Automotive & Assembly Practice

Will autonomy usher in the future of truck freight transportation?

Autonomous trucks offer compelling use cases and benefits to total cost of operation that could translate to an approximately $600 billion market in 2035.

This article is a collaborative effort by Ani Kelkar, Kersten Heineke, Martin Kellner, and Timo Möller, with Robert Brennecke and Saral Chauhan, representing views from McKinsey's Automotive & Assembly Practice.

Autonomous vehicles (AVs), with their potential to reduce shipping costs and address a scarcity of drivers, will likely be delayed by another year, according to McKinsey analysis. Major OEMs are continuing their commitment to autonomous trucking and are investing to bring the first vehicles of this kind on the road in the second half of this decade (see sidebar, "The technology underpinning autonomous trucks").

Industry and economic factors increasingly supporting autonomous trucking

AVs could help address several challenges facing the trucking industry.

Driver shortages. Already, a shortage of truck drivers is one of the most pressing issues facing trucking companies. The United States has a shortage of more than 80,000 drivers; that number is expected to double by 2030.[1] The median age of a truck driver in the United States is 46, compared with 42 for the workforce overall.[2] In Europe, the situation is even worse: about 7 percent of total truck driving jobs (more than 200,000) are unfilled; that number is expected to increase to 745,000 by 2028. Only 5 percent of truck drivers in Europe are under 25 years old, compared with 33 percent who are older than 55.[3]

Regulations. Most autonomous-trucking regulations to date have been either supportive or neutral. The European Union has approved regulations for type approval of AVs that are now incorporated into laws of member countries.[4] The US federal government has yet to enact autonomous-driving regulations; however, most US states explicitly or implicitly allow testing of autonomous systems, with several states also allowing commercial use.[5]

Transportation costs. Transportation costs have increased substantially in recent years. For example, spot rates are up 28.0 percent in Europe since 2017[6]; in the United States, the cost of logistics as a share of nominal GDP climbed from 7.5 percent in 2020 to 8.7 percent in 2023.[7] Key causes are higher driver salaries and costs for fuel and tolls, and these are expected to further increase with shifts to higher emissions standards and zero-emission vehicles. These additional costs could be offset meaningfully through lower costs of truck operations enabled by autonomous driving.

1 "The truck driver shortage in the US continues," *American Journal of Transportation*, August 3, 2023.
2 "Navigating the lanes: Understanding the truck driver shortage in the US," Truck Driver Rights, April 20, 2024.
3 "Global driver shortages: 2023 year in review," IRU, December 21, 2023.
4 "Interpretation of EU regulation on the type approval of automated driving systems," Connected, Cooperative & Automated Mobility, February 29, 2024.
5 Valerie Yurk, "Truck rule is first test drive of federal autonomous vehicle oversight," Roll Call, February 21, 2024.
6 "European road freight rates Q1 2024: Both spot and contract rates fall," IRU, May 14, 2024.
7 Eric Kulisch, "US logistics inflation remains high despite 11% drop in costs," FreightWaves, June 18, 2024.

The technology underpinning autonomous trucks

Supporting autonomous driving requires OEMs to add hardware and software to trucks:

- Hardware includes sensors, such as cameras, light detection and ranging (LiDAR) systems, and radars to detect objects and lanes in proximity to the truck; high-performance computers; and redundant braking, steering, and power supply systems, which enable the truck to maneuver safely if the main system fails.
- Software includes environmental perception software (for example, object detection, classification, and prediction); sensor fusion algorithms (combining data from multiple sensors and improving accuracy); decision-making software; path-planning software; and vehicle motion control. Some additional software is also required to perform a minimal risk maneuver in case of failure of the main software. Software functionality is enhanced with AI (for example, to detect objects, predict object movements, and understand road signs), with some companies developing end-to-end AI software that covers all elements of the technology stack.

Major challenges to scaling autonomous trucking include the detection and handling of edge cases (situations that rarely occur but must be accounted for); the commercial availability of trucks that fulfill redundancy (backup system) requirements; and the availability of core parts, such as LiDAR and redundant braking and steering systems in large quantities for commercially viable prices. Retrofitting existing trucks is cost prohibitive given the changes required to vehicle architecture (to ensure safety) and the additional hardware required.

