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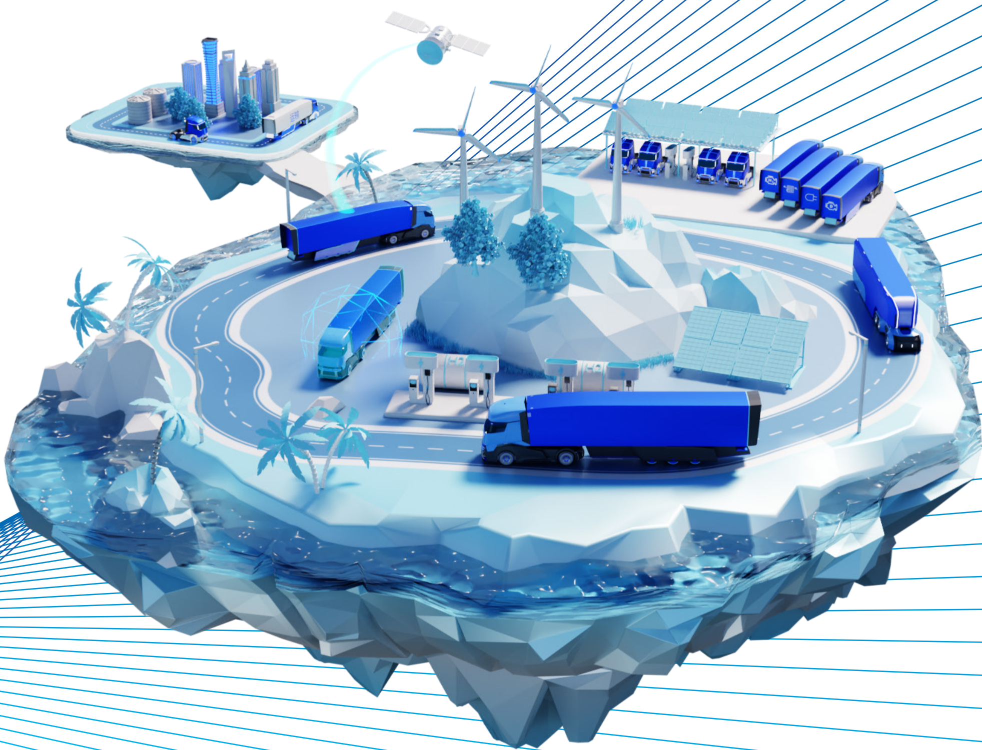

Automotive & Assembly Practice

On the route to success

Commercial vehicle compendium

September 2024

Preamble

Dear reader,

The global truck industry is at a critical juncture. The development of zero-emission (ZE) trucks entails much more than changing powertrain technology—it requires the entire truck ecosystem and its economics to transform. To successfully navigate this evolution, OEMs and other industry players will need to address several challenges:

— ZE truck economics need to accelerate at a higher pace than today to meet anticipated target cost through 2030. High initial R&D expenditures, battery costs, and/or hydrogen technologies cost imply significant challenges for OEMs to maintain their profitability throughout the transition. Over time, the higher Capex and lower Opex of ZE trucks compared to Diesel trucks necessitate an even stronger focus on lifecycle revenues. This change also enables a shift of control points from mechanical components to data, software, and battery cells (Article "The bumpy road to zero-emission trucks").

— To compensate for the higher system cost of ZE trucks, OEMs will need to evolve their business models. An innovative service ecosystem—that includes, for example, truck-as-a-service and advanced connectivity offerings—will emerge as new sources of revenues. McKinsey estimates that in 2035 OEMs could earn up to 75 percent of their profits from recurring lifecycle services (Article "Truck as a service").

— Amid technological uncertainty, capital allocation and partnership strategies are critical to manage multiple powertrain technologies in parallel, including diesel technology and a stable supply chain as well as advanced battery and fuel cell technology for heavy duty trucks and other e-powertrain solutions (Article "How batteries will drive the zero-emission truck transition"). These strategies extend to software and electronics technology. OEMs can work to secure new skills, gain access to technology, scale software platforms across vehicles, and, eventually, solidify standards to advance next generation electrical and electronics architecture (Article "The big shift: Moving commercial vehicle OEMs to centralized E/E"), connectivity offerings (Article Article "Driving the future: How connectivity will shape the truck industry") and ADAS/AD features (Article: "Will autonomy usher in the future of freight transportation?") while selectively maintaining control of the value chain.

— Beyond the truck, meeting ZE truck targets in 2030 will require an estimated capital investment of €5 billion to upgrade charging infrastructure and the power grid. So far, less than a quarter of this investment has been committed to publicly. In addition to more investment, deploying ZE trucks at scale in 2030 will require OEMs to connect more chargers to the grid faster and quicker regulatory approval processes (Article: "Building Europe's electric-truck charging infrastructure").

— As with the passenger car market, China has set the benchmark for the speed of development and deployment of ZE trucks. The Chinese truck market is advancing ZE trucks, autonomous driving, and connectivity rapidly and with some remarkable differences compared to other regions. The global ambitions of Chinese OEMs pose a threat to Western incumbents that is reminiscent of the electric bus market, propelling other regions with a sense of urgency (Article "A new era: Trends shaping China's heavy-duty trucking industry").

