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Introduction

Of the many major advancements within the auto industry in recent decades, autonomous driving (AD) technology stands out as a path to revolutionize the future of mobility. Vehicles with various autonomous driving features have already been widely adopted by leading automotive manufacturers.

At the same time, automotive industry players (e.g., OEMs, startups, suppliers, academic institutions, and governmental bodies) are making progress in the development of more advanced autonomous driving technology—the creation of fully autonomous (driverless) vehicles.

Robotaxi and autonomous trucks are two common use cases for AD technology. Over the past couple of years, robotaxi companies have received widespread public attention and significant investments, yet investors and other participants of the AD industry have gradually realized that the commercialization of robotaxi may take longer than promised. Autonomous trucking, on the other hand, is a relatively under-tapped area with a larger total addressable market (TAM) and huge commercialization potential.

This report aims to provide insight into the technology and commercialization of autonomous trucking in both the U.S. and China.
Potential Benefits of Autonomous Driving (AD)
The concept of autonomous driving (AD) has been around for decades. However, the development of this technology has seen many twists and turns, and practical application has only become possible in recent years. This was made possible by advancements in artificial intelligence technologies such as computer vision, machine learning and deep learning, as well as the falling costs and improving performance of supporting hardware, particularly sensors and computing units.

Driver-in: Many Advantages Brought by Assistive Autonomous Driving Features

Improved road safety

In China, 43,413 people died from motor vehicle traffic accidents in 2019. In the United States, there were 33,244 fatal motor vehicle crashes in 2019, resulting in 36,096 deaths. Meanwhile, the number of people injured in crashes involving large trucks more than doubled from 74,000 to 159,000 from 2009 to 2019. With increasing traffic accidents, injuries and fatalities, truck fleets are exposed to higher levels of risk, which means higher deductibles and premiums, resulting in substantial increase in insurance costs over the last few years.

Driving behaviors involved in fatal crashes include speeding, driving under the influence of alcohol/drugs/medication, distraction, carelessness, and fatigue, among many others. According to National Highway Traffic Safety Administration (NHTSA), “94% of serious crashes are due to human error. Automated vehicles have the potential to remove human error from the crash equation, which will help protect drivers and passengers, as well as cyclists and pedestrians.” With the advent of AD technology, driving no longer demands human drivers’ full and prolonged attention, making it possible to reduce the number of traffic accidents caused by human error, or even eliminate them completely.

Improved comfort and satisfaction

A myriad of autonomous driving features, e.g., automatic parking, lane departure warnings (a system that warns the driver when the vehicle deviates from its original lane), adaptive cruise control (which detects the distance from the vehicle in front, and controls the vehicle’s motion to maintain a safe distance), to name a select few, have been widely adopted by leading automotive manufacturers, significantly enhancing driving comfort, especially for professional drivers.

Improved fuel efficiency and reduced environmental impact

Fuel efficiency is critical for road freight transportation, in which fuel costs make up around 20%–30% of total motor carrier costs. With the application of autonomous trucks, a reduction in fuel consumption of around 10% could be achieved. Additional gain from consistency across drivers could be realized as the most efficient drivers can outperform average ones by 10%–15% and the least efficient ones by 30% in terms of fuel saving.

9 Research Institute of Highway, Ministry of Transport & G7,《基于大数据的中国公路货运行业运行分析报告（2017）》(Big Data Based China Road Freight Operation Analysis Report), https://www.g7.com.cn/tmg/03%E5%9F%BA%A4%E6%8A%A7%E6%95%B0%E6%8D%AE%E7% A4%84%E4%B8%AD%E5%9B%BD%E5%8A%A1%E5%B1%855%88%AC%E8%B1%AF%E8%82%AF%E9%80%8A%E8%91%8C%E4%B8%9A%E8%BF%90%E8%A1%9C%E5%88%9E%E9%90%86%E6%8A%A5%E5%91%8A.pdf.
Multiple factors contribute to the fuel efficiency of autonomous vehicles.

- Firstly, advanced sensors, enhanced by software algorithms that fine-tune their output\(^{11}\), could provide accurate perception data on the vehicle’s surroundings, eliminating blind spots and enhancing the field of view as compared with human vision. In addition, data on real-time vehicle weight, wind and rolling resistance could also be collected.

- Secondly, maps used by autonomous vehicles could provide road slope data, in addition to two-dimensional location data, which could identify ascending or descending road conditions along the vehicle’s trajectory.

- Lastly, software algorithms could carry out speed and route planning based on perception, vehicle weight, wind resistance, rolling resistance, and map data, to select a more fuel-efficient route (e.g., a route with lighter traffic, fewer slopes, and fewer undesired stops), and adopt more fuel-efficient speed and trajectory control on a given route (e.g., a more stable speed), in comparison to human drivers.

The fuel efficiency that autonomous vehicles achieve could lead to lower energy consumption and greenhouse gas (GHG) emissions. To put the reduction in carbon footprint into perspective, we have made a rough estimate of the impact AD technology could have on the reduction of energy consumption and greenhouse gas emissions, taking the example of heavy-duty trucks in operation in the United States and China. (See Exhibit 1.)

### Exhibit 1 - Estimated Reduction in Fuel Consumption and Greenhouse Gas Emissions from the Application of AD Technology in Long-Haul HDT

<table>
<thead>
<tr>
<th></th>
<th>Annual savings... in fuel consumption</th>
<th>Annual savings... in CO(_2) emissions</th>
<th>Annual savings... in forests(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>4.4 billion liters</td>
<td>11.5 million metric tons</td>
<td>1 million hectares</td>
</tr>
<tr>
<td>China</td>
<td>14.3 billion liters</td>
<td>37.7 million metric tons</td>
<td>3.4 million hectares</td>
</tr>
</tbody>
</table>

**Source:** IHS Markit; lit research.

**Note:** As of 2020, according to IHS Markit, the number of long-haul heavy-duty trucks in operation in the US and China was estimated at around 1.5 million and 4.9 million, respectively. Assuming the trucks operate at an average speed of 65 km/h, 10 hours per day, 300 days per year, with fuel consumption at 0.3 liters of diesel per kilometer, and assuming a 10% reduction in fuel consumption from AD technology and a 50% adoption rate of the technology in heavy-duty trucks for both markets. Carbon emissions were calculated at an exchange rate of 0.717 kg of carbon per liter of diesel.

\(^1\) Carbon sequestration potential. The carbon sequestration rate was estimated at 3 metric tons per hectare per year (varying based on the type of trees: 0.8 to 2.4 metric tons per year in boreal forests, 0.7 to 7.5 metric tons in temperate regions, and 3.2 to 10 metric tons in the tropics).

\(^{11}\) To add more color, the algorithms could enhance sensor output, taking into consideration sensor vibration and drifting due to road conditions, acceleration/deceleration, as well as poor light levels on highways especially at nights/in tunnels.
Based on our assumptions of a 10% reduction in fuel consumption and a 50% adoption rate of AD technology in heavy-duty trucks, we estimate that the total fuel reduction in a year would amount to 4.4 billion liters and 14.3 billion liters in the U.S. and China respectively, corresponding to a reduction in CO2 emissions of 11.5 million metric tons and 37.7 million metric tons, respectively. As a point of reference, the total CO2 emissions of Norway and Switzerland in 2019 were 33.6 million metric tons and 38.2 million metric tons, respectively.

**Driver-out: Higher-level AD features, when human drivers are removed from the vehicle, could unlock more benefits**

Driver costs account for approximately 40% of taxi fares. In freight transportation, driver costs on average make up 42% of total freight revenue. With advanced AD technology taking over drivers’ positions in vehicles, both passenger and freight transportation costs can be reduced significantly. The shortage of drivers has been a long-standing issue in the trucking industry. The existing driver workforce is aging, while the new generation is less willing to enter the industry for various reasons, including but not limited to the less stimulating nature of the job and the lifestyle requirements of constant travel. The driver shortage in the trucking industry was estimated to be more than 60,000 in 2018 and is expected to continue to increase. The advent of driverless AD technology can alleviate the constraints on the supply side and fulfill the unmet demand in road logistics.

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Market opportunities and Use Cases of Autonomous Trucking
Definitions of AD Levels

The Society of Automotive Engineers (SAE) has defined six levels of driving automation, which have become widely accepted within the industry, ranging from no driving automation (Level 0, L0) to full driving automation15 (Level 5, L5). These levels have also been adopted by the U.S. Department of Transportation in developing policy and guidance on automated vehicles16.

The SAE level definitions take into account the roles played by the human driver, the driving automation system, and other vehicle systems and components (e.g., the wheels, throttle) in the performance of the driving task, and/or any task fallbacks. (Exhibit 2.) A high-level description of the six levels is as follows17:

- **L0**: A human driver performs all driving tasks and constantly supervises road conditions, with limited driver support features, such as forward collision warning, blind spot warnings, lane departure warnings, etc.

- **L1**: A human driver performs all driving tasks and constantly supervises road conditions, with some steering or braking/acceleration support, such as lane centering, adaptive cruise control, etc.

- **L2**: A human driver performs all driving tasks and constantly supervises road conditions, with both steering and braking/acceleration support, such as lane centering and adaptive cruise control, etc.

- **L3**: A human driver is not actively driving when the automated driving features are engaged but must act when prompted by the features. The automated features can drive the vehicle under limited conditions, such as traffic jams, etc.

- **L4**: No human driver is actively driving when the automated driving features are engaged, and a human driver will not be required to take over driving. The automated features can drive the vehicle under limited conditions. Pedals/steering wheel may not be installed.

- **L5**: No human driver is actively driving when the automated driving features are engaged, and a human driver will not be required to take over driving. The automated features can drive the vehicle under all conditions.