Use cases for autonomous trucking

Autonomous trucking will likely develop with two overlapping use cases from 2027 to 2040: first, constrained autonomy with hub-to-hub driverless operations and, eventually, full autonomy (Exhibit 1).

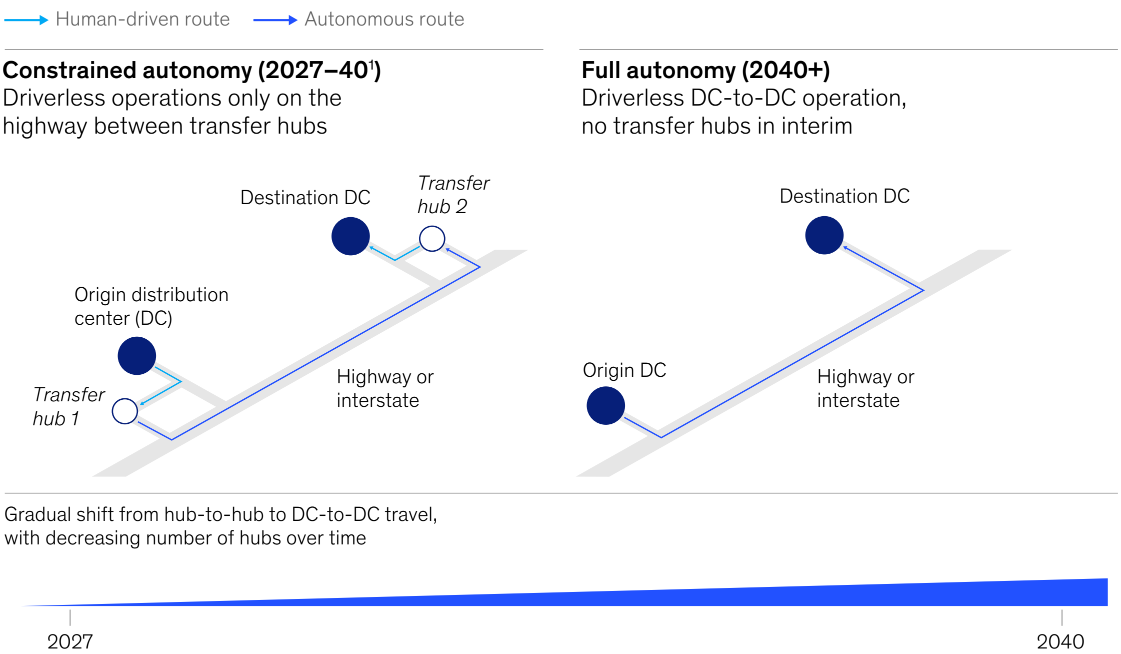
Constrained autonomy. The first use case is for driverless operations (SAE Level 4)[8] on highways and for transport between transfer hubs.[9] Driverless trucks will operate throughout the interstate highway system and other "geofenced" areas (where autonomous trucks are permitted to travel subject to weather and visibility conditions). Drivers collect a trailer at a distribution center (DC) or other location and drive it manually to a transfer hub. At the transfer hub, the trailer is decoupled from the manual truck and coupled onto an autonomous truck. After a predeparture check, the truck is autonomously driven to another transfer hub, where the trailer is again swapped and a manual driver transports the trailer to the ultimate destination, navigating city streets, local and pedestrian traffic, parking lots, and loading docks. This use case is mainly suitable for scheduled traffic between logistics points (for example, DCs, factories, and terminals) and the long-haul leg of multimode transport. To some degree, constrained autonomy could also work on nonscheduled point-to-point routes, but it is unlikely to be operationally viable on very short routes (such as milk runs or delivering goods from DCs to stores).