On top of these challenges, the fundamentals of the truck industry have made mastering the transition to ZE trucks even more difficult. Thin order books and high interest rates strain OEMs' wallets and inhibit their ability to invest in necessities for the transition. Moreover, rising energy costs and volatile raw material prices for ZE trucks have stymied TCO advancements, causing OEMs to choose between satisfying customer demands and meeting regulatory targets—which, in themselves, are both subject to rising uncertainty.

At the current speed of change, our analysis shows that global emission targets will not be met.
A concerted effort of the entire truck ecosystem—OEMs, suppliers, infrastructure players, utilities, financial institutions, and regulators—is needed to accelerate progress. Such an effort could marshal the resources needed and create the optimal conditions to accomplish the transition successfully.

Mikael Hanicke, Anna Herlt, Tobias Schneiderbauer

Automotive & Assembly Practice

The bumpy road to zero-emission trucks

The shift to zero-emission trucks brings opportunities and challenges for the industry in areas such as powertrain, service, and vehicle digitization. Making it happen will require greater cooperation.

This article is a collaborative effort by Anders Suneson, Anna Herlt, and Malte Hans, with Christian Begon and Henrik Becker, representing views from McKinsey's Automotive & Assembly Practice and the McKinsey Center for Future Mobility.

As major trucking companies decarbonize their fleets, they are prioritizing lower-carbon fuels such as natural gas and biofuels over zero-emission trucks. Adopting these fuels marks a positive step toward sustainable commercial mobility but represents only an intermediate step toward zero-emission mobility in the commercial sector. Meanwhile, true zero-emission mobility in the form of electric or hydrogen-based trucking appears to be stuck in traffic as massive challenges delay adoption.

The transition to zero-emission trucks involves more than just replacing a powertrain. Disruptions will occur across the ecosystem: OEMs are devoting substantial development, production, and sales resources to developing new powertrains and higher degrees of digitization. A multibillion-dollar infrastructure challenge is on the horizon, and utility companies face a wave of new demand on their grids. In addition to those supply-side issues, fleets hesitate to commit to the transition in the face of challenges ranging from stretched capital expenditure budgets to unwieldy business cases to operational hurdles.

1. Hitting regulatory targets: What would it take?

The transition to zero-emission powertrains is largely driven by regulatory interventions and supported by decarbonization efforts across industries. Medium- and heavy-duty trucks (MHDTs) must become emission-free to decarbonize the transportation sector in line with long-term targets. To make this shift happen, regulators in the European Union and North America are following a two-pronged approach: first, they are pushing truck OEMs to decarbonize their product portfolios, and second, they are creating subsidy programs to bridge gaps in total cost of ownership (TCO) and ease capital expenditure burdens in infrastructure deployment.

Regulations and incentives

The European Union has some of the toughest emissions regulations worldwide, with reductions of 43 percent required in sales for new MHDT by 2030 and 90 percent by 2040, enforced by hefty fines for noncompliance.[1] Additional regulations focus on infrastructure build-out (AFIR),[2] proposed exceptions to vehicle dimension standards for zero-emission trucks, and discounts on distance-based road tolls aimed at facilitating the transition.[3] These are complemented by subsidy programs, such as a German initiative that covers up to 40 percent of charging infrastructure costs, encouraging the deployment of zero-emission trucks.[4]

In the United States, national-level targets proposed by the Environmental Protection Agency require a slower yet still significant deployment of zero-emission trucks by 2030.[5] Depending on the truck segment, zero-emission powertrains are expected to account for 25 to 60 percent of new annual sales by 2032.[6] However, the State of California and other states[7] that have adopted the California Air Resources Board's Advanced Clean Trucks regulation aim for stricter targets of 30 to 50 percent by 2030.[8] In addition, the federal Inflation Reduction Act provides tax credits to manufacturers and fleet operators for zero-emission truck sales, batteries, charging infrastructure, and hydrogen production and distribution.[9]

These incentives are particularly critical for encouraging fleet operators in both the United States and the European Union to decarbonize their operations. Operators face increased pressure from regulators, freight buyers, and investors to decarbonize their fleets while seeing a clear lack of willingness on the customer side to pay for the transition. For example, starting in 2024, the Advanced Clean Fleets regulation in California sets zero-emission vehicle requirements for priority fleets such as drayage operations as well as fleet operators with more than 50 vehicles.[10] In the European Union, Germany has introduced a CO_2-based toll on combustion-engine trucks equivalent to €200 per metric ton of carbon dioxide emitted.[11] The European Union is also set to launch the EU Emissions Trading System 2 in 2027. The carbon-trading scheme covers emissions from fuel suppliers

