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Autonomous driving's future: Convenient and connected

By 2035, autonomous driving could create $300 billion to $400 billion in revenue. New research reveals what's needed to win in the fast-changing passenger car market.

This report is a collaborative effort by Johannes Deichmann, Eike Ebel, Kersten Heineke, Ruth Heuss, Martin Kellner, and Fabian Steiner, representing views from the McKinsey Center for Future Mobility.

January 2023

The dream of seeing fleets of driverless cars efficiently delivering people to their destinations has captured consumers' imaginations and fueled billions of dollars in investment in recent years. But even after some setbacks that have pushed out timelines for autonomous-vehicle (AV) launches and delayed customer adoption, the mobility community still broadly agrees that autonomous driving (AD) has the potential to transform transportation, consumer behavior, and society at large.

Because of this, AD could create massive value for the auto industry, generating hundreds of billions of dollars before the end of this decade, McKinsey research shows.[1] To realize the consumer and commercial benefits of autonomous driving, however, auto OEMs and suppliers may need to develop new sales and business strategies, acquire new technological capabilities, and address concerns about safety.

This report, which focuses on the private-passenger-car segment of the AD market, examines the potential for autonomous technologies to disrupt the passenger car market. It also outlines critical success factors that every auto OEM, supplier, and tech provider should know in order to win in the AD passenger car market. (Other McKinsey publications explore the potential of shared AVs such as robo-taxis and robo-shuttles, as well as autonomous trucks and autonomous last-mile delivery.)

Autonomous driving could produce substantial value for drivers, the auto industry, and society

AD could revolutionize the way consumers experience mobility. AD systems may make driving safer, more convenient, and more enjoyable. Hours on the road previously spent driving could be used to video call a friend, watch a funny movie, or even work. For employees with long commutes, driving an AV might increase worker productivity and even shorten the workday. Since workers can perform their jobs from an autonomous car, they could more easily move farther away from the office, which, in turn, could attract more people to rural areas and suburbs. AD might also improve mobility for elderly drivers, providing them with mobility options that go beyond public transportation or car-sharing services. Safety might also increase, with one study showing that the growing adoption of advanced driver-assistance systems (ADAS) in Europe could reduce the number of accidents by about 15 percent by 2030.[2]

Along with these consumer benefits, AD may also generate additional value for the auto industry. Today, most cars only include basic ADAS features, but major advancements in AD capabilities are on the horizon. Vehicles will ultimately achieve Society of Automotive Engineers (SAE) Level 4 (L4), or driverless control under certain conditions. Consumers want access to AD features and are willing to pay for them, according to a 2021 McKinsey consumer survey. Growing demand for AD systems could create billions of dollars in revenue. Vehicles with lidar-based Level 2+ (L2+) capabilities contain approximately $1,500 to $2,000 in component costs, and even more for cars with Level 3 (L3) and L4 options. Based on consumer interest in AD features and commercial solutions available on the market today, ADAS and AD could generate between $300 billion and $400 billion in the passenger car market by 2035, according to McKinsey analysis[3] (Exhibit 1).

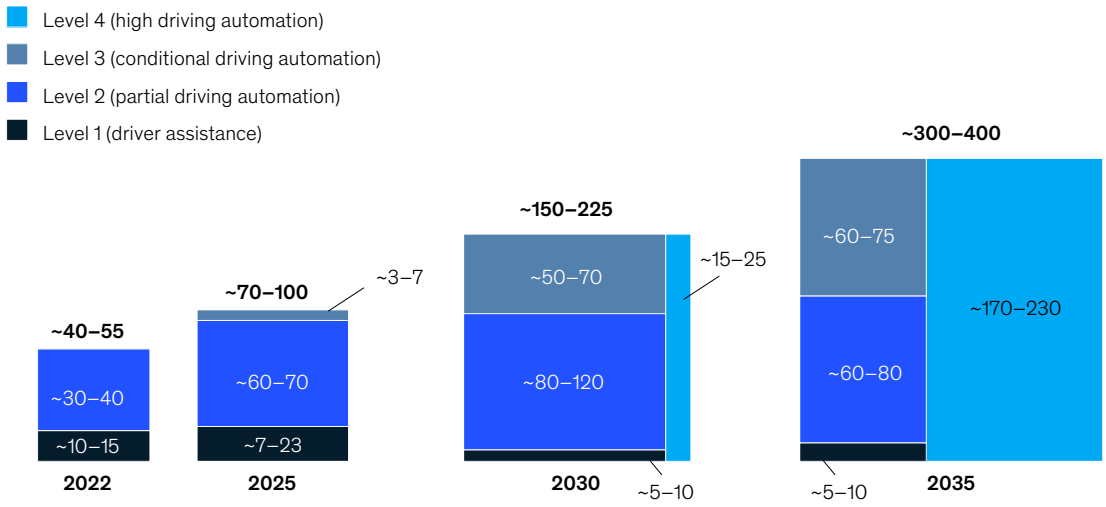
The knock-on effects of autonomous cars on other industries could be significant. For example, by reducing the number of car accidents and collisions, AD technology could limit the number of consumers requiring roadside assistance and