Full autonomy. The second use case is driverless DC-to-DC operation (SAE Level 4) with transfer hubs required only for recharging or refueling on longer routes or to swap trailers for deliveries to a location other than a DC that cannot be reached by autonomous trucks. Because some DCs are already so close to a highway that they can be reached directly without a transfer hub, this use case can be adopted today for some DCs. As autonomous-driving software improves over time, more DCs will become reachable, and the shift to full autonomy will take place gradually from 2027 to 2040 (Exhibit 2).

8 SAE International has defined levels of autonomous driving. Level 4 is defined as having a driver in the vehicle but not operating the vehicle, even if they are seated in the driver's seat. The driver will not be expected to take over driving at any time.
9 A transfer hub is a large, paved area that provides space for trailer swapping, trailer storage, and predeparture checks. It could include additional infrastructure such as facilities for washing, refueling, recharging, maintenance, and load consolidation.

Exhibit 1

Autonomy will gradually shift from hub-to-hub driverless operation in the short term to driverless operation between distribution centers in the long term.



[1]Number of distribution hubs required decreases over time to zero.
Source: McKinsey Center for Future Mobility Autonomous Truck Adoption model

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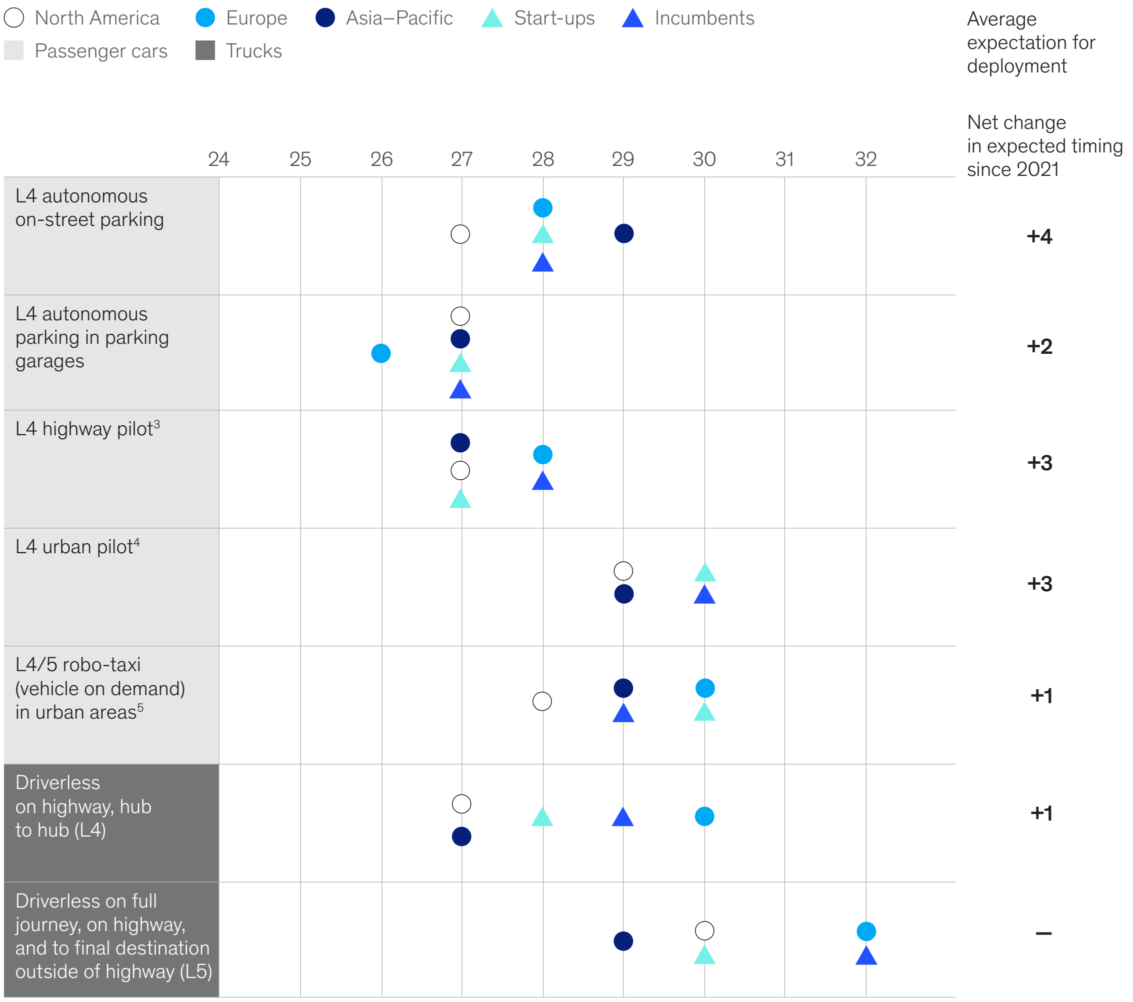
Exhibit 2