1 Regulation (EU) 2024/1610 of the European Parliament and of the Council, *Official Journal of the European Union*, May 14, 2024.
2 "Alternative Fuels Infrastructure Regulation," European Commission, accessed August 22, 2024.
3 Regulation (EU) 2023/1804 of the European Parliament and of the Council, European Union, September 13, 2023; "Commercial vehicles—weights and dimensions (evaluation)," European Union, accessed August 22, 2024; *Road charges in the EU: A fairer and environmentally friendlier system*, European Parliament, October 25, 2018.
4 "Funding to continue for commercially used fast-charging points," NOW GmbH, May 21, 2024.
5 Yihao Xie and Ray Minjares, "How U.S. and EU proposals could steer the transition to zero-emission truck and bus fleets," International Council on Clean Transportation, September 19, 2023.
6 Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles—Phase 3, Environmental Protection Agency, *Federal Register*, April 22, 2024, Volume 89, Number 78.
7 "States that have adopted California's vehicle regulations," California Air Resources Board, updated June 2024.
8 "ZEV sales percentage schedule," in Advanced Clean Trucks Regulation, California Air Resources Board, accessed August 22, 2024.
9 Inflation Reduction Act of 2022, US Congress, August 16, 2022.
10 Based "Advanced clean fleets regulation overview," California Air Resources Board, July 3, 2024.
11 "Entwurf eines Dritten Gesetzes zur Änderung mautrechtlicher Vorschrifte," German Bundestag, August 23, 2023.

for buildings, road transport, and other sectors such as small industries. The system is intended to help EU member states meet their emission-reduction targets and achieve climate neutrality by 2050.

These developments indicate that regulatory pressure, especially on OEMs, is intensifying, and public announcements of powertrain and R&D focus shifts can be interpreted as signs that the industry is embracing the regulatory goals (Exhibit 1). But what would have to happen for the ecosystem to achieve these ambitious targets?

To meet regulatory targets, McKinsey estimates that well over a third of new MHDT trucks sold in the United States and the European Union would have to run on zero-emission powertrains by 2030. This sales increase will translate into zero-emission parc shares that exceed 10 percent after 2035. This appears to be a daunting task, given that zero-emission trucks—battery electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs)—account for less than 2 percent[12] of new MHDT sales in the United States and the European Union, with the largest sales numbers in use cases focused on regional and urban applications for heavy-duty trucks.[13]

Pure regulatory pressure is highly unlikely to successfully steer a complex ecosystem of very different players to achieve such high ambitions. As one author once wrote,[14] "You don't rise to the level of your ambitions; you fall to the level of your systems." While ambitions are high, the systems in question do not always work in the needed ways.

Ultimately, what is required is a functioning market and an ecosystem that does not rely on regulatory enforcement or subsidies. Fleet owners must want to buy zero-emission trucks, not be forced to buy them because no alternatives exist or because subsidies drive the decision. To achieve this, the ecosystem must improve on the two main buying criteria for fleet owners: the reliability of the "infrastructure vehicle system," and lifetime TCO parity versus current powertrain alternatives.

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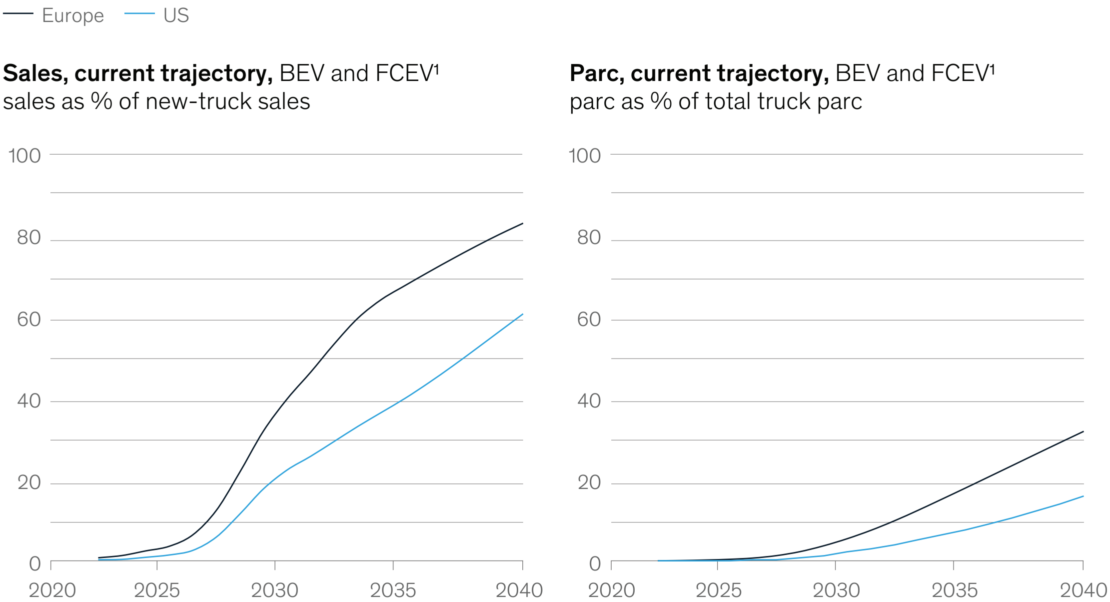
[12] Yihao Xie, *Zero-emission bus and truck market in the United States: A 2022–2023 update*, International Council on Clean Transportation, June 18, 2024; Alessia Musa et al., *Race to zero: European heavy duty vehicle market development quarterly (January–March 2024)*, International Council on Clean Transportation, June 20, 2024.

[13] "Trends in electric heavy-duty vehicles," in *Global EV outlook 2023: Catching up with climate ambition*, International Energy Agency, April 2023.

[14] James Clear, *Atomic Habits: An Easy & Proven Way to Build Good Habits & Break Bad Ones*, New York City, NY: Avery, 2018.

Exhibit 1

New-truck sales in the United States and the European Union will aggressively transition to zero-emission powertrains by 2040.