### Exhibit 2 - SAE J3016 Levels of Driving Autonomation

<table>
<thead>
<tr>
<th>Level 0</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driver support features</strong></td>
<td><strong>Automated driving features</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warnings</td>
<td>Steering OR braking/acceleration support</td>
<td></td>
<td>Traffic jam pilot</td>
<td></td>
<td>Drives the vehicle under all conditions</td>
</tr>
<tr>
<td></td>
<td>Lane centering OR Adaptive cruise control</td>
<td></td>
<td>• Local driverless taxi • Pedals/steering wheel may or may not be installed</td>
<td></td>
<td>Same as level 4, but capable of driving anywhere and in all conditions</td>
</tr>
<tr>
<td>Example features</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Forward collision warning • Blind spot warning • Lane departure warning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Driving (features' OFF)</strong></td>
<td><strong>Driving (features' ON)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human driver</td>
<td>Autonomous driving system</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supervision of features¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant supervision by human drivers</td>
<td>Prompts indicate when to drive</td>
<td></td>
<td>No supervision required</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Source:** SAE International; BCG analysis.

¹ Autonomous driving features, as discussed above.

¹¹ Features will not operate unless all required conditions are met.

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15 SAE International, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, April 2021, https://www.sae.org/standards/content/j3016_202104/.


17 SAE International, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, April 2021, https://www.sae.org/standards/content/j3016_202104/.
A similar categorization approach, defined by Edge Case Research (ECR), proposes four operational modes based on both the roles and responsibilities of the human driver and separately how the vehicle is operated, i.e., assistive (human driving), supervised (eyes on the road), automated (eyes off the road), and autonomous driving (no human driver). (See Exhibit 3.)

- **Assistive**: Regardless of any vehicle support features, a human driver is responsible for all driving tasks, ensuring driving safety, and other aspects of safety (e.g., passenger safety); the driving support features include cruise control, automatic emergency braking, etc. This corresponds to SAE levels L1 and L2.

- **Supervised**: The driving automation system can perform steering and speed control, while a human driver constantly monitors driving safety and takes control when needed. This category corresponds to SAE levels L2 and L3.

- **Automated**: The driving automation system is responsible for driving and ensuring driving safety. However, a responsible person is required for other aspects of safety, such as children in the vehicle and securing cargo. This category corresponds to SAE levels L4 and L5.

- **Autonomous**: The driving automation system is responsible for driving and ensuring driving safety, along with other aspects of safety, with no human supervision. This category corresponds to SAE levels L4 and L5, as well as other safety issues beyond the scope of SAE levels.

Exhibit 3 - ECR Categorizes Vehicle Automation Based on the Driver’s Role and Responsibility for Vehicle Operations

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Human Role</th>
<th>Driving</th>
<th>Driving Safety</th>
<th>Other Safety¹</th>
<th>SAE level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assistive</td>
<td>Driving</td>
<td>![Driver Icon]</td>
<td>![Driver Icon]</td>
<td>![Driver Icon]</td>
<td>L1–L2</td>
</tr>
<tr>
<td>Supervised</td>
<td>Eyes ON the road</td>
<td>![Vehicle Icon]</td>
<td>![Driver Icon]</td>
<td>![Driver Icon]</td>
<td>L2–L3</td>
</tr>
<tr>
<td>Automated</td>
<td>Eyes OFF the road</td>
<td>![Vehicle Icon]</td>
<td>![Vehicle Icon]</td>
<td>![Driver Icon]</td>
<td>L4–L5</td>
</tr>
<tr>
<td>Autonomous</td>
<td>No human driver</td>
<td>![Vehicle Icon]</td>
<td>![Vehicle Icon]</td>
<td>![Driver Icon]</td>
<td>L4–L5</td>
</tr>
</tbody>
</table>

Source: Edge Case Research; BCG analysis.

¹ Other safety tasks beyond actual driving, e.g., passenger safety.

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Adoption of AD Levels

SAE L2 adoption. Advanced driver assistance systems (ADAS), or SAE L2 automation technology, are increasingly becoming part of the standard package for newly released vehicles, especially passenger vehicles. For instance, in China, the installation rate of L2 AD features on insured passenger cars was 16.1% from January to November 2020\(^{19}\). Further, more and more OEMs struggle to sell new models without L2 features in key markets.

On the other hand, commercial vehicles’ volumes are much lower than passenger cars, and the requirements for reliability and robustness are higher since trucks’ expected lifetime is significantly longer than passenger cars. Trucks also present greater challenges for vehicle control, for example due to significantly longer stopping distances, less room to maneuver in the lane, articulation, large disturbances from wind, pneumatic brakes with significant latency, etc. As a result, commercial vehicles have a lower penetration rate of electronically controlled actuation (drive-by-wire) systems such as steering, acceleration and braking\(^{20}\). Moreover, the adoption of AD technology lags behind passenger vehicles, and most commercial vehicle OEMs are still focusing on developing L2 AD features for mass-produced models.

SAE L2+ adoption. SAE L2+ is the most advanced level of automation available for mass-produced vehicles today and is currently only available for passenger vehicles. The key difference between L2+ and L2 is that an L2+ AD system allows for integrated adapted cruise control\(^{21}\) (IACC) and automatic lane changing\(^{22}\) (ALC). Tesla was among the first automakers to mass produce passenger vehicles with SAE L2+ AD technology, naming the AD feature Navigate on Autopilot (NoA\(^{23}\)). Other automotive players, including NIO\(^{24}\), XPeng\(^{25}\), and Li Auto\(^{26}\), have also rolled out similar L2+ features.

SAE L3 adoption. SAE L3 features include traffic jam pilot (an autonomous driving system that can take over in designated traffic jam scenarios), highway pilot system (an autonomous driving system that can take over in designated highway driving scenarios), and automated valet parking (an autonomous parking system integrated into the autonomous driving system). It is important to note that the “eyes off” functionality is a critical differentiating factor between SAE L2/L2+ and L3 features, for example the difference between traffic jam assist (the driver needs to monitor the AD system) and traffic jam pilot. To date, no mass-produced L3 vehicles have become available. In March 2021, Honda began leasing of a small number of L3 automated vehicles in Japan, featuring the traffic jam pilot function\(^{27}\). Mercedes-Benz is also planning to roll out mass-produced new 2021 S-Class models with L3 features\(^{28}\).

SAE L4 and L5 adoption. Although advanced driverless automation is not yet ripe for commercialization, leading automotive manufacturers are actively developing SAE L4 and above autonomous driving features for future passenger and commercial vehicle models. For instance, General Motors acquired the start-up company Cruise in 2016 to develop autonomous vehicles and expects to begin operating self-driving taxis in Dubai in 2023, reaching 4,000 driverless shuttles by 2030\(^{29}\). Waymo, which is backed by Google, was formed in 2009 out of Google’s internal self-driving project and rolled out its fully autonomous ride-hailing service in the suburbs of Phoenix in 2020\(^{30}\). A myriad of startup companies, such as Argo.ai, Aurora, Pony.ai, Plus, and TuSimple are developing SAE L4 autonomous driving solutions, with many already conducting global road tests in collaboration with OEMs.

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20 Electronically controlled systems are a prerequisite for driving automation systems.
21 IACC allows for autonomous driving system assisted single-lane driving, including lane keeping assist, traffic jam assist, etc.
22 ALC allows the autonomous driving system to change lanes after the driver’s lane change confirmation.
27 The traffic jam pilot function allows the automated driving system to drive the vehicle in congested traffic on an expressway unless a handover request is made for the driver to take over the driving task, https://hondanews.eu/et/corporate/media/pressreleases/329456/honda-launches-next-generation-honda-sensing-elite-safety-system-with-level-3-automated-driving-feat.
SAE L2+ is the most advanced level of automation available for mass-produced passenger and commercial vehicles today.
Use cases of L4 and Above Levels of AD Technology

Advanced (i.e., SAE L4 and above) autonomous driving technology can be applied in different use cases. We have highlighted the main use cases below based on the purpose of use and operating environment. (See Exhibit 4.)

Along the purpose of use dimension, we can impose further subdivisions based on what is being transported—people/passengers vs. goods/cargo. This segment use cases by the type of vehicles used—passenger vehicles (e.g., cars) and commercial vehicles (e.g., trucks, vans). Based on the operating environment, use cases could be segmented into closed environments and open roads. The former has fixed operating zones, including campuses, parking lots, airports, and industrial sites, and the latter encompasses public roads with higher traffic complexity and more unpredictable human/vehicle movements. The main use cases along these two dimensions are summarized below:

Exhibit 4 - Autonomous Driving Use Cases Can Be Segmented by Purpose of Use and Operating Environment

Source: Lit research; BCG analysis.

1 Note: PV stands for passenger vehicle; CV stands for commercial vehicle.

Robotaxi is also known as autonomous driving taxi.
Transporting passengers

- **Autonomous passenger vehicles for special purposes:** Includes automated valet parking functions (allowing the vehicle to park itself automatically), and autonomous shuttle vehicles in closed environments such as parks and airports.

- **Robobus:** Autonomous buses that serve commuting needs, either in closed/semi-closed or open environments.

- **Robotaxi:** Autonomous cars operated by ride-sharing companies, providing ride-hailing services.

Transporting cargo/goods

- **Autonomous commercial vehicles for special purposes:** Includes autonomous trucks operating at ports, airports, and other closed venues for freight transportation.

- **Autonomous commercial vehicles for last mile delivery:** Serving last mile supply chain logistics, commonly small, inexpensive sidewalk autonomous vehicles for food and grocery delivery.

- **Autonomous trucking:** Also known as robotrucks, operated by shippers or third-party commercial operators to serve logistics needs.
AD in Open Road Conditions Presents A Greater Market Opportunity Than AD in Closed Environments

As discussed above, advanced autonomous driving (SAE L4 and above) can be applied in closed environments (e.g., parking lots, airports, and industrial sites) and in open road conditions (e.g., city roads and highways).

In terms of commercialization potential, AD in closed environments is generally considered to be more ready for deployment than AD in open road conditions. Typically, AD use cases in closed environments are associated with fixed routes and/or low-speed requirements, where traffic conditions are simpler and human movements are more predictable. Regulatory requirements in closed zones are also expected to be less stringent than in open road scenarios.

Nevertheless, open road use cases present significantly higher market potential and a higher entry barrier than closed environment applications. Therefore, they have attracted more attention and investment. Top-valued startup companies in the autonomous driving space, according to the most widely used rankings, are almost exclusively focused on open road use cases, especially robotaxi. (See Exhibit 5.)

