this market. However, the automotive industry has long design times, long product life cycles, and high regulatory and safety requirements relative to other semiconductor end use markets.⁵⁵ As a result, automotive companies have significantly higher performance expectations for components and feature longer qualification times for suppliers of those components. Because of the long qualification time and high quality expected, automotive chips are more “sticky” than standard consumer electronic chips.⁵⁶

U.S. Production

U.S. firms have led the semiconductor industry ever since Texas Instruments developed the first integrated circuit in 1958. In 2018 seven of the top-15 semiconductor firms, representing roughly 47 percent of annual worldwide sales, are headquartered in the United States.⁵⁷ The U.S. industry’s competitiveness is comprehensive, with firms providing all types of semiconductors to each of the end use markets mentioned in Figure 2. Several U.S. semiconductor firms have made substantial investments in the automotive semiconductor market and are among leading firms worldwide in supplying this end use market. Texas Instruments (5th largest semiconductor manufacturer globally), ON

⁵² World Semiconductor Trade Statistics Program, “End Use Report 2017,” 2018.

⁵³ Coffin and Kim, “U.S. Firms Are Becoming Leaders in the Automotive Semiconductor Market,” USITC, 2017.

⁵⁴ Burghardt, et al, “What’s Ahead for Automotive Semiconductors,” April 2017; Cappel, “Automotive IC Industry Trends,” 2018.

⁵⁵ Qualcomm, “Form 10K,” 2018. 13.

⁵⁶ Lawrence and VerWey, “The Automotive Semiconductor Market – Key Determinants of U.S. Firm Competitiveness,” May 2019.

⁵⁷ IC Insights, “Nine top-15 2018 Semi Suppliers Forecast to Post Double-Digit Gains,” November 2018.

Semiconductor (7th) and Microchip Technology (8th) were all in the top 10 firms globally in 2017, with the other leading firms being concentrated in Europe and Japan.⁵⁸ Several U.S. semiconductor firms derive a significant percentage of their annual revenue from the automotive market (Table 4).

Table 4 Exposure to automotive market for select U.S. semiconductor firms, 2018

Firm Name	Operating Model	Automotive Semiconductors Market(s) Served	2018 Total Revenue, millions	Automotive End Use as a Percent of Total Revenue	Notable Acquisition(s)
Analog Devices	IDM	Analog; Logic	6,201	16%	Linear Technology Corporation
Intel	IDM	Logic	70,848	<5%	Mobileye
Maxim	Fabless	Analog; Logic	2,480	21%	
Microchip	IDM	Analog; Logic	3,980	25%	Microsemi
NVIDIA	Fabless	Logic	9,714	6%	
ON Semiconductor	IDM	Analog; Logic; Discrete	5,878	31%	SensL
Texas Instruments	IDM	Analog; Logic	15,784	20%	
Vishay Intertechnology	IDM	Discrete; Optoelectronics	3,035	28%	Capella, UltraSource
Xilinx	Fabless	Logic	2,539	17%	

Source: Author's compilation using annual company filings.

Leading U.S. Semiconductor Firms Engaged in Autonomous Market

The leading U.S. firms engaged in the autonomous vehicle sub-segment of the automotive semiconductor market are Intel and Nvidia. In addition, though it is not a semiconductor firm, Tesla recently introduced a chip designed specifically for autonomous vehicles. Several other U.S. semiconductor firms are engaged in the development of ADAS/autonomous driving products (Table 5). Brief profiles of leading company's investments in the autonomous market are provided below.

⁵⁸ McGrath, "Automotive IC Vendor Ranking," 2017.

Table 5 Notable U.S. Firm ADAS/autonomous driving product offerings

Company	ADAS/Autonomous Driving Products
Intel	Atom E3900 Processor
	Atom E3800 Processor
	Atom C3000 Processor
	Xeon processors
	Arria 10 FPGA
	Mobileye 5 Series
	Mobileye 6 Series
Nvidia	Mobileye Shield+
	NVIDIA DRIVE PX 2
	NVIDIA DGX-1
Qualcomm	Xavier supercomputer chip
	Snapdragon 820A
	RFCMOS (radio frequency complementary metal-oxide-semiconductor) radar system QCA6696
AMD	Radeon Instinct MI6 accelerator
Xilinx	Zynq UltraScale+ MPSoC (multiprocessor system-on chip)
Tesla	FSD Chip

Source: Wells Fargo Semiconductor Industry Primer; Authors Compilation.