[1]BEV is battery electric vehicle; FCEV is fuel-cell electric vehicle.
Source: McKinsey Center for Future Mobility

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2. What will it take to realize zero-emission trucks at scale?

Making the anticipated rapid transition to zero-emission trucks will require the entire ecosystem to act in concert, with unprecedented efforts from each player to address multiple challenges simultaneously (Exhibit 2). However, in its current form, the market for zero-emission trucks is not working properly, leading to delays in the transition.

OEMs and suppliers

OEMs and suppliers have a tough task ahead. They need to create a comprehensive zero-emission-vehicle (ZEV) portfolio, build a new supply chain catering to this portfolio, scale up production capacities, and drive a real step change in product cost.

Develop products and solutions. OEMs must rethink product designs and develop new lines of products and solutions optimized for the zero-emission-truck market. They should include new platform strategies featuring prioritized powertrain offerings and specifications (for example, power ranges, battery sizes, and payload). OEMs must balance the offering of a new competitive product portfolio across relevant market segments against keeping development costs and operational complexity under control.

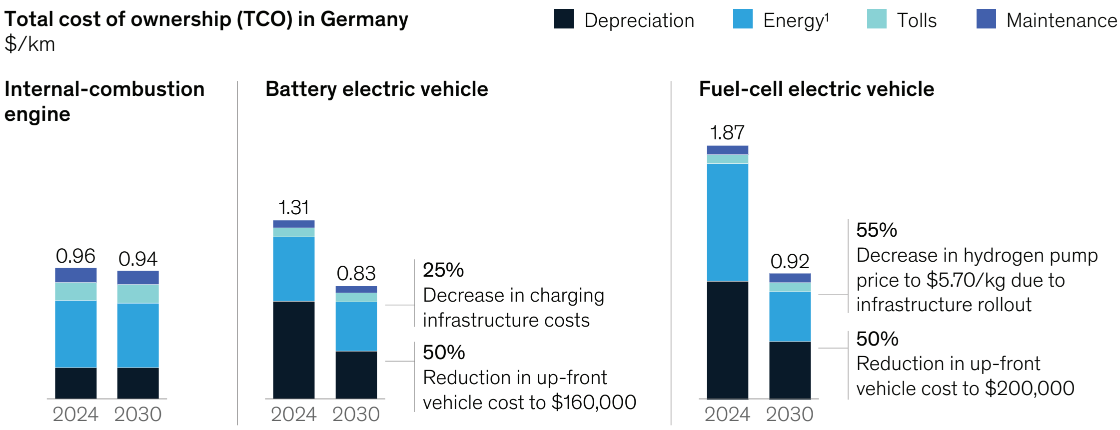
Reduce product costs. Today, McKinsey analysis shows that zero-emission trucks have a TCO disadvantage of up to 40 percent, especially in the heavy-duty long-haul segment. Subsidies and use cases that better fit the electric vehicle (EV) powertrain (such as short-haul and medium-duty) can reduce this difference, but product cost reduction will be the key to driving adoption. The race to achieve major cost improvements for key powertrain components will intensify over the next several years: for battery packs, McKinsey analysis reveals that a cost reduction to about $105 per kilowatt-hour or less will be needed to offer competitive products in long-haul segments. To make this happen, further scale in volumes and improved packaging will be required. McKinsey estimates that cost reductions of more than 50 percent will be required for fuel-cell systems to achieve TCO parity. A mix of scale, synergies, and effective collaboration with key suppliers and other partners will be integral to success.

Scale up production. Current ZEV production systems cannot capture the same scale effects as those generated by traditional powertrain architectures. Only scaling up production to new volume levels will enable manufacturing cost reductions to line up with product cost reductions as outlined above.

Exhibit 2

Reaching parity in zero-emission truck total cost of ownership by 2030 will require a significant reduction in energy and depreciation costs.

Heavy-duty line-haul truck (40-ton tractor); 350 km daily range (90K km per annum); 350 kW engine power



[1]Includes distributed cost of charging infrastructure required for battery electric vehicle (assumes ~30% of on-the-go charging).
[2]Energy prices: diesel, $1.49/l in 2024, $1.52/l in 2030; electricity, $0.21/kWh in 2024, $0.17/kWh in 2030; hydrogen, $11.90/kg in 2024, $5.70/kg in 2030.
Source: McKinsey Center for Future Mobility

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Making the anticipated rapid transition to zero-emission trucks will require the entire ecosystem to act in concert, with unprecedented efforts from each player to address multiple challenges simultaneously.

Shift supply chains to new champions. The powertrain supplier landscape faces major disruption as demand shifts away from combustion-engine components and toward new, high-value components such as batteries and fuel cells that require completely different capabilities. New points of differentiation and a different supplier landscape will require a new sourcing strategy for OEMs.

Drive the transition from product to solution. New go-to-market models are required to support customers in the transition to zero-emission trucks. The goal is to provide tailored ecosystem services (for example, financing, insurance, and charging infrastructure) and reduce uptime risk and residual-value risk for fleet operators. As OEMs move beyond vehicle sales, new partnerships will be required to offer a full suite of services .

Get ready for new competitors. New competition will enter the mix in the form of attacking OEMs from overseas markets such as China and South Korea as well as e-truck-only start-ups. McKinsey analysis suggests that new entrants have captured a large share of the early market for zero-emission trucks; incumbents need to drive market positioning to compete successfully.