Compared to the robotaxi segment, which has seen significant investment and development, autonomous trucking is an under-tapped market segment with immense potential.

Exhibit 5 - Last Known Valuation of Leading Autonomous Driving Companies

<table>
<thead>
<tr>
<th>Business focus</th>
<th>Time of latest valuation</th>
<th>Waymo</th>
<th>Cruise</th>
<th>Aurora</th>
<th>TuSimple</th>
<th>Argo.ai</th>
<th>DiDi</th>
<th>Pony.ai</th>
<th>Embark</th>
<th>Nuro</th>
<th>Plus</th>
<th>WeRide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose-built self-driving vehicles for ride-hailing and delivery</td>
<td>May 2020</td>
<td>30,750</td>
<td>30,000</td>
<td>13,000</td>
<td>9,750</td>
<td>7,250</td>
<td>6,000</td>
<td>5,300</td>
<td>5,200</td>
<td>5,000</td>
<td>3,300</td>
<td>3,300</td>
</tr>
<tr>
<td>Development of autonomous driving technology for global truck transportation</td>
<td>Jul 2021¹</td>
<td>30,750</td>
<td>30,000</td>
<td>13,000</td>
<td>9,750</td>
<td>7,250</td>
<td>6,000</td>
<td>5,300</td>
<td>5,200</td>
<td>5,000</td>
<td>3,300</td>
<td>3,300</td>
</tr>
<tr>
<td>Development of autonomous driving technology for fleet services</td>
<td>Jul 2021²</td>
<td>30,750</td>
<td>30,000</td>
<td>13,000</td>
<td>9,750</td>
<td>7,250</td>
<td>6,000</td>
<td>5,300</td>
<td>5,200</td>
<td>5,000</td>
<td>3,300</td>
<td>3,300</td>
</tr>
<tr>
<td>Development of autonomous driving technology for robotaxi and logistics services</td>
<td>Jun 2020</td>
<td>30,750</td>
<td>30,000</td>
<td>13,000</td>
<td>9,750</td>
<td>7,250</td>
<td>6,000</td>
<td>5,300</td>
<td>5,200</td>
<td>5,000</td>
<td>3,300</td>
<td>3,300</td>
</tr>
<tr>
<td>Development of autonomous driving technology for commercial trucks</td>
<td>May 2020</td>
<td>30,750</td>
<td>30,000</td>
<td>13,000</td>
<td>9,750</td>
<td>7,250</td>
<td>6,000</td>
<td>5,300</td>
<td>5,200</td>
<td>5,000</td>
<td>3,300</td>
<td>3,300</td>
</tr>
<tr>
<td>Development of fully autonomous vehicles to deliver mobility as a service to the public</td>
<td>Nov 2020</td>
<td>30,750</td>
<td>30,000</td>
<td>13,000</td>
<td>9,750</td>
<td>7,250</td>
<td>6,000</td>
<td>5,300</td>
<td>5,200</td>
<td>5,000</td>
<td>3,300</td>
<td>3,300</td>
</tr>
</tbody>
</table>

Source: Company websites; Pitchbook; BCG analysis.

Note: Valuation and company description from Pitchbook unless otherwise noted (accessed May 28th, 2021).

¹ Based on Cruise’s estimate following Microsoft’s investment in Jan 2021.

² Based on Aurora SPAC valuation.

³ Based on TuSimple’s market cap as of July 2021.

⁴ Based on Embark SPAC valuation.
Compared to robotaxi, autonomous trucking is an under-tapped market segment with immense potential.
While the robotaxi area has attracted investments from leading automotive industry players, tech giants, private equity and sovereign wealth funds alike, autonomous trucking is relatively under-tapped, yet it presents immense market potential.

China and the U.S. are the biggest ride-hailing/taxi markets globally, with the GMV of each market estimated at $93 Bn and close to $48 Bn in 202131, respectively. Furthermore, China and the U.S. are also the world’s largest freight markets. Revenue in China’s logistics market topped $1.3 Tn in 202032, of which the road freight market is estimated to be worth $900 Bn by 202133. Freight trucking revenue in the U.S. is close to $800 Bn, based on 2019 estimates34.

In terms of employment in the ride-hailing/taxi and road logistics market, the number of taxi drivers in China in 2019 was estimated to be between 1.4 million and 2.8 million35, and the number of registered ride-hailing drivers was 2.9 million in 2020, although many ride-hailing drivers work part-time36. In the US, the number of taxi drivers, ride-hailing drivers, and chauffeurs in 2018 was estimated to be 370,40037. In comparison, there were more than 18 million truck drivers in China in 202038, and more than 3.5 million truck drivers in the U.S. in 201939.

Judging by the potential economic magnitude of savings generated by SAE L4 and above autonomous driving technology in both China and the U.S., the road logistics market presents significant market potential for autonomous driving technology disruption.

Customer acceptance of autonomous trucking is also expected to be higher than robotaxi. In terms of end users, autonomous trucking mainly serves shippers for road logistics, while robotaxi directly transport end users to their destinations. While shippers care about the safe and timely delivery of their goods, robotaxi passengers are also concerned about their safety and comfort and tend to perceive higher risks and be more cautious about using autonomous vehicles as compared to shippers, whose decision-making process tends to be driven by financial savings.

Within the road logistics market, long-haul heavy-duty trucking is the most promising segment for autonomous trucking commercialization, rather than intra-city logistics and inter-city logistics via light or medium-duty trucks. Heavy-duty trucks are trucks with a gross vehicle weight of 26,000 pounds or above. Long-haul heavy-duty trucking refers to heavy-duty trucks operating from hub-to-hub in between cities, with relatively fixed highway routes. Compared with complex intra-city urban traffic conditions, long-haul trucking with relatively fixed routes may be more ready for commercialization40. With higher gross weight than medium-duty or light-duty trucks, logistics revenue from heavy-duty trucks is expected to be higher based on a common ton-mileage revenue model.

Considering the massive market potential and positive commercialization prospects of long-haul autonomous trucking, many leading robotaxi players have also begun to tap into the autonomous trucking space. In the following discussion, we will focus on the long-haul segment within autonomous trucking.

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31 Statista, updated April 2021.
33 EqualOcean Intelligence, assuming exchange rate of USD to RMB at 6.5.
36 Ministry of Transportation, Official Wechat Press Release, January 2021, https://mp.weixin.qq.com/s?__biz=MzI3MDQwMDQSQ==&mid=2247532908&idx=1&sn=1611aa49f2ef5d76b1e233e9a349888f&scene=0.
Development progress and commercialization strategy of autonomous trucking players
Major Autonomous Trucking Players are Focusing on Achieving Highway Autonomy in Various Regions with Different Roadmaps

Several technology startups are involved in the L4 autonomous trucking industry, including dedicated autonomous trucking players (e.g., TuSimple, Plus, and Inceptio) and robotaxi players tapping into the autonomous trucking field\(^1\) (e.g., Waymo and Aurora).

**In terms of addressable market**, these companies vary both in terms of geographic presence and business focus. (See Exhibit 6.)

From the perspective of business focus, these players can be divided into two groups: dedicated autonomous trucking players, and robotaxi players tapping into autonomous trucking.

- Dedicated autonomous trucking players are companies that focus purely on developing autonomous trucking technology, such as TuSimple, Plus, and Inceptio.

- A number of robotaxi pioneers have started to pay more attention to the autonomous trucking segment due to its attractive total addressable market and more promising prospects for commercialization. Examples of robotaxi players tapping into the autonomous trucking field include Waymo and Aurora, which are trying to adapt their AD technology for commercial vehicles.

Nevertheless, several challenges lie along the way. For instance, commercial vehicles operate at higher speeds than passenger cars, carry heavier and more complicated loads, and operate in different environments as compared to passenger vehicles—see Chapter Technology Components and Roadmap for a more detailed analysis.

Geographic presence is defined according to whether the company is road testing fleets in the U.S. or China.

- TuSimple’s commercialization plan focuses on building up an Autonomous Freight Network in the U.S. by 2024, with the intention of expanding into Europe and China.

Exhibit 6 - Leading Players in Autonomous Trucking Have Different Business Focuses and Geographic Presences

![Exhibit 6 - Leading Players in Autonomous Trucking Have Different Business Focuses and Geographic Presences](image)

**Source:** BCG analysis.

\(^1\) These players aim to develop L4 AD solutions, which have multiple business applications (robotaxis, trucking, local delivery, etc.). They began by developing robotaxi technology before expanding into autonomous trucking.

\(^{11}\) Defined according to whether the company is road testing fleets in the U.S. or China.

---

41 These players aim to develop L4 AD solutions, which have multiple business applications (robotaxis, trucking, local delivery, etc.). They began by developing robotaxi technology before expanding into autonomous trucking.
• Plus partners with FAW in China and plans to mass produce a driver-in autonomous driving J7 truck beginning 2021. Meanwhile, in the U.S., Plus has received an order from Amazon for 1,000 autonomous driving systems. Plus is also expanding beyond the U.S. and China through a partnership with IVECO to jointly develop autonomous trucks for China, Europe, and other markets.

• Waymo and Aurora are players with a geographic presence in the U.S.

• Inceptio mainly operates in China.

**In terms of development progress**, these companies vary in terms of financial resources (total funding raised), industry partnerships (with OEMs, shippers, fleets, and strategic investors), commercialization progress (product release date, pre-orders and orders) and management team background. (See Exhibit 7.) For reference, we have listed the top-selling trucking OEMs in China, the U.S., and Europe. (See Exhibit 8.) Among all these players, TuSimple and Plus are pioneers, both in terms of total funding raised and industry partnerships.

**TuSimple** was the first autonomous driving vehicle company to go public, and is dedicated to developing autonomous technology specifically designed for semi-trucks.

TuSimple was founded in 2015 and started testing its L4 AD system between Tucson and Phoenix in 2017. TuSimple began hub-to-hub autonomous hauling for customers in Tucson in August 2018. In May 2019, the company was awarded a contract for a pilot project hauling USPS trailers between Phoenix and Dallas distribution centers, with a safety engineer and a safety driver on board. UPS took a minority stake in TuSimple in August 2019 and started to collaborate on road testing, which had expanded from 10 to 20 round trips per week by the following year.