Intel

Intel is primarily invested in the development of ADAS and safety systems. Following a \$15.3 billion acquisition of Israeli advanced driver assistance systems (ADAS) startup Mobileye in 2017, Intel has become a leading firm in the development of computer vision, machine learning, and mapping for ADAS systems and autonomous driving. It has also engaged in partnerships with Fiat Chrysler Automotive, BWW, and Waymo (Google/Alphabet's AV startup). Several other semiconductor products manufactured by Intel are used in image recognition and natural language processing, both of which are used in autonomous vehicle systems.⁵⁹

Nvidia

Nvidia is heavily engaged in the autonomous vehicle market, offering products for the development environment (training artificial intelligence chips and virtual reality driving simulation) and on-the-road vehicles. Nvidia's Tesla graphics processing units (GPUs) are widely considered the industry gold standard when it comes to training machine learning algorithms such as neural networks for autonomous driving tasks such as perception, localization and planning. Nvidia has also introduced Nvidia DRIVE technology, a unified artificial intelligence computing architecture that trains deep neural networks and then runs them within a vehicle, integrating with inputs from multiple cameras and sensors. Nvidia claims partnerships with 320 automakers, tier-one suppliers, automotive research institutions, and HD mapping companies and has announced AV-related partnerships with Audi, Toyota

⁵⁹ Intel, "Form 10K," 2018.

Motor Corp., Volvo, Volkswagen, Uber, and Mercedes Benz. Nvidia's automotive revenue in 2018 reached \$558 million, up 15 percent year on year.⁶⁰

Tesla

Tesla is an automotive company that has developed an autonomous driving chip. First introduced in 2019, the Full Self-Driving Chip (FSD Chip) was designed by Tesla for use in their own vehicles and targets autonomous levels 4 and 5. The FSD Chip is a full system-on-chip designed by Tesla at their headquarters in California and manufactured by Samsung (South Korea) at its Austin, Texas facility. "System-on-chip" refers to the fact that this is a chip of chips, incorporating one graphics processing unit, two neural processing units, a CPU, and memory (SRAM), along with a camera serial interface, video encoder, image signal processor and security system.

Eventually every Tesla vehicle will incorporate a full self-driving computer (FSD Computer) which will consist of a printed circuit board that has two FSD Chips. Though packaged on the same board, the two FSD chips will operate separately from each other for safety purposes. When the vehicle is powered on, inputs from the automobile's 8 vision cameras and 12 ultrasonic sensors will feed readings such as location, speed, radar, GPS and inertial measurement to each of the chips separately but simultaneously. The two chips independently decide upon a course of action based upon these inputs and send their proposed plan to the car's safety system, which determines whether agreement was reached. Once a plan is agreed upon, the commands are confirmed and sensors feed information back to confirm that the commands executed the plan.⁶¹

Xilinx, AMD, and Qualcomm

Several other U.S.-headquartered semiconductor firms have announced investments targeting the autonomous vehicle market. Xilinx, a leading supplier of Field Programmable Gate Array (FPGA) chips, recently announced a partnership with the German firm ZF Friedrichshafen AG (ZF), a supplier of driveline and chassis technology, to power ZF's automotive control unit (ZF ProAI) to enable automated driving applications.⁶² There are over 160 million Xilinx chips used in automotive systems currently, nearly half of which are used in driver-assistance applications such as cruise controls that keep a set distance from other vehicles.⁶³ In February 2019 Qualcomm unveiled its second-generation Connected Car Reference Platform (known as the QCA6696 chip), part of its Snapdragon Automotive Platforms, which is designed to combine a variety of technologies (GPS, 5G cellular connectivity, Wi-Fi 6, Bluetooth) for use in vehicles.⁶⁴ AMD reportedly provided some of the intellectual property incorporated by Tesla in the development of its FSD Chip and has been subject to speculation that it will enter the autonomous chip market independently.⁶⁵

⁶⁰ Nvidia, "Form 10K," 2018.

⁶¹ Tesla, "Autonomy Investor Day," April 22, 2019.

⁶² Xilinx. "Xilinx and ZF to Jointly Enable Autonomous Driving Development," 2019.

⁶³ Nellis. "German Supplier Adds Xilinx Chips," 2019.