All of the above must be optimized in a highly uncertain environment of changing regulatory and subsidy landscapes, a volatile battery market, and technologies (such as batteries and fuel-cell systems) that are still maturing and thus prone to technological disruptions. Hence, OEMs need a new, resilient approach to capital expenditures, portfolio planning, and component sourcing to react effectively to technology disruptions and unexpected changes in demand.

The key ingredients of a successful strategy are agile product-renewal cycles that allow for quick reactions to customer feedback and competitive products , a resilient supply chain with a balanced supplier portfolio across geographies, a clear path toward product cost reductions, and an upgraded go-to-market approach that includes digital services and turnkey solutions for fleet operators. The speed of product renewal will be especially crucial for players to stay ahead of the game: as innovation cycles get shorter, model cycles need to follow for products to stay competitive because customers are highly willing to switch brands for a better cost position.

Charging and hydrogen refueling infrastructure players

Charging infrastructure and hydrogen refueling infrastructure are required for a zero-emission-truck rollout at scale, but McKinsey research estimates that such infrastructure will require investments across the United States and Europe of $30 billion by 2035 and $60 billion by 2040.[15] Only a fraction of that has been committed. These investments must be committed now despite the low adoption of corresponding vehicles, requiring a calculated risk-taking approach and commitment to the market.

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[15] For more details on charging infrastructure, see Anna Herlt, Eugen Hildebrandt, and Henrik Becker, “Building Europe’s electric truck charging infrastructure,” McKinsey, September 2024.

[16] Moritz Tölke and Alan McKinnon, *Decarbonizing the operations of small and medium-sized road carriers in Europe*, Smart Freight Centre and Kühne Logistics University, January 2021.

For BEV trucks, our research suggests that urban and regional distribution routes will be the first to electrify via private depot charging stations. However, public high-speed charging infrastructure is required to electrify long-haul routes across Europe and the United States.

Drive the deployment of charging in the public space. Investors face a chicken-or-egg dilemma during the initial years of infrastructure rollout: too many chargers and not enough zero-emission trucks, or the reverse. At the same time, rapid technology and market developments—such as megawatt charging system standards and liquid versus compressed hydrogen—make business cases challenging, especially considering the increased costs of capital. Hence, infrastructure players need to engage in partnership models with large transportation providers to find anchor customers to act as safeguards against part of the utilization risk.

Pave the way for faster grid upgrades. Early practical experience suggests substantial challenges exist in upgrading grids to allow for private charging at scale. Infrastructure providers must invest in their networks to enable these use cases because they offer the biggest opportunity for electrification at scale without relying on a public charging network buildup. Incentive schemes shifted toward these network improvements can act as a transformation accelerator.

Customers

Small fleets, with fewer than 50 trucks each, dominate the European market.[16] Only a few large fleets exist, and large logistics companies often outsource significant portions of their business to retain the benefits of being asset-light operations and to enable quick responses to changes in demand. While larger logistics players face some pressure from shareholders to decarbonize their operations and have access to funding that would allow them to procure zero-emission trucks, small-fleet operators typically lack both incentives. In addition, freight buyers have shown limited willingness to pay for green logistics, leaving little incentive for small-fleet operators to transition to zero-emission trucks at this point.

As a result, fleet operators hesitate to move to zero-emission trucks because of significant concerns and uncertainties about cost, reliability, and operational fit. Based on a McKinsey survey of fleet operators, the main pain points with BEVs are range anxiety and practicality, while costs and availability are among the main concerns about FCEVs (Exhibit 3). But customers can become part of the solution by employing the following key changes:

Cut through the powertrain clutter. Powertrain options available to truck fleets have proliferated significantly, and strong evidence suggests that optimal powertrains for many use cases exist today. For example, FCEVs are unlikely to be relevant in medium-duty truck fleets or short-haul-focused applications but make sense in long-haul situations, while BEVs are less competitive in heavy-duty long-haul applications but can work well in local fixed-route applications. Therefore, fleets should assess their driving patterns to see where the best technology choices are possible today.

Don't plan for the worst case: vehicle considerations. Electrified fleets require a more targeted approach and assessment than diesel fleets, in which vehicles are very much "one size fits all" in terms of range, although driving cycles vary significantly across use cases. Fleet operators and consumers today tend to fall into similar traps, basing vehicle choices on the extreme 1 percent use case (such as long-distance winter driving in mountainous regions), driving vehicle technology costs up, and TCO parity out. Fleet owners need to break down their operations profiles into distinctive use cases and actively capture the opportunity to tailor their vehicle fleets to their true needs rather than employing a one-size-fits-all approach.

Don't plan for the worst case: infrastructure considerations. A similar fallacy is seen in infrastructure planning. Fleet operators rarely examine vehicle use and charging patterns, leading to large and costly implicit buffers in their estimated charger and charging-power requirements. Energy demands are overstated, resulting in even longer timelines and slower scale-up of vehicles toward zero-emission trucks. As with vehicles, fleet operators need to assess their expected use case patterns for charging infrastructure and find the sweet spot between a sufficient capacity buffer and low capital expenditures.