Apart from collaboration with carriers, TuSimple has also entered into partnerships with several OEMs and Tier 1 suppliers (Navistar, ZF, Traton, etc.) to co-develop L4 autonomous trucks. According to the company’s investor presentation, TuSimple plans to roll out its Autonomous Freight Network in phases to cover major road freight routes in the U.S. by 2024.

TuSimple completed a $1.35 billion IPO on Nasdaq in April 2021, becoming the world’s first autonomous trucking technology company to go public in the U.S. using the symbol TSP. According to its first quarter 2021 shareholder letter, it operates seventy L4 trucks with 3.7 million accumulated road miles and has 6,775 purpose-built L4 truck reservations from approximately ten customers for deployment starting 2021.

**Plus is expected to be the second autonomous trucking company to go public in the U.S.** Plus was founded in 2016 and has been focusing on enabling large-scale autonomous commercial trucking fleets. Plus demonstrated its full-stack L4 autonomous trucking solution on a Las Vegas truck route during CES in 2019. In December 2019, Plus completed a coast-to-coast commercial freight delivery with its L4 autonomous truck, driving over 2,800 miles from California to Pennsylvania through diverse landscapes and mixed weather conditions. In 2020, Plus announced that it had been testing its L4 autonomous trucks in 17 states and planned to expand the testing to cover all states in the continental U.S. where such testing is allowed. According to the 8-K SEC filing, Plus has entered into a master purchase agreement and an initial work order effective January 27, 2021 with Amazon that provides for the purchase of at least 1,000 Plus Retrofit units. In the third quarter of 2021, Plus completed the world’s first driver-out autonomous truck testing on a highway in Jiangsu.

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**42** Human drivers still need to supervise the vehicle during the process.


**45** TuSimple’s prospectus.


**47** TechCrunch, Kirsten Korosec, Self-driving truck startup TuSimple will haul mail for USPS in two-week pilot, [https://techcrunch.com/2019/05/21/self-driving-truck-startup-tusimple-will-haul-mail-for-usps-in-two-week-pilot/](https://techcrunch.com/2019/05/21/self-driving-truck-startup-tusimple-will-haul-mail-for-usps-in-two-week-pilot/).

**48** Company will double its number of driverless trips for big-rig trucks in Arizona, Arizona Republic, Russ Wiles, [https://www.azcentral.com/story/money/business/tech/2020/03/05/tusimple-add-driverless-trips-ups-trucks-arizona/493028502/](https://www.azcentral.com/story/money/business/tech/2020/03/05/tusimple-add-driverless-trips-ups-trucks-arizona/493028502/).

**49** TuSimple investor presentation, [https://ir.tusimple.com/static-files/8b58df53-5193-4ea4-b2d9-1c353248ebbe](https://ir.tusimple.com/static-files/8b58df53-5193-4ea4-b2d9-1c353248ebbe).

**50** TuSimple investor presentation, [https://ir.tusimple.com/static-files/8b58df53-5193-4ea4-b2d9-1c353248ebbe](https://ir.tusimple.com/static-files/8b58df53-5193-4ea4-b2d9-1c353248ebbe).

**51** TuSimple Shareholder letter, [https://ir.tusimple.com/static-files/cd692b77-9a7f-4482-9c2c-d593321779c4](https://ir.tusimple.com/static-files/cd692b77-9a7f-4482-9c2c-d593321779c4).


**56** Form 8-K Hennessy Capital Investment Corp. [V](https://sec.report/Document/0001213900-21-033147/).
### Exhibit 7 - Major Autonomous Trucking Players

<table>
<thead>
<tr>
<th>Basic info</th>
<th>Players</th>
<th>Financial resources</th>
<th>Industry partnership</th>
<th>Commercialization progress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TuSimple</td>
<td>Founded in 2015, 2016</td>
<td>Total funding: ~$1,816 million (2021.4)</td>
<td>Pre-orders/Orders: 4,775 (pre-order)</td>
</tr>
<tr>
<td></td>
<td>Plus</td>
<td>Founded in 2018, 2018</td>
<td>~$1,107 million (2021.3)</td>
<td>6,800 (FTA, pre-order) and 1,000 (Amazon, order)</td>
</tr>
<tr>
<td></td>
<td>Inceptio</td>
<td>Founded in 2018, 2018</td>
<td>~$220 million (2020.10)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Waymo</td>
<td>Founded in 2009, 2017</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Aurora</td>
<td>Founded in 2019</td>
<td>~$1,500 million (2020.10)</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Players

<table>
<thead>
<tr>
<th>Name</th>
<th>Education background</th>
<th>Work experience</th>
<th>Management team background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheng Lu</td>
<td>MBA, Harvard Business School</td>
<td>14+yrs of work experience in strategy and corporate finance (KCA Capital, HOPLI, Cityi, Cyberus, Citi)</td>
<td>Co-founded TuSimple and served as president &amp; CTO after earning his PhD</td>
</tr>
<tr>
<td>David Liu</td>
<td>PhD in Electrical Engineering, Stanford University</td>
<td>20+yrs of work experience, including ~16yrs as a serial entrepreneur (Plus, RedMoon, RMO Networks, Infrablink), ~2yrs as a consultant (MCK-inno) and ~3yrs as an engineer (Silicon Graphics)</td>
<td>Co-founder and CEO of Anki, and ~3 yrs as software lead at Robotix</td>
</tr>
<tr>
<td>Julian Ma</td>
<td>MBA, International Institute for Management Development</td>
<td>~30 yrs of work experience as a professional manager at multiple corporates (Hopito, G7, Tencent, A.T. Kearney, Motorola)</td>
<td>17 yrs of research experience in machine learning and robotics (CMU), including 2 yrs as autonomy architect and perception lead at Uber</td>
</tr>
<tr>
<td>Dmitri Dolgov</td>
<td>PhD in Computer Science, University of Michigan; Teledra Mawakana: JD, Law, Columbia Law School</td>
<td>~16yrs of work experience in autonomous driving, including ~14yrs as CTO at Waymo, ~9yrs as a distinguished software engineer at Google, and ~3 yrs as a researcher (Stanford, Toyota Research Institute); Teledra Mawakana: 20yrs of work experience in government relations and public policy in technology companies (Waymo, eBay, Yahoo, AG)</td>
<td>16 yrs of work experience in autonomous driving, including ~4yrs at Aurora, ~8yrs as lead engineer and CTO in Google’s self-driving car project, and ~8yrs as a researcher (SAIC, Tartan Racing, and CMU)</td>
</tr>
<tr>
<td>Chris Urmson</td>
<td>PhD in Robotics, Carnegie Mellon University</td>
<td>~16yrs of work experience in autonomous driving, including ~14yrs as CTO at Waymo, ~9yrs as a distinguished software engineer at Google, and ~3 yrs as a researcher (Stanford, Toyota Research Institute); Teledra Mawakana: 20yrs of work experience in government relations and public policy in technology companies (Waymo, eBay, Yahoo, AG)</td>
<td>16 yrs of work experience in autonomous driving, including ~4yrs at Aurora, ~8yrs as lead engineer and CTO in Google’s self-driving car project, and ~8yrs as a researcher (SAIC, Tartan Racing, and CMU)</td>
</tr>
</tbody>
</table>

#### Source:

- Pitchbook: Crunchbase; LinkedIn; lit research.
- Includes Plus’s expected funding from its SPAC merger ($500 million).
- Total funding for both robotaxi and autonomous trucking businesses.
- According to TuSimple’s website.
- According to TuSimple’s prospectus, until customers enter into a purchase agreement, which is at the discretion of the customer, the reservation can be canceled and the customer is entitled to a full refund of their deposit. TuSimple has not entered into purchase agreements with any of its customers that have reserved its purpose-built L4 autonomous semi-trucks.
- According to 8-K SEC filings, on June 19, 2021, Plus issued to Amazon a warrant to purchase at an exercise price of $0.46647 per share, up to 420,702,410 Series C-1 preferred shares of Plus, which represents approximately 20% of the fully diluted ownership percentage of Plus.

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#### Pre-Supplementary Notes

- Most advanced degree.
- According to Chris’ LinkedIn page, he worked both as an assistant research professor at CMU and an engineer in Google’s self-driving car project from Feb 2009 to Jun 2011.
- Head of engineering for trucking at Waymo.
In terms of industry partnerships, in September 2019, Plus announced a joint venture with FAW, the largest heavy-duty truck manufacturer in the world by volume, exclusively focusing on autonomous truck development. In July 2020, Plus finalized an agreement with the Transportation Research Center (TRC) to carry out rigorous third-party testing of Plus’s autonomous driving system in real-world conditions. In November 2020, the J7 truck jointly developed by FAW and Plus passed the national certification test at the China Automotive Technology & Research Center (CATARC) and is expected to begin mass production in 2021. In April 2021, Plus announced a Memorandum of Understanding (MOU) with IVECO to jointly develop autonomous trucks for deployment across China, Europe, and other markets.

Exhibit 8 - Top HDT OEMs by 2020 Sales Volume in China, the U.S. and Europe

2020 HDT (Heavy-Duty Truck) Sales Volume Breakdown (K units)

China: 1,427K in total, top 5 account for 82% of the market

United States: 189K in total, top 4 account for 97% of the market

Europe: 157K in total, top 6 account for 87% of the market

Source: IHS Markit; BCG analysis.

CNH Industrial holds IVECO.

Among all these players, TuSimple and Plus are pioneers, in terms of both total funding raised and industry partnerships.
In May 2021, Plus announced that it would become publicly listed on the NYSE using the symbol PLAV through a merger with a publicly traded SPAC (Special Purpose Acquisition Company (SPAC), Hennessy Capital V (ticker: HCIC). Inceptio, a China-based autonomous trucking company, was jointly established by G7, Global Logistic Properties Ltd., and NIO Capital in 2018. The company collaborated with logistics platform Yimidida to start commercial trials in 2019 and released its proprietary full-stack autonomous driving system “Xuanyuan” in March 2021 to support mass-produced L3 trucks by the end of 2021\(^62\). Meanwhile, there are also several robotaxi unicorns attempting to adapt their autonomous driving technology to the autonomous trucking segment.