1 McKinsey Center for Future Mobility analysis.
2 Tom Seymour, "Crash repair market to reduce by 17% by 2030 due to advanced driver systems, says ICDP," *Automotive Management Online*, April 7, 2018.
3 McKinsey Center for Future Mobility analysis. Total revenue potential is derived from McKinsey's base case on ADAS and AD installation rates, with the share of OEM subscription offerings at a 100 percent installation rate, and actual customer take rate and pricing assumptions by segment and ADAS/AD features. Prices are assumed to decline over time as features become industry standards and because of overall cost digression.

Exhibit 1

Passenger car advanced driver-assistance systems and autonomous-driving systems could create $300 billion to $400 billion in revenues by 2035.

Advanced driver-assistance systems (ADAS) and autonomous-driving (AD) revenues, $ billion



Source: McKinsey Center for Future Mobility

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repairs. That may put pressure on those types of businesses as consumer adoption of AD rises. In addition, consumers with self-driving cars might not be required to pay steep insurance premiums, since handing over control of vehicles to AD systems might mean that individual drivers could no longer be held liable for car accidents. As a consequence, new business-to-business insurance models may arise for autonomous travel.

Several automakers are already piloting new insurance products. These companies are gleaning insights on driving behavior from autonomous technology and making personalized offers to their consumers. Since OEMs control the AD system, its performance, and the data that it generates (such as the real-time performance of drivers), auto companies can precisely tailor insurance policies to their consumers, giving them a significant advantage over external insurance providers.

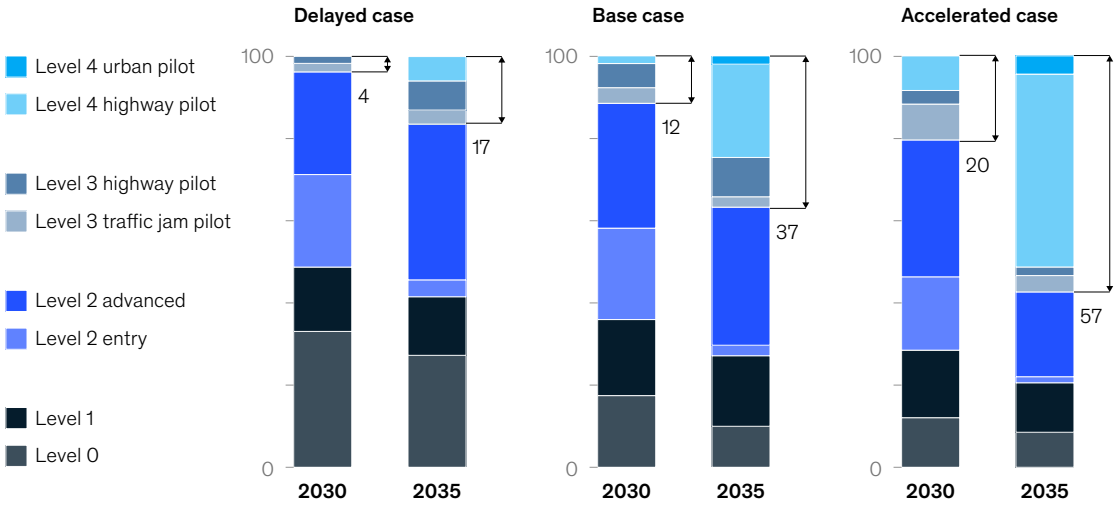
How AD could transform the passenger car market

Given today's high levels of uncertainty in the auto industry, McKinsey has developed three scenarios for autonomous-passenger car sales based upon varying levels of technology availability, customer adoption, and regulatory support (Exhibit 2). In our delayed scenario, automakers further push out AV launch timelines, and consumer adoption remains low. This scenario projects that in 2030, only 4 percent of new passenger cars sold are installed with L3+ AD functions, with that figure increasing to 17 percent in 2035.