⁶⁴ Kaplan. "Qualcomm Draws a Road Map to the Self-Driving Car of the Future," 2019.

⁶⁵ Novet. "Tesla Working With AMD," 2017.

Software: Data Processing, Machine Learning, and Mapping

Autonomous vehicle software systems fall within the broader category of “Internet of Things” (IoT) market, which consists of internet-enabled devices, such as sensors, that gather and transmit data to cloud-based networks for aggregation and analysis.⁶⁶ The automotive IoT sector represented 4.8 percent of the total global IoT market in 2018, with \$4.5 billion in revenue.⁶⁷ This section describes the underlying computer systems and software that companies in the auto sector use in their autonomous vehicles. In particular, this section covers the typical AV data processing system, and applications of machine learning and mapping in AV software.

Data Processing Capacity in Autonomous Vehicles

For autonomous vehicles, an entirely cloud-based IoT system is not the most effective way to process data related to AV operations. Fully cloud-based ecosystems are often limited in their ability to respond quickly based on road conditions due to scale, heterogeneity of systems within a cloud infrastructure, and high latency (the gap in time between the point when a data request is made and the point when the requested information is provided to a user).⁶⁸ To address this, autonomous vehicle manufacturers program data processing applications, including machine-learning algorithms, which require low latency in the vehicle itself, either through a central computer in the vehicle, or via sensors and chips with limited processing capacity. This combined approach allows for vehicles to minimize request-response time of applications at the vehicle level, while also providing for connectivity to centralized cloud resources when needed.⁶⁹

Autonomous vehicles operations are characterized by two broad types of data processing, which combine local (within vehicle) processing with processing on cloud-based networks. First, as a car is driving, it captures data about its surroundings and makes immediate decisions based on this data (such as to stop at a stop sign). This type of data processing requires a rapid response time, including download speeds of higher than 2.5 mbps (megabits per second), upload speeds of above 1 mbps, and less than 100 milliseconds (ms) in latency.⁷⁰ In 2017, the median download speed in the United States across Internet Services Providers was 72 mbps, while median latency ranged from 12 ms to 37 ms for non-satellite broadband.⁷¹ While in theory, these speeds are sufficient to support cloud-based data processing for AV, in practice, speed varies by location, total internet traffic, and type of broadband provider, which means that an autonomous vehicle would likely be unable to consistently access the cloud-based infrastructure required to operate.⁷²

⁶⁶ USITC, *Global Digital Trade I*, August 2017, 192.

⁶⁷ IC Insights, “Revenue of Internet of Things Subsystems,” June 2018.

⁶⁸ NIST, “Fog Computing Conceptual Model,” March 2018, ii. USITC, *Recent Trends in U.S. Service Trade*, 2018, 78.

⁶⁹ NIST, “Fog Computing Conceptual Model,” March 2018, 2.

⁷⁰ Latency is the gap in time between the point when a data request is made and the point when the requested information is provided to a user. Cisco, *Cisco Global Cloud Index: Forecast and Methodology*, 2016, 33.

⁷¹ FCC, *Eighth Measuring Broadband America Fixed Broadband Report*, December 14, 2018.

⁷² FCC, *Eighth Measuring Broadband America Fixed Broadband Report*, December 14, 2018.

There are multiple approaches to embedding needed in-vehicle processing infrastructure in autonomous vehicles.⁷³ For example, NVIDIA's DRIVE AGX platforms are specifically designed for autonomous driving, by configuring all components of a computer onto a single integrated circuit (system on a chip). On DRIVE systems, the chip incorporates redundant AI algorithms, sensor processing, mapping, and driving, while also reducing energy consumption and size of processors relative to traditional multi-chip circuits.⁷⁴ NVIDIA's hardware and software is part of Mercedes-Benz, Volvo, and some iterations of Tesla's AV development, as well as automated electric vehicles in the Netherlands (WEpods).⁷⁵ LiDAR company AEye has developed an alternative to centralized in-vehicle processing, which embeds software directly in their LiDAR devices, rather than having LiDAR transmit data to a central processor.⁷⁶ Similarly, German firm Bosch has developed a camera with some artificial intelligence capacity: the camera is able to determine, for example, whether the edge of a road is passable even if there are not lane markings.⁷⁷