Waymo, a well-recognized first mover and leader in autonomous driving, was founded by Google in 2009 and started its trucking program in 2017. Waymo has been working on an autonomous driving solution for multiple applications (robotaxi, trucking, local delivery, etc.). Waymo, best known for its robotaxi service in Phoenix, started autonomous truck testing in Arizona, Georgia, Florida, and California in 2017\(^63\). In March 2020, Waymo formally launched “Waymo Via”, its trucking business unit, which expanded truck testing to New Mexico and Texas\(^64\). Waymo announced a global strategic partnership with Daimler in October 2020 to integrate Waymo’s autonomous trucking technology into Daimler trucks\(^65\).

Aurora, another U.S. based autonomous driving startup, was founded in 2017 and started its trucking efforts in 2019. Similar to Waymo, Aurora is a self-driving technology company developing autonomous driving technology (Aurora Driver) that can be implemented in both trucks and passenger vehicles. The company first focused on robotaxi and entered the autonomous trucking segment around 2019. In May 2019, Aurora acquired LiDAR developer Blackmore to help create its FirstLight LiDAR technology, which uses frequency modulated continuous wave (FMCW) LiDAR for long-range sensing\(^66\). In May 2021, Aurora announced its first commercial trucking pilots on several key “middle-mile” routes in Texas\(^67\). It has built partnerships with leading truck OEMs Paccar and Volvo\(^68\).

In terms of commercialization strategy of L4 trucking technology, business models are still at an early stage. In the near term (2021–2024), there are two models.

1. The more commonly seen model involves AD companies running small-scale pilots and carrying loads for fleet operators or shippers. These are generally non-exclusive and require relatively large capital expenditures.

2. The other model is jointly producing vehicles by partnering with OEMs and fleets, which are then delivered to fleet customers to operate themselves. This type of partnership tends to be more in-depth and longer-term, with the potential to generate sizable cash flow through sales of autonomous vehicles.

In the long term (2024 and beyond), two different business models have been announced by top players. (See Exhibit 9.)

1. Autonomy-as-a-service model: the AD company partners with OEMs to develop an integrated hardware-and-software solution and monetizes by selling autonomous driving solutions alongside OEMs to fleets (not shippers). Fleets remain responsible for operating the truck, though they are paying significantly less for labor.

2. Fleet-as-a-service model: the AD company acts as a fleet, by operating its own vehicles and providing logistics services to shippers. This model makes the AD company a potential competitor to the customer (fleets) in model (1).

Some autonomous trucking players have announced their roadmaps for the planned commercialization of their autonomous trucking technology. For instance, TuSimple plans to adopt both models above\(^69\), while Plus plans to mainly focus on the autonomy-as-a-service model. The potential advantage of adopting multiple business models is the larger combined addressable market and the prospect of higher revenues, but market cannibalization may become a problem in the long-term as players adopting the fleet-as-a-service business model may have to compete directly with the fleet customers who subscribe to their AD solutions through the autonomy-as-a-service model.

64 Waymo website, https://waymo.com/company/.
66 Aurora website, https://aurora.tech/blog/developing-the-aurora-driver-for-trucks.
68 Aurora website, https://aurora.tech/.
69 Fleet operators purchase TuSimple’s purpose-built L4 autonomous semi-trucks through OEMs and subscribe to TuSimple Path to access AFN.
Certain Technologies, Such As Fleet Management Systems (FMS) and Platooning, Are Relevant to AD But Are Not AD Features by Definition

Apart from autonomous driving, other technologies can also help improve the overall driving experience. (See Exhibit 10.)

**Fleet Management Systems (FMS)** are analytics platforms that enable fleet operators to track and control fuel consumption, operational costs, vehicle equipment, vehicle maintenance, driver safety and compliance, and route planning. FMS mainly provides performance evaluation and management to fleet operators, rather than performing real-time driving optimization. Companies featuring the technology include Lytx and G7.

**Platooning** is the linking of two or more trucks in a convoy, using connectivity technology and automated driving support systems to optimize fuel efficiency. Real-time acceleration, deceleration, speed, position, and other information from the lead truck can be transmitted to the trailing trucks through connectivity technology, allowing the trailing trucks to automatically maintain a fixed, close distance from the truck in front. This technology is highly complex but is centered around optimizing the simultaneous operations of multiple trucks on a single route with human drivers, rather than achieving autonomous driving with a single truck. Companies developing this technology include Peloton and Locomation.

The two technologies mentioned above are relevant to autonomous driving to some degree, but are not generally recognized as advanced AD functions.
Exhibit 10 - Illustration of FMS and Platooning

**FMS**  
(Fleet Management System)

**Platooning**

### FMS report

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</tbody>
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<table>
<thead>
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<th>Fuel consumption: idle speed (L)</th>
<th>Fuel consumption per hundred miles (L/mile)</th>
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<tr>
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</tr>
<tr>
<td>2858</td>
<td>775</td>
<td>773</td>
<td>2</td>
<td>28.2</td>
</tr>
</tbody>
</table>

... ... ... ... ... ...

Source: BCG analysis.
Technology Components and Roadmap of autonomous trucking
AD Systems Are Sophisticated Robotic Systems Composed of Several Key Components

An AD system typically consists of several tightly inter-operating components. Four of those key components are perception, prediction, planning, and control. (See Exhibit 11 and Exhibit 12.)

Perception
Perception determines attributes related to obstacles (e.g., type, outline, and speed) and the environment (e.g., lanes, traffic lights) from raw sensor data. As multiple types of sensors (e.g., radar, LiDAR, cameras, and ultrasonic sensors) are often used simultaneously, sensor fusion is necessary to leverage the capabilities of different sensors to generate accurate perception results. (See Exhibit 13.) In addition, perception integrates mapping and localization capabilities to determine the current position and direction of the vehicle. Currently, perception based on deep learning tends to perform better than conventional approaches.

Prediction
In order for an autonomous vehicle to plan its actions, it must first estimate the intent and future movements of other objects on the road. This task is called prediction. Prediction starts with intention prediction, which forecasts what actions the other objects/obstacles will take from a set of human-defined discrete actions, e.g., lane changing, merging, and turning left. Afterwards, based on the predicted intention, the obstacles’ trajectories can be estimated. Most leading autonomous driving players use machine learning or deep learning for intention prediction (though intention set is defined by human), while trajectory prediction often relies on optimization methods.

Planning
Once prediction is complete, the autonomous vehicle can plan its own move (planning). Three types of planning tasks are performed:

1. **Route planning**: Planning a route from the origin to the destination using a navigation map.
2. **Behavior planning**: Selecting an intention or behavior from a human-defined set of options, e.g., overtaking, yielding or nudging, also known as the “decision module”.
3. **Motion planning**: Calculating the short-term trajectory of the ego autonomous vehicle based on the planned behavior.

Exhibit 11 - Autonomous Driving Algorithms Have Four Main Components

![Exhibit 11 - Autonomous Driving Algorithms Have Four Main Components](image)

Source: Expert interviews; BCG analysis.
Exhibit 12 - Key Components Are Fully Connected, the Output of the Last Component Is the Input for the next

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Perception</th>
<th>Prediction</th>
<th>Planning</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw sensor data from surrounding objects and environment, e.g., camera images, LiDAR point clouds</td>
<td>Object list containing obstacle motion &amp; road info representing lanes, drivable area, and traffic signals</td>
<td>Predicted intention and trajectory of moving obstacles</td>
<td>Optimized route, behavior, and trajectory of ego vehicle, based on current available info</td>
<td>Acceleration/Deceleration/Steering commands to make ego vehicle follow the planned trajectory</td>
</tr>
</tbody>
</table>

Source: BCG analysis.

Exhibit 13 - Sensors Typically Used for Autonomous Driving

<table>
<thead>
<tr>
<th>Function</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cameras</strong></td>
<td>• Image input from CMOS image sensor used to detect obstacles • Detection distance: over 1,000m in AD trucking via long focal length camera</td>
<td>• Low cost • Diversity of view angles • High resolution</td>
</tr>
<tr>
<td><strong>Radar</strong></td>
<td>• Emits electromagnetic pulses to calculate distance between vehicle and obstacles • Detection distance: 0.2–30m for short-range radar and below 200m for long-range radar</td>
<td>• Less impacted by weather conditions • Widely adopted</td>
</tr>
<tr>
<td><strong>Ultrasonic sensors</strong></td>
<td>• High-intensity soundwaves for up to 10m • Usually attached to the rear of the vehicle, main sensors for parking assistance systems • Detection distance: 0.02-10m</td>
<td>• Fairly weather-proof • Low cost</td>
</tr>
<tr>
<td><strong>LiDAR</strong></td>
<td>• Laser-based tech, similar to radar • High accuracy in measuring depth info • Detection distance: generally below 200m</td>
<td>• Sensors offer high accuracy in terms of measuring distance and shape</td>
</tr>
<tr>
<td><strong>IMU</strong>&lt;sup&gt;1&lt;/sup&gt;</td>
<td>• Helps calculate vehicle position and motion</td>
<td>• Supports localization (GNSS can be interrupted)</td>
</tr>
</tbody>
</table>

Source: BCG analysis.

<sup>1</sup>Inertial Measurement Unit (IMU) can extrapolate the data available to estimate the current location of the vehicle when GNSS (Global Navigation Satellite System) signal is unavailable.
While there are well-established solutions in the transportation space for the route planning task, the behavior and motion planning tasks are unique to autonomous vehicles. These often more difficult tasks are generally treated as an issue of optimization—how to optimize safety, comfort and fuel economics simultaneously—rather than an issue of machine learning. Leading players are experimenting with applications of machine learning on the behavior layer, but motion planning will likely remain an optimization issue in the near future.

**Control**

Finally, control algorithms generate real-time commands for actuators (e.g., throttle, brake, and steering wheel) to prevent any deviation of the autonomous vehicle from the planned trajectory. In autonomous driving, mature algorithms for control have been available for decades. However, significant engineering efforts are required to reduce the delay in actuation systems due to the weight of a truck. Computational platforms and real-time operating systems are also important underlying technologies that support autonomous driving, but which will not be discussed in detail in this report.