Exhibit 2

Three scenarios for autonomous-passenger-car sales in 2030 and 2035 show varying levels of consumer adoption.

Estimated passenger vehicles sold with autonomous-driving technologies installed, %



Source: McKinsey Center for Future Mobility

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Our base scenario assumes that OEMs can meet their announced timelines for AV launches, with a medium level of customer adoption despite the high costs of AD systems. By 2030, 12 percent of new passenger cars are sold with L3+ autonomous technologies, and 37 percent have advanced AD technologies in 2035.

Finally, in our accelerated scenario, OEMs debut new AVs quickly, with sizable revenues coming in through new business models (for example, pay as you go, which offers AD on demand, or new subscription services). In this scenario, most premium automakers preinstall hardware that makes fully autonomous driving possible when the software is ready to upgrade. In this scenario, 20 percent of passenger cars sold in 2030 include advanced AD technologies, and 57 percent have them by 2035.

Delivering higher levels of automation

For automakers focused on delivering vehicles with higher levels of automation, there is enormous potential for growth. Consumers interested in the convenience of hands-free driving might want cars with more advanced autonomous functions (including L2+, L3, and L4), which give the autonomous system greater control over driving tasks. Costs for sensors and high-performance computers are decreasing, while safety standards for AD technologies are continuing to advance. (For instance, standards currently available for traffic jam pilots, which allow autonomous vehicles to navigate through stop-and-go traffic while maintaining a safe distance from other cars, could soon extend to other advanced AD functions.) Taken together, these factors could help the auto industry introduce more advanced autonomous features to a broad range of vehicles over time.

Based on McKinsey's sales scenarios, L3 and L4 systems for driving on highways will likely be more commonly available in the private-passenger-car segment by around 2025 in Europe and North America, even though the first applications are just now coming into market. (One luxury European brand offers an L3 conditional self-driving system but restricts usage to certain well-marked highways and at reduced speeds.)

Steep up-front costs for developing L3 and L4 driving systems suggest that auto companies' efforts to commercialize more advanced AD systems may first be limited to premium-vehicle segments. Additional hardware- and software-licensing costs per vehicle for L3 and L4 systems could reach $5,000 or more during the early rollout phase, with development and validation costs likely exceeding more than $1 billion. Because the sticker price on these vehicles is likely to be high, there might be greater commercial potential in offering L2+ systems. These autonomous systems somewhat blur the lines between standard ADAS and automated driving, allowing drivers to take their hands off the wheel for certain periods in areas permitted by law.

L2+ systems are already available from several OEMs, with many other vehicle launches planned over the next few years. If equipped with sufficient sensor and computing power, the technology developed for L2+ systems could also contribute to the development of L3 systems. This is the approach taken by several Chinese disruptor OEMs. These companies are launching vehicles that offer L2+ systems pre-equipped with lidar sensors. The vehicles are likely to reach L3 functionality relatively soon, since the companies are likely using their on-road fleet of enhanced L2+ vehicles to collect data to learn how to handle rare edge cases, or to run the L3 system in shadow mode.

Where true L3 systems are not available, developers might also offer a combination of L2+ and L3 features. This may include an L2+ feature for automated driving on highways and in cities, together with an L3 feature for use in traffic jams.

Car buyers are highly interested in AD features

Consumers benefit from using AD systems in many ways, including greater levels of safety; ease of operation for parking, merging, and other maneuvers; additional fuel savings because of the autonomous system's ability to maintain optimal speeds; and more quality time. Consumers understand these benefits and continue to be highly willing to consider using AD features, according to our research.