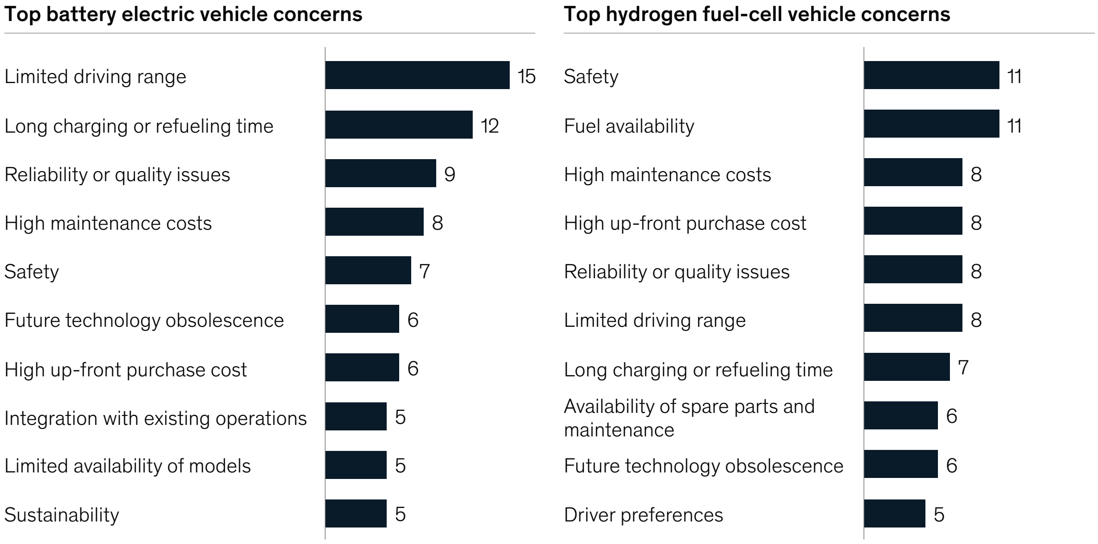
Pilot to test, but plan to scale. Most corporate commercial fleets today operate at least a handful of zero-emission trucks to test their performance in live operations. Firsthand experience cannot be replaced. However, too few fleets accompany the small-scale pilots with a structured assessment of their overall vehicle fleets, infrastructure requirements, and corresponding transition path to both inform vehicle purchase selections and address potential grid upgrade requirements early in the process.

Embrace new models of cooperation and partnership. Harmonizing vehicle specifications

Exhibit 3

Fleet operators have a variety of concerns about acquiring new battery electric or hydrogen fuel-cell commercial vehicles.

Fleet survey[1]



[1]Answers from 400 fleet managers and owner operators in France, Germany, Italy, the UK, and the US (representing 30% of fleets with >€500 million in revenue, 40% of fleets active in line haul and regional hauling, and 40% of medium and large fleets with >10 vehicles).
Source: McKinsey's Off- and On-Highway Equipment Customer Insights, Q4 2023

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and adopting buying-coalition approaches can help reduce up-front costs and create win–win situations for customers and OEMs alike. Several initiatives are already being piloted in Europe and the United States. At the same time, new financial business models are emerging that reduce the capital expenditure barrier to zero-emission trucks by providing transportation as a service (TaaS) models and creating mini-ecosystems among financing players, road freight forwarders, and carrier subcontractors. Similar arrangements should begin to emerge for infrastructure, with networks attempting to build capacity tailored to the demand of larger players and then filling up with zero-emission trucks. Embracing these existing models outside of direct truck purchases can help attenuate the challenges within the transition.

Continue driving the commercialization of green transport. On the ecosystem level, a lack of commercial models related to green transportation is a key issue. As long as green transportation does not generate demand or willingness to pay, adoption will fully rely on TCO parity and reliability. Of course, willingness to pay can't be forced, but commercialization efforts today are still nascent, and more tailored models (for example, through feature bundling and other strategies) need to be tested to optimize customer willingness to pay.

3. The rules of the game are changing: Capturing value in the zero-emission truck world

Zero-emission trucks are expected to reshape the rules of the industry. Higher vehicle capital expenditures and lower operating expenditures compared with diesel trucks will lead to an even stronger focus on financing and asset utilization challenges, with control points shifting from mechanical components to chemicals, electronics, and data. McKinsey's proprietary Commercial Vehicle Value and Profit Pools model suggests the following outcomes as zero-emission trucks begin to take over:

— By 2035, truck industry value pools in the United States and the European Union will surpass $684 billion (Exhibit 4). Zero-emission trucks could account for roughly 20 percent of truck-related value and profit pools by 2035, resulting in up to $140 billion in market size.

— In a zero-emission world, new-truck sales and diesel fuel retailing will no longer be growth drivers for industry profits. Diesel retail will come under pressure because of decreasing demand in a world with growing zero-emission powertrain uptake. The profit pool share of legacy energy carriers will decrease from almost 40 percent of profit pools to only about 20 percent in 2035.

— Internal-combustion-engine (ICE) sales market share could decrease by as much as 40 percent by 2035, but new zero-emission truck sales can compensate in terms of value given their higher vehicle prices. However, zero-emission trucks will be sold at lower margins compared with ICE trucks due to product maturity and scale. Consequently, the loss in the profit pool from lower ICE sales cannot be offset by zero-emission trucks. The new-vehicle profit pool will thus remain between $3 billion and $4 billion.