There is still much work to be done to prepare these technology components for the commercialization of L4 vehicles. In perception, if an unknown object or an unknown combination of different objects (e.g., a piece of furniture) is encountered, the perception algorithm may not yield reliable results. In prediction, the lack of training samples and the limitations of human-defined intentions may affect the accuracy of prediction. In planning, interacting with other road users and avoiding accidents remain challenging due to unreliable results in perception and prediction.

**Examples of possible failure of AD components** include when the perception component fails to detect an object, or when the planning component commands the vehicle to overtake while a human driver would not consider it safe to do so. Such incidents are then recorded as potential failures or near-miss scenarios. Rare scenarios are then known as “corner cases”.

The most essential part in the development of L4 technology is solving these scenarios, and particularly corner cases, by continuously improving algorithms across tech components, so that L4 vehicles can be commercialized over large operational design domains (ODDs). ODD refers to specific conditions under which autonomous vehicles can operate properly, and is typically a combination of weather conditions, road types, and speed ranges. In the case of robotaxi, the road type of the ODD is usually defined as an area, e.g., a district or city, while for autonomous trucks, the road type of the ODD is usually defined as a route, e.g., I-40, I-75 or types of roads e.g., divided highways or ramp-to-ramp highways.

70 Unknown objects did not show up, or were not properly detected in the training process of the AD system.
There Are Two Primary Development Roadmaps Toward L4 Driver-Less Autonomy, i.e., the Direct-to-L4 Roadmap and the Progressive Roadmap

There are two different roadmaps. (See Exhibit 14.)

The direct-to-L4 roadmap is a conventional forward engineering approach. Players selecting this technology roadmap deploy a few hundred retrofitted L4 testing vehicles to collect cases that cannot be handled by current algorithms and make revisions accordingly. In a certain ODD, which is a single route as defined by this roadmap, when a sufficient number of cases have been solved and the performance of the L4 algorithm can be considered comparable to a human driver, some industry participants believe this particular route can then be considered commercialization-ready for the autonomous vehicle. From their perspective, extending the testing and operating routes should eventually result in a set of generalized L4 algorithms.

TuSimple is generally regarded as a leading autonomous driving commercial vehicle player under the direct-to-L4 roadmap. The key assumptions of a direct-to-L4 roadmap are:

- **Corner case distribution:** Corner cases only account for a small proportion of all cases, therefore putting huge effort into collecting corner cases is not necessary for commercialization, and a few hundred vehicles would be sufficient to collect cases.

- **Corner case properties:** Corner cases tend to be similar rather than unique, therefore the efficiency of manual case solving increases with the number of commercialized ODDs and it is acceptable to invest significant manual effort in solving each case under current technology frameworks.

- **L4 technology validation:** As corner cases only account for a small proportion, extensive vehicle testing mileage is not necessary to validate L4 technology.

However, players working with different assumptions, e.g., Plus have adopted a progressive roadmap. The key assumptions are as follows:

- **Corner case distribution:** Corner cases account for a small proportion of all cases. However, due to long tail effects, it is inherently difficult to discover the corner cases, and therefore essential to collect as many corner cases as possible to train the L4 technology.

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*71* TuSimple Company Overview, [https://ir.tusimple.com/static-files/8b58d513-5193-4ea4-b2d9-1c353248ebbe](https://ir.tusimple.com/static-files/8b58d513-5193-4ea4-b2d9-1c353248ebbe)
• **Corner case properties:** Corner cases by nature are difficult to characterize and generalize. Limiting corner case discovery in certain routes can severely reduce corner case coverage and consequently introduce significant biases in the dataset.

• **L4 technology validation:** As corner cases can occur under any condition, their impact on the safety and reliable performance of L4 technology must be measured and validated in a wide range of real-world conditions. **Substantial real-world testing mileage is necessary** to validate the performance of L4 technology in a statistically sufficient manner.

As a result, players following the progressive roadmap believe that the intensive use of machine learning is necessary to validate L4 technology, and collecting massive amounts of data from volume produced L2+/L3 fleets is an inevitable step, as it is the only way to achieve the necessary scale of data collection to ensure a safe L4 product. By feeding the real-world testing data collected to machine learning models across the technology stack, L4 solution performance would be continuously improved. Through this process, safe and scalable L4 technology can be empirically proven for commercial deployment.

In both roadmaps, cases can be collected when the driver in the vehicle discovers that the AD system is not behaving like a normal human driver and requires an intervention, or when the algorithms output a result with a low level of confidence. However, there is a significant disparity in the number of vehicles and human drivers involved in the two roadmaps, directly affecting the efficiency of case discovery.

Players adopting the direct-to-L4 roadmap would typically require their algorithm engineers to analyze the root causes and manually update problematic algorithm parameters or structures accordingly. Solving a new case while ensuring continued safety performance in old cases is no easy feat; therefore, extensive manual efforts are required to manage the large number of human-optimized intentions/rules and parameters. Nonetheless, as this roadmap targets L4 directly, players can often obtain reasonable results in their initial testing ODD relatively quickly. However, they could encounter major challenges when trying to generalize the AD algorithms for application to a larger ODD scope. Due to the presence of many human-defined vehicle intentions/rules and potential overfitting from the limited diversity and representativeness of collected data within limited ODDs, solving overfitting problems is a complex and labor-intensive process when an intention/rule set is changed, and therefore there may be risks if players following the direct-to-L4 roadmap commercialize their product on a larger scale.

In the progressive roadmap with mass-produced L2+/L3 vehicles, L4 algorithms can be improved continuously. The potential overfitting caused by a growing set of human-defined vehicle intentions, rules, and parameters in the direct-to-L4 approach can be reduced by the diversified data collected in the progressive approach. Also, it is more common to adopt efficiency-improving initiatives, e.g., auto-labelling, in the progressive roadmap to deal with massive amounts of data.

The key difference between the two roadmaps lies in the scale and the diversity of data, as well as the confidence of validation. As players adopting the progressive roadmap will validate the performance of L4 technology via high intensity of testing to achieve a statistically confident result, the confidence level of their AD algorithms is higher as compared with the direct-to-L4 roadmap.

In addition, not all L2+/L3 vehicles can be used in the progressive roadmap. To make the roadmap viable, the L2+/L3 system should be able to accurately reconstruct scenario information for training without reducing data dimensions. Equipping vehicles with LiDARs in the testing process can make scenario reconstruction easier and more accurate, as it can provide more accurate depth information and object detection.

The key differences between the direct-to-L4 roadmap and the progressive roadmap are summarized as below. (See Exhibit 15.)
These Two Roadmaps Correspond to Different Commercialization Roadmaps

The Direct-to-L4 roadmap is focused on route-by-route expansion, while the progressive roadmap tries to ensure generalization from the beginning.

The intrinsic differences between the two development roadmaps lead to different commercialization approaches, especially in terms of route expansion strategies. (See Exhibit 16.)

The direct-to-L4 roadmap aims to make one route commercialization-ready first and then roll out more commercialized routes one by one, assuming that route expansion can be achieved sequentially. Following this roadmap, the routes usually have clear geo-fences or fixed origins and destinations. Players adopting the direct-to-L4 roadmap generally assume that routes are largely similar, with only a few new corner cases to address in each new route, and therefore the time and costs involved in route expansion will fall as the number of commercialized routes increases.

As a result, this approach could possibly speed up the initial commercialization of L4 vehicles for select routes. However, the expansion costs could be much higher than originally estimated if the similarities between cases and routes are less significant than originally predicted or the fine-tuning of human-defined vehicle intention/rule sets becomes more labor-intensive.

On the other hand, according to the progressive roadmap, mass produced L2+/L3 driver-in solutions that are sold to fleets would provide the initial source of revenue. Once the L4 tech stack is sufficiently trained, it can be further generalized, at least for scenarios frequently encountered by L2+/L3 driver-in vehicles. Therefore, ODDs are defined by scenarios or road conditions, such as expanding from divided highways to more local driving conditions, instead of defined by routes or location. As a result, multiple routes can be commercialized simultaneously. This commercialization approach of the progressive roadmap is a result of the assumption that the ODD cannot be expanded on a route-by-route basis and generalization should be ensured from the beginning via testing across a wide range of geographies.

Currently, in-vehicle human drivers are required for both roadmaps as none of the current players, including TuSimple and Plus, are ready for L4 commercialization. In the end, which roadmap will achieve driverless commercialization first depends on the MPCI requirement for commercialization. MPCI refers to Miles Per Critical Intervention—situations in which driver intervention is necessary to prevent a safety-critical or dangerous situation. There is currently no consensus in the industry or academia on the required MPCI performance, due to the wide range of complexity of ODDs and the potential for auxiliary approaches to facilitate commercial readiness of L4 driver-out technology.

Source: BCG analysis.
Wide range of complexity of ODDs: Certain ODDs are more complex and pose different requirements for commercialization. If we rank common scenarios in terms of complexity from high to low, urban areas are the most complex areas, followed by suburban areas, warehouse-to-warehouse, ramp-to-ramp, and highway-only scenarios. The more complex the scenarios are, the more challenging the cases and corner cases autonomous trucks should expect to encounter; thus, the requirement for commercialization would be different across scenarios/ODDs.

Auxiliary approach to facilitate commercialization: An auxiliary approach can be adopted to enable the performance of autonomous trucks to reach the level required for commercialization. For example, tele-operators (remote drivers ready to take over at any time) can be used to accelerate the process of commercialization. Benefits include reduced labor costs (traditionally one driver takes care of each vehicle, but with tele-operators, human drivers can be removed from the vehicle, and a single tele-operator could take care of multiple vehicles). Through an auxiliary approach, the requirement for commercialization can be lowered.

One school of thought believes that the MPCI performance of driverless L4 commercialization should be 10x the MPF (Miles Per Fatality) of human drivers, or over 60 million miles\(^7\), and to get a statistically reliable result, such performance should be validated by data on the scale of 10 times the target miles.