In McKinsey's 2021 autonomous driving, connectivity, electrification, and shared mobility (ACES)[4] survey, which polled more than 25,000 consumers about their mobility preferences, about

Consumers benefit from using AD systems in many ways, such as greater levels of safety, and some are highly willing to consider using AD features.

[4] Timo Möller, Asutosh Padhi, Dickon Pinner, and Andreas Tschiesner, "The future of mobility is at our doorstep," McKinsey, December 19, 2019.

a quarter of respondents said they are very likely to choose an advanced AD feature when purchasing their next vehicle. Two-thirds of these highly interested customers would pay a one-time fee of $10,000 or an equivalent subscription rate for an L4 highway pilot, which provides hands-free driving on highways under certain conditions (Exhibit 3). This represents a price point and willingness to pay that is consistent with a few top-of-the-line AD vehicles launched in the past few years, as well as with our value-based pricing model.

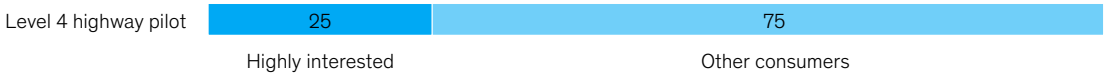
Since consumers have such different lifestyles and needs, AD systems may benefit some consumers far more than others, making them much more likely to pay for AD features. For instance, a sales manager who drives 30,000 miles a year and upgrades to an autonomous car could use all of that time previously spent driving to contact new leads or to create in-depth sales strategies with his or her team. On the other hand, a parent who uses a car primarily for shopping or for driving the kids to school might be more reluctant to pay for AD features.

Exploring the values of different consumer personas could enable OEMs and dealerships to tailor their value propositions and pricing schemes. For instance, they might implement a flexible pricing model that includes a fixed one-time fee, subscription offerings, and, potentially, an on-demand option such as paying an hourly rate for each use of a traffic jam pilot. Our research indicates that consumers prefer having different pricing options. Of the highly interested consumers, 20 percent of ACES survey respondents said they would prefer to purchase ADAS features through

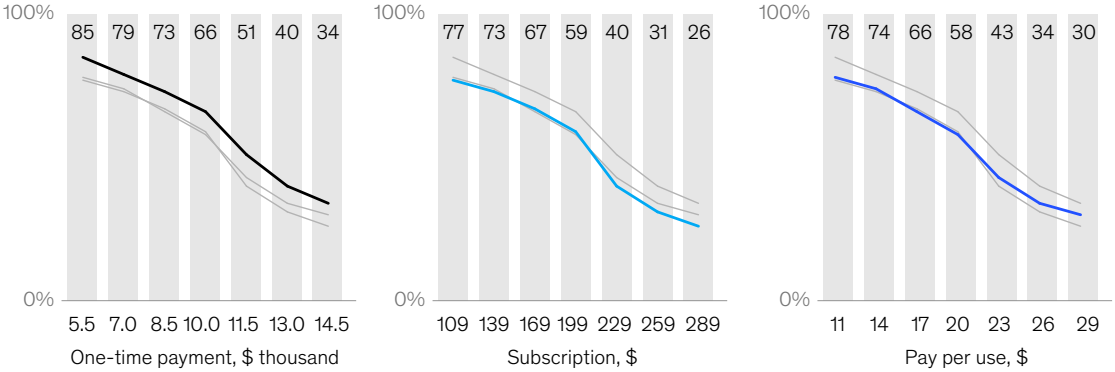
Exhibit 3

A quarter of car buyers are highly interested in autonomous driving, with two-thirds of this group willing to pay $10,000 for a premium feature.

Interest in advanced autonomous-driving function when buying next car, share of respondents



Preferred price point and method of payment for an advanced highway pilot, share of respondents



Source: McKinsey Center for Future Mobility ACES Consumer Survey, Dec 2021, n = 26,285

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a subscription, while nearly 30 percent said they would prefer to pay each time they use a feature. In addition, one in four respondents said they would like to be able to unlock additional ADAS features even after purchasing a new car.