Timelines for Level 4 and Level 5 autonomous-vehicle use cases have extended by two to three years on average.

Respondents' expectations for emergence of Level 4 (L4) and Level 5 (L5)[1] use cases,[2] weighted average across regions and by company types



[1]L4 vehicles are fully autonomous within controlled environments, such as robo-taxis restricted to use within a city. L5 vehicles are autonomous under all conditions.
[2]Question: In your estimation, what is the rollout (ie, commercial availability of vehicles or service) timeline for autonomous driving across use cases in your region?
[3]Driver can use time on highways for work or leisure activities using in-car or own solutions but needs to take over at highway exits.
[4]Driver can use time on highways in urban environments for work or leisure activities using in-car or own solutions, but there might be certain situations in which the driver needs to take over.
[5]Robo-taxis are driving everywhere in fully automated mode with no driver and are accepting and conducting transportation requests (goods, passengers). Passenger can use the travel time for work or leisure activities.
Source: McKinsey Center for Future Mobility survey of global decision makers, 2023 (n = 86, 40 from North America, 37 from EU, 3 from China, 6 from other) and 2021 (n = 75, 31 from North America, 33 from EU, 11 from Asia–Pacific)

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A third use case, Level 2+ or Level 3—in which the system drives autonomously but is observed by a driver who can override the system at any time—could also be adopted. Benefits of this use case include a reduction in accidents and more fuel-efficient driving. Especially in China, Level 2+ and Level 3 could further reduce the total cost of ownership (TCO) through longer acceptable shifts for drivers and the elimination of the need for a second driver per truck.

Varying TCO savings by route length

TCO benefits will be critical to widespread adoption of autonomous heavy-duty trucks, but they will vary depending on route distances, as illustrated by an example from the United States (Exhibit 3).

For the constrained autonomy (hub-to-hub) use case, fleet operators will be unlikely to profitably roll out autonomous trucking on short routes (less than 100 miles), given high one-time costs (for example, detour to transfer hub, predeparture check, higher costs for manual first and last mile, and trailer swapping, which occurs for every tour, independent of distance) that can be offset only if the distance traveled is sufficiently long. Additionally, distances between 200 and 400 miles will become profitable only as autonomous-trucking costs decline over time (as hardware matures and software requires less remote assistance).

However, under the same use case, autonomous trucking promises significant TCO savings to fleet operators for longer-distance routes (more than 1,500 miles). According to McKinsey analysis, TCO for heavy-duty trucks could be reduced by 42 percent per mile despite increased costs for AV kits, AV services (for example, cost for a control center to monitor the fleet), and trucks with redundant braking, steering, and power supply systems.

These higher costs will be more than offset by savings from driver salaries (drivers are typically compensated at a higher rate for nights away from home, moderately lower fuel consumption, and lower repair costs through optimized driving with fewer accidents). Moreover, the TCO benefit will likely increase over time as prices for sensors and actuators come down, costs for remote operations and insurance decline as software matures, and hub costs decline as trucks can bypass them and travel directly to DCs. The TCO benefit is then distributed among the fleet, the OEM, and the developer of the autonomous-trucking software, depending on the competitive environment and purchasing power.