Second, data about the individual vehicle's performance on the road can be aggregated with data from the entire fleet of vehicles, and analyzed to improve the operation and decision making of the software system embedded in the vehicle. Since this data is not time sensitive, and more valuable when it can be centrally stored and processed, this data is transmitted from individual vehicles to cloud data centers.⁷⁸ For example, General Motors vehicles learn from the shared knowledge base of each vehicle, and send data on specific on the ground conditions (such as a road closure) to inform the rest of the fleet.⁷⁹ One autonomous vehicle company, AutoX, runs a more cloud intensive operation than its competitors do by adding remote operators to help control vehicles. While AutoX acknowledges that the high-resolution video used for these remote operations can place a burden on the network, their vehicles use multiple channels of high-speed internet from different carriers in order to maximize upload speeds.⁸⁰

Machine Learning and Mapping

Autonomous vehicles rely on algorithms developed using a subset of artificial intelligence (AI), called machine learning, to make real time driving decisions.⁸¹ Machine learning focuses on designing computer algorithms that can automatically build analytical models for new data without a programmer first giving the algorithm the solution.⁸² Machine learning has a variety of applications, such as detecting credit-card fraud, or forecasting, but two applications of algorithms developed using machine learning

⁷³ See semiconductors section above for more information on in-vehicle processors.

⁷⁴ The NVIDIA Xavier processor is capable of 30 trillion operations per second while consuming only 30 watts of energy. NVIDIA, "NVIDIA DRIVE AGX" (Accessed May 3, 2019); Automotive World, "Special Report: Artificial Intelligence and the Autonomous Vehicle," 2019, 22.

⁷⁵ Tencent, "Experimental Security Research of Tesla Autopilot," March 2019, 2; Automotive World, "Special Report: Artificial Intelligence and the Autonomous Vehicle," 2019, 23-24; Shapiro, "WEpod Becomes first Driverless Car to Play in Traffic," February 1, 2016.

⁷⁶ Zoia, "AEye Bucks Trend with its Intelligent Solid-State Lidar," April 1, 2019.

⁷⁷ Amend, "Bosch AI-Camera Sharper Than Human Eye," September 3, 2019.

⁷⁸ Cisco, *Fog Computing and the Internet of Things*, 2015, 4.

⁷⁹ General Motors, "2018 Self-Driving Safety Report", 2019, 5.

⁸⁰ AutoX "The Autox Safety Factor," 2018, 25.

⁸¹ Broadly speaking, this is a type of "weak" or "specific" AI, which makes a computer adept at performing a particular type of task (such as driving) very well, but cannot generalize that knowledge to other tasks. Castro and New, "The Promise of Artificial Intelligence," October 2016, 3; Reese, *The Fourth Age*, 2018.

⁸² Castro and New, "The Promise of Artificial Intelligence," October 2016, 2.

are particularly relevant to AVs: interpreting unstructured data, such as images, video and audio; and interacting with the physical environment by analyzing data from sensors, cameras, GPS systems, and maps.⁸³ The global market for the hardware, software, and services related to automotive AI was about \$1.2 billion in 2017.⁸⁴

In order to use machine learning to make driving decisions, most autonomous vehicles currently under development require three-dimensional maps of surroundings as a baseline to compare against data from sensors, so that vehicles can focus on abnormalities in the driving environment. These maps tend to be more detailed than satellite imagery, and include characteristics of the physical environment such as road types, curb dimensions, bike lanes, and speed bumps.⁸⁵ They can also be annotated to include relevant traffic regulations and guidance like speed limits and traffic signals: Ford also notes that their maps include information like whether pedestrians typically jaywalk on particular streets.⁸⁶ However, the level of detail required on these maps limits the scalability of autonomous vehicle fleets: currently, AVs can only drive on roads that have been mapped. In practice, this means that current AV developers are focused on cities, and are unlikely to be able to navigate roads that are unmarked, unlit, or unpaved in the near future.⁸⁷ In addition to market-size concerns, this limitation may help explain some of the city-focused business models of AV developers. For example, Mercedes-Benz envisions their electric vehicles as a tool for improving congestion in cities, while Ford is testing approaches to use AV to improve efficiency in last mile deliveries.⁸⁸ Machine learning in AV also faces implementation challenges, particularly in terms of cybersecurity. First, feeding input into a machine learning algorithm to back out what data it uses to make decisions, can be used to alter driving patterns of autonomous vehicles.⁸⁹ Using inconspicuous stickers, researchers have discovered that they can modify stop signs so that an AV misinterprets them as 45 mph speed limit signs, and to guide a vehicle into driving on the wrong side of the road.⁹⁰ Hacking of autonomous vehicle systems also poses a concern for AV adoption, particularly if hackers are able to take control of functions like steering, as Tencent Keen Security Lab was able to do in tests of Tesla's autopilot in 2018.⁹¹