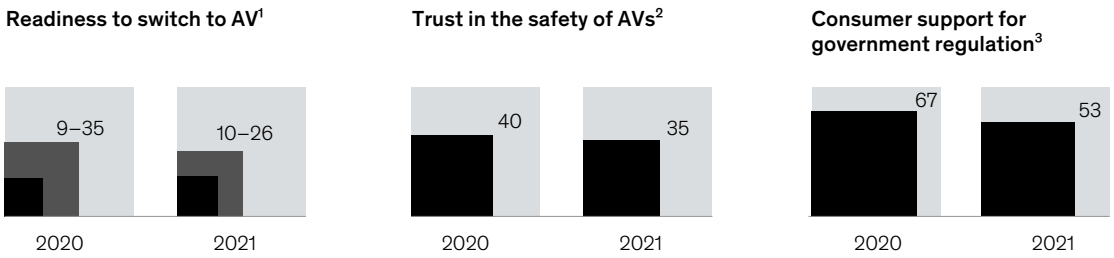
Although consumers continue to be very interested in autonomous driving, they are also adopting more cautious and realistic attitudes toward self-driving cars. For the first time in five years, consumers are less willing to consider driving a fully autonomous vehicle, our ACES consumer surveys show. Readiness to switch to a private AV is down by almost ten percentage points, with 26 percent of respondents saying they would prefer to switch to a fully autonomous car in 2021, compared with 35 percent in 2020 (Exhibit 4).

Our ACES consumer research also reveals that trust in the safety of AVs is down by five percentage points, and that the share of consumers who support government regulation of fully self-driving cars has declined by about 15 percentage points. While safety concerns are top of mind, consumers also want opportunities to test-drive AD systems and more information about the technology. To help customers become more comfortable with AVs, OEMs may need to offer hands-on experiences with AVs, address safety concerns, and educate consumers about how autonomous driving works.

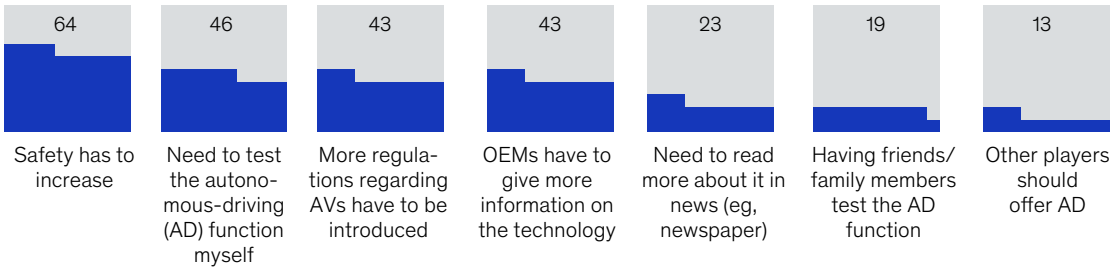
Exhibit 4

Consumers are less open to driving fully autonomous vehicles, with only 26 percent saying they would switch to an autonomous vehicle.

Indicators of consumer interest in owning fully autonomous vehicles (AVs), % of respondents



Factors that would increase consumer confidence in AVs, % of respondents



[1]Question: If the car maker of your choice offered a fully autonomous car, would you want to keep your old car or switch at the same costs? Answers included "I would definitely switch to a fully autonomous car" or "I would rather switch to a fully autonomous car."
[2]Responses to the statement: I would feel good with my family members driving in a fully autonomous car.
[3]Question: Do you think the government should legalize fully autonomous vehicles on all roads?
Source: McKinsey Center for Future Mobility ACES Consumer Survey, Dec 2021, n = 26,285

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Regulatory support is critical

Support from regulators is essential to overcoming AD safety concerns, creating a trusted and safe ecosystem, and implementing global standards. So far, most public officials have strongly advocated for the inclusion of ADAS capabilities in existing regulations, laying the groundwork for autonomous driving. This has resulted in a much higher penetration of ADAS functions, both in passenger cars and commercial vehicles.

The auto industry and public authorities agree on autonomous driving's potential to save lives. Today, basic SAE L1 and L2 ADAS features are increasingly coming under regulation. This includes Europe's Vehicle General Safety Regulation, along with Europe and North America's New Car Assessment Program (NCAP), a voluntary program that establishes standards for car safety. NCAP is a key advocate for the integration of active safety systems in passenger cars.