Incumbent OEMs and suppliers will face pressure on multiple fronts

OEMs and suppliers need to redesign their product portfolios, go-to-market approaches, and sourcing strategies at the same time while keeping up profitability across both ICE and zero-emission product lines.

Manage the zero-emission truck margin challenge. Regulatory targets assume a fast ramp-up of zero-emission truck sales, enforced with hefty fines for noncompliance. If the build-out of corresponding infrastructure is slower than required or OEMs cannot bring down product costs quickly enough, low or negative profitability of the zero-emission trucks portfolio will likely result, at least in the near term.

Oversee ICE profit erosion. OEMs will also see the profits of their longtime core ICE businesses erode. With a higher share of zero-emission trucks in new sales, fewer diesel vehicles with robust margins will be sold. McKinsey research notes that new-truck sales will likely lose two to three percentage points of share in profit pools—equaling $1 billion in profit—over the next ten years (Exhibit 5). However, the future margin development of truck powertrains is uncertain, with the potential for both positive and negative outcomes.

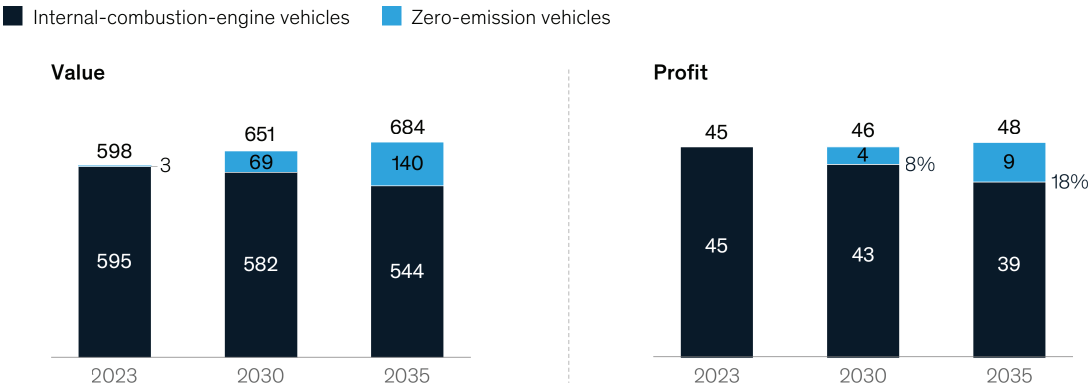
Handle aftermarket growth. The aftermarket will experience some growth, mainly driven by an increase in overall parc. Zero-emission trucks will partly compensate for the lower maintenance effort they require with the higher value of the spare parts needed. McKinsey's proprietary Truck Value and Profit Pools model suggests that the aftermarket profit pool may reach $17 billion to $18 billion by 2035.

Develop sunsetting strategies. As the market potential for ICEs declines, players must prepare sunsetting strategies for their ICE programs. Although ICE technology will still play a role in a global context both in niche applications and in markets that are electrifying more slowly, OEMs and suppliers must find ways to uphold profitability at a lower scale.

Exhibit 4

Zero-emission trucks will affect the truck industry's value and profit pools, increasing their share to approximately 20 percent by 2035.

MHDT[1] value and profit pools in the US and EU for all players, $ billion



Note: Figures may not sum, because of rounding.
[1]Medium- and heavy-duty trucks.
Source: McKinsey Center for Future Mobility

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Reassess vehicle components. At the same time, there should be a fundamental shift in the supplier landscape. The value of zero-emission powertrain-related components is likely to more than double, according to McKinsey research. However, this increase in value is driven by batteries or fuel-cell systems, whereas the market for electric powertrains will be much smaller than today's market for diesel powertrains. Given the limited overlap with traditional ICE control points, existing suppliers do not necessarily have a right to win in these new components. As a result, we will likely see continued consolidation in the supplier space among players holding major shares in ICE-related component groups while new supply chains for batteries and fuel-cell system components are shaping up, with new suppliers entering the space.

Among zero-emission truck components, OEMs will have to develop new sourcing strategies or in-house capabilities. For example, the market for truck batteries is expected to reach $13 billion by 2035, according to the McKinsey model, a large fraction of which will be captured by battery cell manufacturers. Similarly, the model also suggests that the hydrogen tank and fuel-cell systems market will reach $7 billion, opening a door to new component suppliers that master these new technologies.