Market

It is difficult to define precisely the scope of the market for autonomous vehicle software because the tools and infrastructure needed for developing this software comes from a variety of sources, some of which are open source (source code is made freely available). Cloud infrastructure as a service (IaaS),

⁸³ Structured data has specific data fields appearing in a static location in each record, like a spreadsheet. Unstructured data does not have a set format. Castro and New, "The Promise of Artificial Intelligence," October 2016, 5; Shacklett, "Unstructured Data: A Cheat Sheet," July 14, 2017.

⁸⁴ Tractica, "Artificial Intelligence for Automotive Applications", 3Q 2018.

⁸⁵ Waymo, "Waymo Safety Report," 2017, 18; Uber Advanced Technologies Group, "A Principled Approach to Safety," 2018, 22.

⁸⁶ Ford, "A Matter of Trust," 2018, 12.

⁸⁷ Rus, "AVs Need New Tech To Navigate Beyond Densely Mapped Cities," April 10, 2019.

⁸⁸ Ford, "A Matter of Trust," 2018, 6, Mercedes-Benz and Bosch, "Reinventing Safety," 2018, 9.

⁸⁹ Knight, "How Malevolent Machine Learning Could Derail AI," March 25, 2019.

⁹⁰ Knight, "How Malevolent Machine Learning Could Derail AI," March 25, 2019; Tencent, "Experimental Security Research of Tesla Autopilot," March 2019, 33.

⁹¹ Tencent, a Chinese firm, purchased a 5 percent stake in Tesla in 2017, and reports results of these tests to Tesla's US Product Safety team so that security can be improved. Tencent, "Experimental Security Research of Tesla Autopilot," March 2019, 15; Linert, "Tesla Deal Boosts Chinese Presence in U.S. Auto Tech," March 28, 2017.

providers, which could provide infrastructure for the machine learning algorithms AV firms use, accounted for \$30.5 billion in revenue in 2018 globally.⁹² The largest firms in the IaaS sector are almost exclusively U.S. providers.⁹³ These firms can sell data storage and processing space to AV developers: for example, Uber uses both Amazon's AWS and Google for its cloud infrastructure.⁹⁴

At the same time, AV firms both use and collaborate on a variety of open-source tools to build the environment for doing machine learning. For example, Uber's machine learning platform "Michelangelo" combines open source Apache libraries for big data management and Python-based machine learning framework TensorFlow, along with in-house developed components.⁹⁵ Firms in the AV market can also work collaboratively via partnerships on open platforms. For example, Chinese company Baidu's Apollo architecture provides an open platform for testing autonomous vehicles, and aggregating AV test data across partners (including vehicle manufacturers, software and hardware developers and university partners).⁹⁶ Similarly, in August 2019, U.S. firm Waymo released high-resolution sensor data collected by its vehicles for research purposes.⁹⁷ While these tools facilitate the development of AV software, since they are not monetized, they are difficult to value.

Despite these challenges, individual firm financial statements can shed some light on the value of the AV software. Automobile manufacturing firms entering the autonomous vehicle market have pursued different strategies for developing AV software, which makes it challenging to isolate the value of AV software systems from other company operations. First, some vehicle manufacturers have acquired software development firms. GM acquired an AV software development firm (Cruise) to become its software development arm for \$1.15 billion, and GM Cruise had an estimated total revenue of \$306,000 in 2017.⁹⁸ Other vehicle manufacturers, like Ford, Volvo, and Mercedes-Benz have partnered with software development firms for their AV development. Nvidia, Volvo's software development partner, had approximately \$200,000 in revenue in their non-hardware business lines in 2017, some of which likely reflects this partnership.⁹⁹ Many of these companies are also characterized by high levels of investment, indicating that there is appetite for future development of AV software and systems. As of early 2019, GM Cruise reported a total investment valuation of \$19 billion, while Ford-partner Argo AI was reportedly valued at approximately \$4 billion.¹⁰⁰

⁹² Some firms may also use in-house cloud systems rather than purchasing them from a third party.