In 2020 and 2022, OEMs seeking the NCAP's highest, five-star safety rating were faced with the challenges of implementing features such as automatic emergency braking (AEB) and automatic emergency steering (AES). As a result, US and European OEMs in all segments have developed these features, with more than 90 percent of all European- and American-made cars offering L1 capabilities as a baseline.

There is already sufficient regulation to enable companies to pilot robo-shuttle services in cities, primarily in the United States, China, Israel, and now in Europe. Companies will continue their test-and-learn cycles with the robo-shuttle pilots and move into a phase of stable operations over the next few years. Still missing, however, are global standards regarding AD functions for use in private vehicles, although many regulators are working on them.

The United Nations Economic Commission for Europe has a rule on automated lane-keeping systems that regulates the introduction of L3 AD for speeds up to 60 kilometers per hour. In addition, the UN's World Forum for Harmonization of Vehicle Regulations (WP.29) is working on additional regulation for using AD functions at higher speeds. This group plans to extend the use of advanced autonomous systems to speeds of up to 130 kilometers per hour, with the rule coming into force in 2023. Germany has also offered comprehensive legislation on AD that has allowed one European OEM to launch the first true L3 feature in a current model. Similar legislation exists in Japan and has recently been authorized in France. The development of global AD standards for private-passenger vehicles is clearly in motion.

Succeeding in the passenger car market

To succeed in the autonomous passenger car market, OEMs and suppliers will likely need to change how they operate. This may require a new approach to R&D that focuses on software-driven development processes, a plan to make use of fleet data, and flexible, feature-rich offerings across vehicle segments that consider consumers' varying price points. Decoupling the development of hardware components and software for AD platforms could allow automakers and suppliers to keep design costs more feasible, since the AV architecture could then be reused.

To win over consumers, auto companies could also develop a customer-centered, go-to-market strategy. Moreover, leaders might explore different ownership models and sales methods with the end-to-end (E2E) business case in mind, taking into account the entire life cycle of the autonomous vehicle. Finally, leaders may also need to create an organization that will support all of the above changes.

Creating a new R&D strategy

Succeeding in AD may require OEMs to make a mindset change. Simply put, the old ways of doing things are no longer valid. Successful OEMs should focus on building up in-house competencies such as excellence in software development. Although the automotive industry has honed its ability to split development work among multiple partners and suppliers, the sheer complexity of an L3- or L4-capable AD stack limits the potential for partnering with many different specialists.

Indeed, developing AD capabilities requires much stronger ownership of the entire ecosystem, as well as the ability to codevelop hardware and software—in particular, chips and neural networks. This suggests leading OEMs should either develop strong in-house capabilities or form partnerships with leading tech players tasked with delivering the entire driving platform.

OEMs would also benefit from holistically managing their road maps for developing AD features and portfolios of offerings. They should ensure that the AD architecture is flexible and reusable where possible. Moreover, to stay competitive over a vehicle platform's life cycle, systems must be easy to upgrade. Developing new strategies to collect fleet data, selecting relevant testing scenarios, and using the data to train and validate the AD system are also likely to be essential.

Developing customer-centered, go-to-market strategies

OEMs and their dealer networks should work to dispel the many uncertainties faced by consumers when deciding to buy a car with AD capabilities. Although consumers remain highly interested in AD, most buyers have not yet driven an autonomous car. Consumers receive many different (and sometimes contradictory) messages throughout the car-buying journey, from sources that hype up the technology to those that tout significant safety concerns. To win the trust of consumers, OEMs and dealerships may need to deliver additional sales training so that employees can pitch AD systems to customers and explain the technologies in enough detail to alleviate customer concerns.

Enabling customers to experience AD firsthand is critical, so auto companies may want to offer a test-drive that introduces the AD platform. Changing the business model from offering one-time licensing to an ongoing subscription plan could make it easier for customers to afford an AV and provide additional upside for OEMs. Our research indicates that in the future, all three business models (one-time sales, subscription pricing, and pay per use) may generate significant revenue. This implies that OEMs and other companies might need to adapt their go-to-market approach in order to sell subscriptions.

OEMs might consider offering subscriptions that go beyond AD features and potential vehicle ownership, such as in-car connectivity.