Market size and sources of revenue

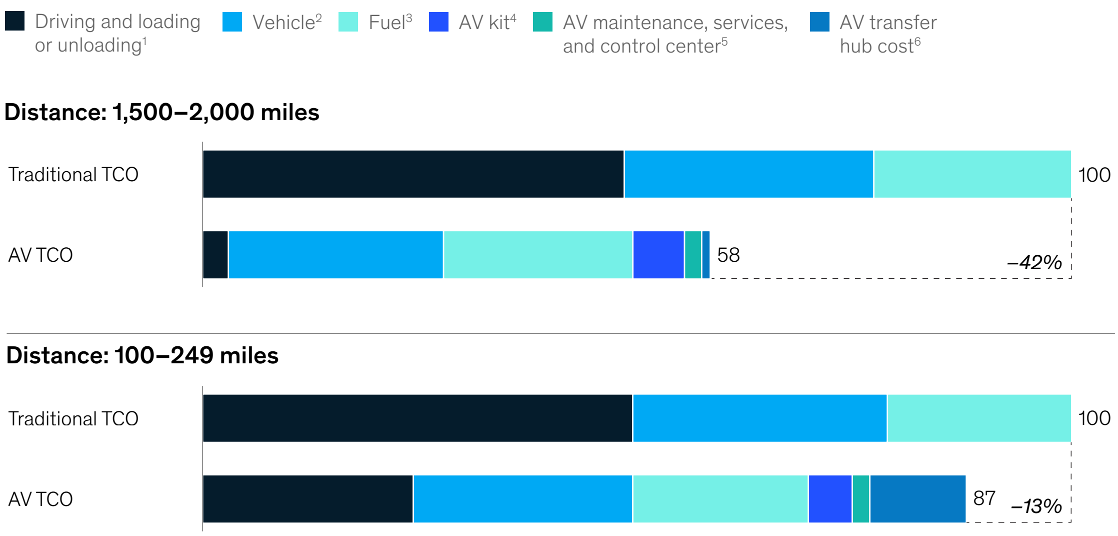
According to McKinsey projections, the autonomous heavy-duty trucking market could reach an aggregated $616 billion in 2035 in China (about $327 billion), the United States (about $178 billion), and Europe (about $112 billion) (Exhibit 4).[10]

[10] The market in the rest of the world amounts to another $100 billion.

Exhibit 3

Beyond 2035, total cost of ownership shifts in favor of autonomous heavy-duty trucks over traditional trucks for longer distances.

Comparison of total cost of ownership (TCO) for traditional vs autonomous vehicle (AV) heavy-duty trucks, US market, 2035, (index 100 = TCO costs of traditional truck in 2035)



[1]Including driver cost and loading or unloading.
[2]Including tires, vehicle depreciation, maintenance, tolls, and insurance.
[3]Fuel savings.
[4]Trailer swap, inspection, and time slot at hub.
[5]Including AV kit depreciation and integration.
[6]Including AV maintenance, services (eg, software cost, subscription, and over-the-air updates), and control center.

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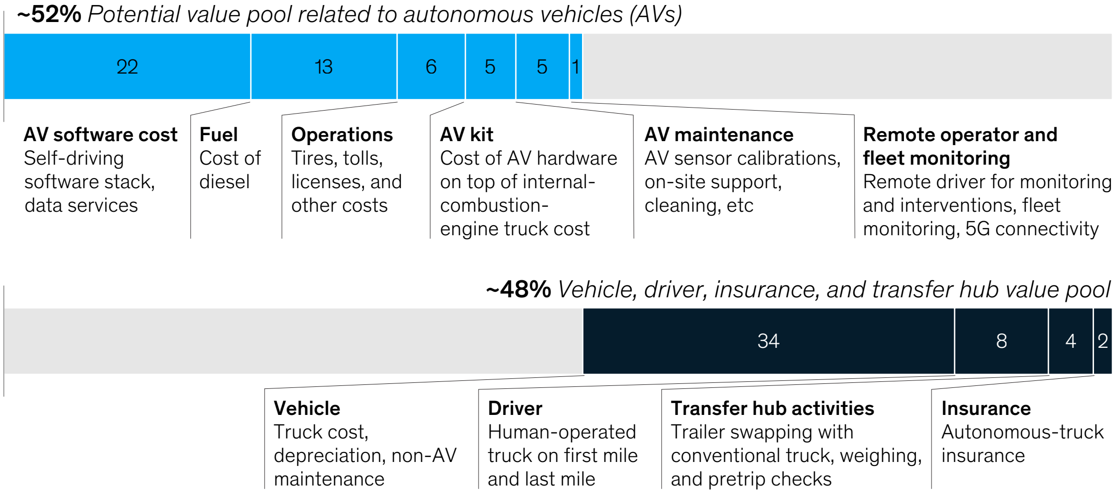
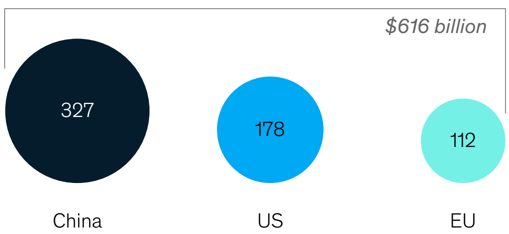
Exhibit 4