While there is no consensus on the MPCI performance requirements for commercialization, another source of uncertainty is government regulations. If the MPCI performance required by governments and the scientific community is relatively low, players adopting a direct-to-L4 roadmap could achieve faster commercialization within limited routes (e.g., highway only), potentially with help from auxiliary approaches. However, if the MPCI performance required for commercialization is relatively high when it comes to complex scenarios, it will be more challenging for players following the direct-to-L4 roadmap to expand their routes quickly. In this case, the efficiency of the progressive roadmap would emerge, resulting in faster commercialization to cover these scenarios.

Source: Lit research; BCG analysis.

\(^1\) Miles per critical intervention.

Exhibit 17 - Autonomous Trucks Face Different Technological Challenges Across Tech Components Than ADPVs

<table>
<thead>
<tr>
<th>Perception</th>
<th>Prediction</th>
<th>Planning</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception distance</td>
<td>Prediction horizon</td>
<td>Planning objective</td>
<td>Drive-by-wire (DBW) readiness</td>
</tr>
<tr>
<td>Sensor vibration</td>
<td>Prediction scope</td>
<td>Behavior planning</td>
<td></td>
</tr>
<tr>
<td>Corner cases</td>
<td>Trajectory planning</td>
<td>Trajectory planning</td>
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<tr>
<td></td>
<td></td>
<td>Trajectory planning</td>
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<tr>
<td></td>
<td></td>
<td>Vehicle dynamics</td>
<td></td>
</tr>
</tbody>
</table>

### Key differences between ADCVs and ADPVs

- **Perception**
  - Longer perception distance required due to longer braking distance, increased safety requirements on highways, and larger buffer for fuel efficiency planning.
  - Trucks have more severe vibration, therefore special image processing is required. Sensor vibrations can be ignored or solved in passenger vehicles by cropping the frames of images.
  - Longer prediction horizon required for safety buffer and fuel saving, usually 5s+ for trucks and only 3s for passenger vehicles.
  - Larger prediction scope required for same reasons as longer prediction horizon.

### Key differences in perception:

- A longer perception distance is required due to the longer braking distance, higher safety requirements on highways (accidents are more likely to be fatal), and added fuel saving requirements.
  - Commercial vehicles and passenger vehicles also face different corner cases due to the different driving environments, e.g., farm machinery and wild animals are common in the driving environments of commercial vehicles.
  - There are few markers for localization on highways compared with urban areas.

### Key differences in prediction:

- Longer prediction horizon (the autonomous driving system needs to predict the intention and potential trajectory of perceived obstacles) for fuel saving and to provide a safety buffer. Usually passenger vehicles require 3-second time horizons while commercial vehicles must predict time horizons of 5 seconds or longer.
  - Larger prediction scope, autonomous trucking requires a wider and longer physical range to capture the intentions and potential trajectories of obstacles in comparison to passenger vehicles.

Source: BCG case experience; Expert interviews; BCG analysis.

1 ADCV = Autonomous driving commercial vehicle.
2 ADPV = Autonomous driving passenger vehicle.

Autonomous Trucks Present Specific Technological Challenges, Resulting in High Entry Barriers for Robotaxi Players Focused on Passenger Cars

Although the tech components for autonomous trucks and autonomous driving passenger vehicles (ADPVs) are similar, autonomous trucks present specific technical and operational challenges. This can prevent ADPV players from easily entering the autonomous trucking sector. (See Exhibit 17.)

Key differences in perception:

- A longer perception distance is required due to the longer braking distance, higher safety requirements on highways (accidents are more likely to be fatal), and added fuel saving requirements.

- Vibrations in trucks are more severe than in passenger vehicles. This is the case with conventional and cab-over heavy trucks, and the effect of vibration becomes greater if sensors are perceiving objects at a longer distance. Therefore, it is more challenging to ensure proper sensor function in trucks.

- Commercial vehicles and passenger vehicles also face different corner cases due to the different driving environments, e.g., farm machinery and wild animals are common in the driving environments of commercial vehicles.

- There are few markers for localization on highways compared with urban areas.
Key differences in planning:

- Fuel consumption is a major cost item for commercial vehicles; therefore, fuel saving is also an objective in the planning component for ADCVs.
- Bound setting is required to ensure stable and safe output of planning for commercial vehicles, all planning results should be within bounds.
- Behavior planning will face different requirements considering fuel saving.
- As wind and rolling resistance cannot be neglected in trucking, more sophisticated modeling is required for trajectory planning to reflect wind and rolling resistance, in order to save fuel.

Key differences in control:

- Heavy-duty trucks have multi-rigid bodies with a higher center of gravity compared with the single-rigid bodies of passenger vehicles. In addition, as the fuel which accounts for a significant portion of the mass inside the trailer can move, the mass of heavy-duty trucks may change during the driving process.
- DBW (Drive-by-wire) actuation systems are less mature in commercial vehicles than in passenger vehicles. Redundant, functional-safety compliant products in actuation, particularly steering and braking, are not yet widely available from established suppliers.

Solving these problems will require significant engineering efforts and research innovation, which creates an entry barrier for ADPV players. Therefore, ADPV players cannot directly transfer their capabilities into the ADCV sector, and it will take them several years to conquer the technical challenges.

One example is the vibration problem of long-focal cameras mentioned above, which could cause the perception algorithm to miss certain objects and lead to a collision. This problem still lies in the framework of the classic vision-based perception, but significant engineering efforts would be needed to associate images from multiple adjacent frames to form a correct input for the perception module. (See Exhibit 18.)

Exhibit 18 - Significant Engineering Efforts Required for ADPV Players to Enter the ADCV Space

<table>
<thead>
<tr>
<th>Perception</th>
<th>Prediction</th>
<th>Planning</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception distance</td>
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<td>Planning objective</td>
<td>Vehicle dynamics</td>
</tr>
<tr>
<td>Sensor vibration</td>
<td>Prediction scope</td>
<td>Behavior planning</td>
<td></td>
</tr>
<tr>
<td>Corner cases</td>
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<td>Trajectory planning</td>
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</table>

Barriers for ADPV players entering the ADCV\textsuperscript{11} space

- **Mainly need to solve sensor calibration problems over long distances**
  - Feature/semantic-based association required to address this issue
- **Need to accumulate cases on highways**
  - Corner cases on highways exhibit a much longer tail distribution and therefore take longer to accumulate
  - More historical data needed as an input, and more parameters should be considered:
    - To improve the prediction accuracy of longer horizons, more accurate perception results are required
    - Algorithm structure optimization required to predict more objects with less computing power
- **Engineering efforts required to tune model to save fuel**
  - Need to collect wind and rolling resistance data as a benchmark (calibration process), and then estimate wind and rolling resistance data in actual practice
  - Engineering efforts required to estimate mass in real time, incl. load sensors mounted on vehicles, and algorithms to further improve accuracy

Source: Expert interviews; BCG analysis.

\textsuperscript{1} ADPV=Autonomous driving passenger vehicles.

\textsuperscript{11} ADCV=Autonomous driving commercial vehicles.
Considering the rapid development of L4 and above autonomous trucking technology, we are cautiously optimistic about its prospects for commercialization. Nevertheless, safety and regulation are key factors that will have a major impact on the commercialization timeline.

Safety has been discussed extensively as the precondition for the implementation of AD technology. The safety of autonomous driving is mainly determined by the maturity of technology. Although there is not yet an industry consensus on the number of testing miles needed to train a safe AD system at L4 and above, it is generally believed that tests covering a few billion miles are required to demonstrate a relatively safe AD system.

Regulation is mainly determined by policies in different countries. Despite the difficulty of establishing regulation for technologies that are not yet mature, governments of major countries have committed to providing a regulatory environment conducive to the innovation, testing and deployment of high-level AD technology.

Technology Perspective

From a technology perspective, the industry-recognized precondition for large-scale commercialization is for the injury and fatality rate resulting from L4 and above level autonomous vehicles to reach a level equal to or lower than that of human drivers. According to the U.S. Bureau of Transportation Statistics, the reported occupant fatality rate for large trucks per 100 million truck miles traveled by human drivers is 0.23 as of 2019.

To prove the performance of AD technology, road tests are a must. The RAND corporation estimated that vehicles would have to be driven 8.8 billion miles to demonstrate the same fatality rate as that of human drivers.

Taking the above analysis into consideration, it is expected to take 50,000 trucks testing on highways for an entire year to demonstrate that they can reach a fatality rate equal to or lower than that of human drivers, assuming that the trucks operate at 12 hours a day, and 40 miles per hour on average.

Regulation Perspective

Regulation should be established in parallel with improvements in technology, and we expect regulation to be gradually introduced as L4 and above AD technology matures. Exemptions and waivers are acting as mainstream near-term regulatory tools for L4 and above AD technology. Meanwhile, regulation is developing towards the legalization of AD commercialization. Regulatory landscapes in major markets are encouraging the development of advanced AD technology.

In summary, the overall regulatory environment for autonomous driving is supportive, progressive and empirical.

• Supportive: Governments in major markets have taken a positive rather than restrictive attitude toward autonomous driving. They are positioning autonomous driving as a national strategic initiative and tend to encourage its application through relatively friendly and flexible regulation.

• Progressive: The evolution of regulation is continuous, not intermittent. In major countries, regulations have been introduced even faster in recent years to keep up with the rapidly evolving market.

• Empirical: Regulation has been based on empirical testing results. As more testing vehicles hit the roads, more testing data can be accumulated. Safe driving records will add to governments’ understanding of AD technology and lead to a more permissive regulation environment, which will in turn encourage the production of more AD vehicles.

74 Autonomous driving players, e.g. Waymo, TuSimple, are running driverless road tests with a remote safety driver to ensure safety.
78 Autonomous vehicles would have to be driven 8.8 billion miles to demonstrate that vehicles have a fatality rate within 20% of the human driver fatality rate, with a 95% confidence level.
The U.S. regulatory environment is relatively permissive, with bold driverless road-testing regulations. In the U.S., both the federal government and states have issued AD-related regulations. (See Exhibit 20.) The federal government is responsible for setting Federal Motor Vehicle Safety Standards (FMVSS) and Federal Motor Carrier Safety Regulation (FMCSR), with light regulatory requirements to promote AD tech innovation. Demonstration of vehicle safety depends mainly on voluntary self-assessment and self-certification by AD developers. States are responsible for licensing, registration, traffic law enforcement, safety inspections, infrastructure, and insurance and liability regulations. Overall, the federal government mainly provides guidelines and leaves actual regulation at the state level.