Making an end-to-end business case

With new forms of revenue coming in through subscriptions and pay-per-use offerings, OEMs may need to rethink how they calculate the business case for their vehicles and shift toward E2E marketing strategies. That means considering subscription pricing and length, sales of upgrades, software maintenance, and potential upselling to more advanced systems. For subscription pricing, OEMs are likely to face higher up-front costs, since they have to equip all vehicles with the technologies that will make AD features run. In return, they might expect higher customer use and revenues over the vehicle's life cycle.

Based on McKinsey's customer research and business case studies, AD subscription models may initially be economically viable only for premium D-segment vehicles (large cars such as sedans or wagons) and above, particularly those that already exhibit higher revenues from ADAS/AD functions. OEMs may need to adjust their internal key performance indicators (KPI), financing structures, and strategies for communicating with investors, since the E2E business model reduces short-term profitability in exchange for long-term revenue.

Reorganizing the company

Software is the key differentiator for AD, so organizations must excel in several areas: attracting coding talent, the development process, and capabilities in simulation and validation. It's worth noting that leading AD players do not necessarily have the biggest development teams. In fact, the development teams deployed by leading disruptive players are often significantly smaller than those of some other large OEM groups and tier-one suppliers. This highlights the importance of having the *right* talent, combined with effective development processes and best-in-class tool chains.

Experience suggests that deploying more resources can backfire, creating additional fragmentation and making communication needlessly complex for companies managing development projects.

Achieving long-term success may also require suppliers to articulate their competitive advantage and strategies. A targeted approach may yield higher returns.

This is why it is often not a winning formula to install managers experienced in hardware development or embedded-software development to lead AD systems' software development teams.

Implications for suppliers

Suppliers may also need to adapt to new industry success factors. They face fierce competition for full-stack solutions that may likely lead to a consolidation of players. To compete, suppliers must be focused and nimble. They might benefit from offering different delivery models to OEM customers, from stand-alone hardware solutions to fully integrated hardware–software solutions. In return, new opportunities may open up for developing joint business models closer to end customers, potentially including the possibility of revenue sharing.

For state-of-the-art AD solutions, companies will need access to large amounts of fleet data to train algorithms to achieve low-enough failure rates. While OEMs have fleet access and only need to find suitable technology to extract data from their customer fleets, suppliers must depend on partners or key customers to gain access. Consequently, it is mission critical for suppliers seeking to develop state-of-the-art AD systems to recruit a close lead customer early on for codevelopment and fleet access.

A lack of access to substantial amounts of fleet data, funding, and sufficient talent will probably limit the number of companies that can successfully offer full-stack AD systems. The result may be a "winner takes most" market dynamic. Companies with the best access to data and funding will likely enjoy a strong competitive advantage over those that do not have this information, since they will have a better chance to advance their technology and get ahead of their competitors.

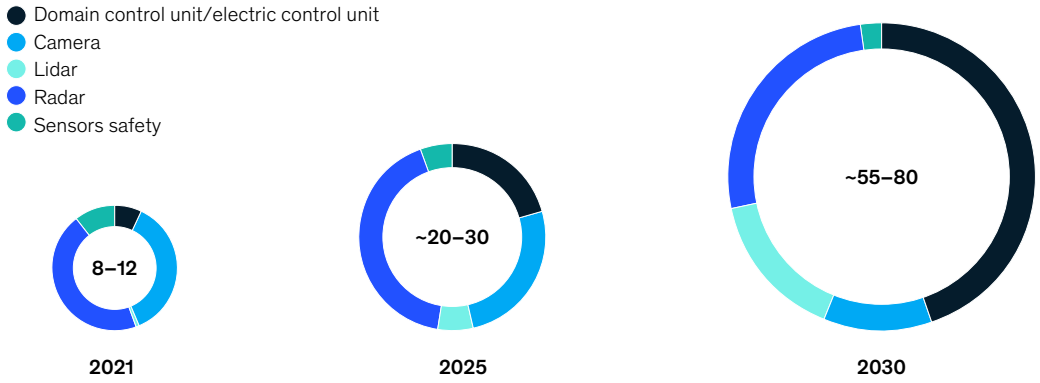
As a result, the number of successful suppliers or tech companies delivering a full AD system could likely remain limited to a handful of companies, in both the West and China. For the first generation of AD systems, joint development of software and the required chips may help the full system achieve better performance and efficiency, with a lower risk of late integration issues. This could further limit the number of potential industry winners.