A sizable portion of the trucking industry revenue pool is attributable to autonomous-vehicle services.

Share of autonomous heavy-duty truck revenue pool by spending element, 2035, global,[1] base scenario



Autonomous heavy-duty truck revenue pool by country, $ billion



Note: Assumes AV trucks run on diesel.
[1]Assumes 12% of AV trucks operating in full-autonomy approach and 88% operating with constrained autonomy (hub-to-hub) approach.
Source: McKinsey Center for Future Mobility Autonomous Truck Market model

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Furthermore, according to the projection, the United States will have the fastest adoption rate, with autonomous trucks accounting for 13 percent of heavy-duty trucks on the road in 2035. High salaries and a scarcity of truck drivers create strong financial incentives for automation. Likewise, long distances between major cities and a weak train network favor autonomous trucking.

By comparison, McKinsey projects that Europe, despite having the highest potential TCO savings, will have the slowest adoption rate by 2035, with 4 percent of heavy-duty trucks on the road, due to higher complexity (curvier roads, snow, and tunnels) and operational challenges (shorter routes, on average). Additionally, a significant portion of total transport volume in Europe takes place across shorter distances, and the TCO benefits on these routes likely won't become evident until after 2040.

Finally, China will see higher adoption rates of autonomous trucks than Europe by 2035, with 11 percent of heavy-duty trucks on the road, propelled by its distinct economic and logistical landscape. On the one hand, China has the lowest driver salaries among the three regions, which makes the automation less financially urgent. On the other hand, China has a higher percentage of long-distance transportation sectors that could benefit from autonomous fleets and has many OEMs with leading capabilities.

Certain preconditions will need to be met to attain these adoption numbers and market size. First, achieving a favorable TCO will depend on a substantial decline in vehicle and AV hardware costs, the cost of the remote operations center, and maintenance costs related to the AV system. Second, autonomous trucks will need proven superior safety compared with human-operated trucks. Only a few fatal accidents could result in a negative public perception of autonomous trucking. Third, AV trucks need to be reliable. Shutting down a major highway or causing a major traffic jam would also likely cause the public and regulators to reject autonomous trucks.

Emergent new business models

Two likely business models are emerging for autonomous trucking.

Driver as a service (DaaS). DaaS lets fleet customers lease or buy trucks from an OEM and pay for virtual drivers by mile. OEMs or AI firms handle truck operations, earning from truck sales (autonomous trucks cost $50,000 to $100,000 more than other trucks, according to McKinsey analysis) and per-mile fees. Fleet customers, such as freight or e-commerce companies, still manage logistics but outsource truck operation. DaaS lowers TCO compared with hiring drivers, crucial in low-margin industries. It also boosts safety and provides OEMs with new revenue streams, improving customer TCO and easing the transition to autonomous trucks.

Capacity as a service (CaaS). In the CaaS model, the OEM or AV technology developers fully manage trucks, route planning, and deliveries, bypassing fleet customers to serve end customers directly. This model offers benefits similar to those of DaaS, with potentially higher margins but also greater risks. OEMs face challenges entering last-mile logistics, competing with existing customers, and taking on financial and operational responsibilities. CaaS requires OEMs to bear the costs and risks associated with maintaining high-cost trucks on their balance sheets.