⁹³ In 2018, the top six global IaaS providers were Amazon (AWS), Microsoft, Google, Alibaba (China), IBM and Oracle. Gartner, "Gartner Forecasts Worldwide Public Cloud Revenue," April 2, 2019; MSV, "10 Key Takeaways from Gartner's 2018 Magic Quadrant for Cloud IaaS," June 2, 2018.

⁹⁴ Novet, Jordan, "Uber Paid Google \$58 Million," April 11, 2019.

⁹⁵ Hermann and Del Balso. "Meet Michelangelo," September 5, 2017.

⁹⁶ Apollo. "Apollo Open Platform" <http://apollo.auto/> (Accessed July 8, 2019).

⁹⁷ Waymo, "Waymo Open Dataset," August 21, 2019.

⁹⁸ Hawkins, "GM's self-driving division Cruise Raises another \$1.15 billion," May 7, 2019; Waymo, <https://waymo.com/> (accessed May 31, 2019); Bureau Van Dijk, Orbis database (accessed May 31, 2019).

⁹⁹ Nvidia's business lines include Graphics Processing Units, Tegra system on a chip devices, and "all other" which includes NVIDIA DRIVE. To calculate this revenue estimate, the percent contribution of this segment to total sales in fiscal year 2017 was applied to the total revenue in 2017. Author's calculations using data from Bureau Van Dijk, Orbis database (accessed May 31, 2019).

¹⁰⁰ Rauwald and Naughton, "Ford, VW discuss \$4 billion value for Argo AI, report says" Automotive news, February 14, 2019.

On the other side, some software development firms, such as Waymo (a division of Alphabet, which also owns Google), Uber, and Aptiv, develop autonomous vehicle software independently, then embed their technology in vehicles provided by vehicle manufacturers.¹⁰¹ In 2017, Waymo’s total estimated revenue was approximately \$3 million, while in 2018 Aptiv’s total sales in their “Advanced Safety and User Experience” business segment were approximately \$4 million, .¹⁰²

Finally, there are also companies that focus specifically on creating the detailed maps needed for AV software development. Companies such as Carmera (\$450,000 estimated revenue in 2017), DeepMap (\$420,000 estimated revenue in 2017), Civil Maps, and Mapper.ai all sell mapping services specifically designed for autonomous vehicles.¹⁰³

Conclusion

This working paper outlines the current state of the automated driving industry in the United States. The paper analyzes major trends in the market for driving automation. The three major inputs whose usage is likely to increase in autonomous vehicles—sensors, semiconductors, and software— were discussed in detail. Vehicle manufacturers, parts suppliers, hardware companies, software companies, and semiconductor companies are all involved in autonomous vehicle development, and U.S. firms are involved in each of these sub-markets for driving automation. Future research on the automated driving industry could further examine the role of mergers, acquisitions and joint ventures in accelerating investment and development, the role of regulatory reform in accelerating the advent of automated driving, and the extent to which U.S. firms face competition from international peers.

¹⁰¹ Waymo uses vehicles from Fiat Chrysler and Jaguar, Uber from Toyota, Volvo and Daimler, and Aptiv from Audi (Volvo). Uber Technologies, “Form S-1,” April 11, 2019, 161 ; Aptiv “Our Journey” <https://www.aptiv.com/our-journey> (accessed May 31, 2019); Bigelow, “Waymo Firms of Plans for Autonomous Car Assembly plant in Detroit, April 23, 2019.

¹⁰² Aptiv’s “Advanced Safety and User Experience” segment likely includes autonomous vehicle software, but is not necessarily comprised exclusively of software related to driving autonomy. Bureau Van Dijk, Orbis Database (accessed May 31, 2019).

¹⁰³ Civil Maps <https://civilmaps.com/> (Accessed July 8, 2019), Mapper.ai “On-Demand Maps” <https://mapper.ai/product/> (Accessed July 8, 2019), Deepmap “Our Solutions” <https://www.deepmap.ai/> (Accessed July 8, 2019). Carmera “Our Products” <https://www.carmera.com/products/#products> (Accessed July 8, 2019). Revenue estimates: Bureau Van Dijk, Orbis Database (accessed July 8, 2019).

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