At the federal level, the U.S. Department of Transportation (USDOT) has published a series of advisory guidelines on AD. (See Exhibit 21.) Federal guidelines have become increasingly permissive and have removed unintended and unnecessary barriers to innovative AD technologies.

At the state level, regulation on AD differs. According to the National Conference of State Legislatures (NCSL), 31 states and the District of Columbia enacted legislation related to autonomous vehicles between 2013 and 2020, 11 states issued executive orders, and 5 states both issued an executive order and enacted legislation. According to Morgan Stanley, currently 43 states allow autonomous truck testing, of which 24 states permit autonomous truck commercial deployment.

In terms of testing and deploying high-level AD technology, exemptions and waivers are still key near-term tools. The NHTSA continues to grant exemptions from the FMVSS to provide flexibility for testing of autonomous driving systems and to enable limited commercial deployment of vehicles that do not currently comply with FMVSS if an equivalent level of safety is demonstrated in a compliant vehicle. Nevertheless, exemptions from the FMVSS and FMCSR have been limited in terms of time, the number of vehicles, and in some cases location. Updates to regulation are a must for large-scale deployment, and such updates are currently underway.

The USDOT is also actively developing rules and engaging in research to adapt the existing FMVSS and FMCSR to remove unintended and unnecessary barriers to the introduction of novel vehicle designs and advanced AD features. As a result, the USDOT has already issued multiple NPRMs (Notice of Proposed Rulemaking) and ANPRMs (Advance Notice of Proposed Rulemaking) related to AD systems, for example the safe integration of AD system-equipped commercial motor vehicles and a framework for AD system safety.

Source: BCG analysis.

Exhibit 19 - Overall Regulation Environment for Autonomous Driving Is Supportive, Progressive and Empirical

Supportive
Progressive
Empirical

Regulation environment is supportive, rather than restrictive
Regulation is undergoing continuous and progressive evolution
Regulation is empirical and is expected to become more open, forming a virtuous cycle

More vehicles tested
More data accumulated
More permissive regulation

More vehicles tested
More data accumulated
More permissive regulation

Source: BCG analysis.

Exhibit 20 - In the U.S., Safety Standards Are Regulated at the Federal Level, While Registration & Operations Are Handled at the State Level

- **Federal**
  - NHTSA—part of USDOT
  - National Highway Traffic Safety Administration
  - Responsible for safety rules to reduce deaths, injuries and economic losses resulting from motor vehicle crashes
  - Sets performance standards, enforces safety for motor vehicles, and issues Federal Motor Vehicle Safety Standards (FMVSS)
  - Issues exemptions and waivers for AD applications

- **State**
  - DMV
  - Department of Motor Vehicles
  - Responsible for vehicle registration and driver licensing

<table>
<thead>
<tr>
<th>Responsibilities</th>
<th>Main function with respect to AD</th>
<th>Department</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal</td>
<td>Regulates transportation system</td>
<td>USDOT (U.S. Department of Transportation)</td>
</tr>
<tr>
<td>State</td>
<td>Regulates vehicle safety</td>
<td>NHTSA—part of USDOT, FMCSA—part of USDOT, DMV</td>
</tr>
</tbody>
</table>

Source: government websites; BCG analysis.

*1 State DOTs have limited roles in AD regulation.*

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**Exhibit 21 - Evolution of USDOT Guidelines: Increasingly Permissive to Foster Private AD Regulation**

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Guidelines</th>
<th>Highlights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 2016</td>
<td>Federal Automated Vehicles Policy: Accelerating the Next Revolution in Roadway Safety</td>
<td>• AD developers required to submit safety self-assessment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No federal legal barrier to sales of AD if compliant with FMVSS¹ regulatory framework</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <em>Voluntary</em> safety self-assessment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• <em>Guidance</em> on best practices for state-level legislature on AD to help promote state legislature progress</td>
</tr>
<tr>
<td>Oct. 2018</td>
<td>Automated Driving Systems 2.0: A Vision for Safety</td>
<td>• Clarified that FMCSA² regulations will no longer assume that the commercial motor vehicle driver is always a human</td>
</tr>
<tr>
<td></td>
<td>Preparing for the Future of Transportation</td>
<td>• That a human is necessarily present onboard a commercial vehicle during its operation.</td>
</tr>
<tr>
<td>Feb. 2020</td>
<td>Automated Vehicles 4.0: Ensuring American Leadership in Automated Technologies</td>
<td>• Issued by both the White House and USDOT, indicating that the development of AD policies is now a government-wide endeavor</td>
</tr>
<tr>
<td></td>
<td>Ensuring American Leadership in Automated Technologies</td>
<td>• Added a focus on coordinated efforts among 38 federal agencies to ensure a consistent approach to AD technologies</td>
</tr>
<tr>
<td>Jan. 2021</td>
<td>Automated Vehicles Comprehensive Plan</td>
<td>• Described actions taken by USDOT to support safe integration of L3–L5 automated driving systems, incl. promoting collaboration and transparency, modernizing the regulatory environment, and preparing the transportation system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Explored five L3–L4 use cases² to illustrate USDOT’s activities in different aspects of AD technology, vehicles, and operational environments</td>
</tr>
</tbody>
</table>

¹FMVSS=Federal Motor Vehicle Safety Standards.
²FMCSA=Federal Motor Carrier Safety Administration.
³Includes occupant-less low-speed vehicles, passenger vehicle conditional driving automation, passenger vehicle automated driving systems, automated trucking operations, and low-speed passenger shuttles.
China is also advancing its AD regulation, creating a friendly environment for the future commercialization of L4 and above AD technology. In China, AD related regulations are mainly issued by the MIIT, MPS, and MOT. (See Exhibit 22.) The MIIT is mainly responsible for macro-level industry guidance and setting of standards, the MPS for road traffic safety management, and the MOT for road construction and maintenance.

Since 2015, the Chinese government has issued several national-level strategic guidelines and regulatory rules to foster the development of AD technology. (See Exhibit 23.) In May 2019, the MIIT proposed developing AD-related regulations and standards as a key focus of the government, accelerating the introduction of AD-related regulations. In February 2020, the Strategy for Innovation and Development of Intelligent Vehicles was released, setting clear short-term goals for AD development in China, namely establishing a systematic AD regulatory framework and achieving L3 mass production and L4 commercialization in select cases by 2025. In March 2021, the MPS issued a proposal to revise the Law on Road Traffic Safety, adding an item regulating road testing and the applications of AD technology. This is a significant milestone, marking the first time China has proposed specific legislation for autonomous vehicles.

At the local level, more than 20 provinces and cities have issued AD guidance and local road-testing regulations since 2017. In addition, more than 50 AD testing zones have been built and road-testing licenses have been issued to OEMs including FAW, Daimler, SAIC, and Dongfeng. By 2022, more than 20 smart highways are scheduled for construction across 13 provinces, promoting the testing and application of AD technology, especially for AD trucking.

In summary, governments of major markets have positioned autonomous driving as a national strategic initiative and have introduced friendly and flexible regulations to encourage its application. We expect the regulatory environment to continue to evolve with the development of L4 and above autonomous driving technology.
Exhibit 23 - Evolution of China’s National Guidelines: Increasing Openness for AD Technology

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Guidelines</th>
<th>Issuer</th>
<th>Highlights</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2015</td>
<td>Made in China 2025</td>
<td>State Council</td>
<td>• Proposed intelligent connected vehicle (ICV) development goal to master core AD technologies and promote AD industrialization by 2025</td>
</tr>
<tr>
<td>Apr. 2018</td>
<td>Administrative Rules on ICV Road Testing</td>
<td>MIIT, MOT, MPS</td>
<td>• Applicants for road testing must be independent legal entities registered in China</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Tests only on designated roads selected by local authorities</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• A test driver must be present and take over when needed</td>
</tr>
<tr>
<td>May 2019</td>
<td>Intelligent Connected Vehicle Standardization Work Key Points</td>
<td>MIIT</td>
<td>• Proposed developing AD related regulations and standards as the key focus for government</td>
</tr>
<tr>
<td>Feb. 2020</td>
<td>Strategy for Innovation and Development of Intelligent Vehicles</td>
<td>11 ministries &amp; commissions</td>
<td>• Set clear short-term goals for AD development by 2025</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Aims to establish a systematic AD regulatory framework by 2025 (e.g., for technology, industry ecosystems, infrastructure, regulations, cyber security)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Aims to achieve L3 mass production and L4 commercialization in select scenarios by 2025</td>
</tr>
<tr>
<td>Jan. 2021</td>
<td>Administrative Rules on ICV Road Testing and Demonstration Application</td>
<td>MIIT</td>
<td>• Allowed L4 AD to conduct official testing and trial applications on specified public roads (including highways)</td>
</tr>
<tr>
<td></td>
<td>(Draft for Comments)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar. 2021</td>
<td>Road Traffic Safety Law</td>
<td>MPS</td>
<td>• Added a new item to regulate road testing and the application of AD technology</td>
</tr>
<tr>
<td></td>
<td>(Draft Proposed Amendments)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: government websites; BCG analysis.

Considering the potential benefits, current development status, and regulatory environment, we are cautiously optimistic about the prospects of the autonomous trucking market. Improved road safety, driver comfort, and fuel efficiency, together with reduced environmental impact and driver costs are the main benefits of autonomous trucking. Leading players, including both dedicated autonomous trucking players (e.g., TuSimple, Plus, and Inceptio) and robotaxi players tapping into the autonomous trucking field (e.g., Waymo and Aurora), are rapidly moving towards mass-production and commercialization of their AD technologies. From a technology perspective, two roadmaps toward L4 exist in the market—the direct-to-L4 roadmap and the progressive roadmap—which differ in their validation approach. Nevertheless, billions of miles of road tests will be required to demonstrate the safety of autonomous driving technology. From a regulatory perspective, the overall regulatory environment for autonomous driving in major markets is supportive, progressive and empirical, and we expect that regulations will be gradually introduced as L4 and above AD technology matures.
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