Implications for the mobility system and participant responses

Autonomous trucking will have a ripple effect throughout the mobility ecosystem, necessitating responses from industry participants.

Implications on the ecosystem
As costs fall, demand for autonomous fleets will accelerate and fleet volumes will increase. Scale will become more important as operators seek to distribute fixed costs for monitoring and servicing trucks over a larger installed base of fleets.

Some industry consolidation may occur as smaller fleets struggle to finance required capital expenditure investments in autonomous trucks and associated infrastructure. At the same time, new participants may emerge, such as companies that specialize in building and maintaining hub infrastructure, operating hubs, and running service centers to maintain autonomous trucks.

It is too early to anticipate which companies will capture the benefit of reduced costs and how much of this benefit will be passed through to shippers. Under one scenario, if only a few dominant technology providers emerge to offer AV software and AV trucks, these companies (AV tech players and OEMs) could accrue most of the cost benefits. If, on the other hand, the market is highly competitive, most of the cost benefits could be passed through to fleet operators and shippers.

How to become a leading player in autonomous trucking
Companies across the trucking industry can work in earnest now to consider their options and develop strategies to guide their participation in this burgeoning industry segment.

Fleet owners and operators. Fleet owners can begin to gain an understanding of autonomous-fleet operations and their effect on overall operations by conducting early pilots with technology providers. They can redesign their networks to enable autonomous driving (for example, by moving distribution centers closer to highways) and prioritize the rollout of autonomous driving based on real traffic flows, complexity of the environment, and potential TCO savings. Routes with the most difficult weather conditions, for example, could be low on the priority list. Meanwhile, savvy fleet owners are already preparing for the electrification of autonomous trucks in discussions with OEMs, planning for charging stations, and anticipating other related activities.

Infrastructure providers. These companies can focus on developing advanced infrastructure such as transfer hubs with maintenance, sensor calibration, and fueling, as well as charging facilities. They could form public–private partnerships to collaborate with government entities on smart highways and urban infrastructure, for example, to provide additional information on critical road elements such as intersections.

OEMs. OEMs should take several actions to stay relevant in autonomous driving. They can design trucks to enable autonomous driving, for example, by including redundant braking, steering, and power supplies. Emerging leaders will also build capabilities in developing autonomous-driving software, at a minimum for testing and validating autonomous trucks, which will likely be needed for type approval. If the software is not developed in-house, partnerships with AV technology companies are key to sell or operate autonomous trucks.

As sustainability of autonomous driving becomes more important over the medium to long term, they can simultaneously plan for zero-emission autonomous trucks. They can also prepare to swap truck powertrain technology from the internal-combustion engine (ICE) to hydrogen (fuel cell or hydrogen ICE) or battery electric trucks using megawatt charging or battery-swapping technology. Battery electric trucks with battery swapping and hydrogen trucks would support higher truck utilization compared with battery electric trucks using megawatt charging. To further expand the footprint in autonomous driving, OEMs can build the infrastructure required to support the initial hub-to-hub use case or become an operator of autonomous trucks, offering CaaS.

AV technology developers. These companies can lead innovation by driving the development and integration of cutting-edge autonomous systems and technologies. They can establish partnerships with OEMs, infrastructure players, and logistics companies for the initial stages of autonomous-truck deployment and conduct pilots to learn about operations and real-world requirements of autonomous driving.

Component suppliers. Suppliers that develop and manufacture essential hardware components such as light detection and ranging (LiDAR) sensors,, high-performance computers, redundant braking, and steering systems will be critical enablers of autonomous driving. Additional opportunities lie in software products for autonomous trucks, such as truck motion controls or an independent backup path to perform a minimal risk maneuver. Success in this market will require them to build capabilities in functional safety to reduce the risk of system failures by implementing protective measures.

Autonomous trucking has the potential to make commercial transport more efficient, affordable, and sustainable—a win for consumers, OEMs, fleet operators, and others in the mobility ecosystem.

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