Achieving long-term success may also require suppliers to articulate their competitive advantage, value proposition, and strategies. They should decide whether or not to become a full-stack player for the most advanced systems or concentrate on dedicated areas of the stack, which could be either hardware components or software elements. Our research shows that a targeted approach may yield higher returns for many suppliers and potentially offer substantial and attractive value pools. The total value of the passenger car AD components market could reach $55 billion to $80 billion by 2030, based on a detailed analysis that assumes a medium AD adoption scenario (Exhibit 5). In this

Exhibit 5

The total value of advanced driver-assistance systems and the autonomous-driving hardware market could reach $55 billion to $80 billion by 2030.

Autonomous-driving hardware value pools,[1] $ billion



[1]Estimates are for the passenger car market.
Source: McKinsey Center for Future Mobility

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scenario, most of the revenue would be generated by control units.

OEMs often follow different strategies for their lower-end ADAS and higher-end AD solutions, so suppliers that want to play across the entire technology stack may need to work within flexible delivery models. This could include supplying components, delivering stand-alone software functions such as parking, or delivering fully integrated ADAS or AD stacks. While delivering components is a business model that allows partnering with many different OEMs, supplying targeted software solutions or fully integrated software stacks is only possible when OEMs have decided to outsource.

Because most leading OEMs in AD development use in-house development for their most advanced systems, the number of potential customers for full-stack solutions is quite limited. For singular functions or add-ons (for example, parking or less sophisticated ADAS systems), there is a larger range of customers looking for suppliers. ADAS and AD systems are highly dependent on software, so supply chain monetization strategies could change. For instance, instead of charging a one-time fee for each component, suppliers might charge for performing regular system updates. They might even transition to a revenue-sharing model, which would increase the financial incentive to keep features up to date.

New technology companies are also entering a market previously reserved for tier-one automotive suppliers. Tech companies currently active in the passenger car market are mainly starting from a system-on-chip competency and building the software suite on top. There is also the chance that, in the future, L4 robo-taxi and robo-shuttle technology providers may enter the auto-supply market, but these companies will need to evaluate the applicability of AD technologies and cost positions against what customers require from passenger cars.

At first glance, these new tech companies may appear to threaten incumbent tier-one auto suppliers, since they compete for business from the same OEMs. But tech companies and incumbent tier-one suppliers could potentially benefit from new partnership opportunities in which they provide complementary capabilities in software and hardware development that would also help to industrialize AD solutions.

Securing a leading position as an AD supplier will likely be challenging. It may require companies to develop strong capabilities in technology and economies of scale to attain a position as cost leader. But as suppliers begin to talk to OEMs about equipping fleets with new technologies, additional new business opportunities—including profit sharing—could arise. Critically, suppliers could benefit from a new operating model for working with OEMs that ensures sufficient upside beyond just sharing risks, since suppliers do not have the direct access to car buyers or drivers that would allow them to communicate certain value propositions.

High potential, high uncertainty

New AD technologies have tremendous potential to provide new levels of safety and convenience for consumers, generate significant value within the auto industry, and transform how people travel. At the same time, the dynamic and rapidly evolving AD passenger car market is producing high levels of uncertainty. All companies in the AD value chain—from automakers and suppliers to technology providers—must have clear, well-aligned strategies. Companies seeking to win in the autonomous passenger car market could benefit from a targeted value proposition, a clear vision of where the market is heading (including well-developed scenarios that cover the next ten years at minimum), and an understanding of what consumers want most.

To start, companies can evaluate their starting positions against their longer-term business goals and priorities. The result should be an AD portfolio strategy, feature road map, and detailed implementation plan that addresses each critical success factor. Companies will likely benefit from securing key capabilities, revamping the organization, updating internal processes, and developing external relationships with partners and regulators. With OEMs regularly revisiting timelines for rolling out new AD vehicles, companies may also need to frequently review and update their business strategies. Success in AD is not a given. But to realize the full promise of autonomous driving, forward-looking companies and regulatory bodies can pave the way.

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