Fuel players need to develop solutions for charging and hydrogen

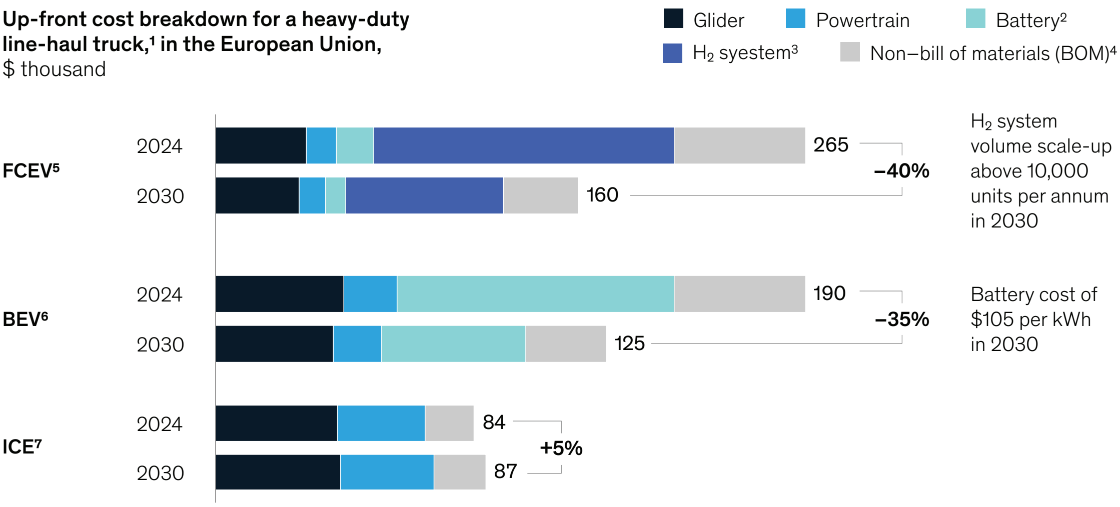
Players active in fuel production and retailing need to refocus on a set of new energy carriers and retail formats. Diesel-fuel-related profit pools are expected to decline by up to 40 percent by 2035, according to McKinsey analysis. While dampened by a growing total vehicle parc, the decline is expected to continue as zero-emission vehicles gain market share.

Prepare for changes in fuel retail and service. Because zero-emission powertrains will have different refueling patterns, the fuel retail footprint and service formats will likely have to change. Electric trucks are expected to charge up primarily in fleet hubs, while hydrogen truck operations are expected to focus on long-distance routes on highways.

Exhibit 5

Product costs of zero-emission trucks need to drop by 30 to 40 percent by 2030 to allow for a competitive total cost of ownership.

Heavy-duty line-haul truck (40-ton tractor); 350 km daily range (90,000 km per annum); 350 kW engine power



[1]Class 8 tractor with ~350 kW motor power and ~350 km range between refueling stops. Battery electric vehicles could change from a ~500 kWh battery (1.26 kWh/km, $175/kWh) in 2024 to ~440 kWh (1.10 kWh/km, $105/kWh) in 2030. Fuel-cell electric vehicles have a ~60 kWh auxiliary battery, a ~270 kW fuel-cell system, and a ~36 kg H_2 tank.
[2]Includes cells.
[3]Includes fuel-cell stack, balance of plant, and H_2 tank.
[4]Non-BOM cost of goods sold includes direct labor, production support (engineering, quality), transport and duties, and warranty.
[5]Fuel-cell electric vehicle.
[6]Battery electric vehicle.
[7]Internal-combustion-engine vehicle.
Source: McKinsey Commercial Vehicle Electrification model based on McKinsey Center for Future Mobility analysis

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Find a new balance point. These trends translate into declining business for classic fuel retail outside of larger hubs and major corridors. For on-highway locations, a well-balanced offering of hydrogen, fast charging, and overnight charging along with corresponding ancillary services will be key to success. But incumbent fuel retailers are not alone in this space; utilities and pure-play charging or hydrogen refueling players are advancing into the market. In serving the remaining ICE fleet on the road, alternative fuels can help sustain fuel retail sales for longer.

New opportunities emerge in services

While industry value pools are growing, global profit pools will likely stay flat over the next ten years. Because sales of new vehicles, traditional aftermarket products and services, and fuels won't be major profit growth drivers anymore, players need to focus on verticals relevant to zero-emission trucks (Exhibit 6). McKinsey research suggests new opportunities will arise with the transition to zero-emission trucks, including financial services, data-enabled services, and charging and energy, which will likely emerge as major profit pools by 2035.

Focus on financing. The higher up-front costs of zero-emission trucks will increase the demand for and the value of financing and leasing offerings. Captive OEM financial-services offerings will gain in importance, with OEMs holding an important control point, but major banking and leasing players and infrastructure investment funds will have growth opportunities as well.

Reexamine insurance. The large ICE parc makes up the bulk of the profit pool, but zero-emission trucks will push the value at stake given higher insurance rate pricing because of their higher up-front costs, more expensive replacement parts, and complex technology.

Proliferate ZEV charging and energy. The procurement and installation of charging infrastructure (private depot and public on-highway charging) as well as increases in the ZEV parc will drive new energy demand. This is a completely new business for the industry and will trigger new business relationships and active players in the market that were formerly active in the energy, utility, and industrial space.

Pursue data-enabled services. Business models and ecosystems will focus on data-enabled services, which are the key enablers for the successful uptake of zero-emission trucks. With the increasing digitization of vehicles, digital solutions related to vehicle data need to address customer concerns regarding vehicle range and charging (for example, advanced route planning with in-route charging management). Captive OEM solutions will compete with third-party offerings.

Capture recurring life cycle services. By 2035, up to 75 percent of OEM profits could come from recurring life cycle services, according to McKinsey's proprietary Truck Value and Profit Pools model. Overall, industry players will focus on capturing these recurring profits in competition with OEMs. The value in new ZEV-related opportunities and services could be distributed among competitors.

Consequently, players need to navigate the upcoming value chain shifts and be very strategic about their positioning across the value chain steps. Potential moves could include new cooperative links, partnerships, M&A, and especially new business building (for example, TaaS).

4. Cooperation across the industry ecosystem is needed to drive the transformation

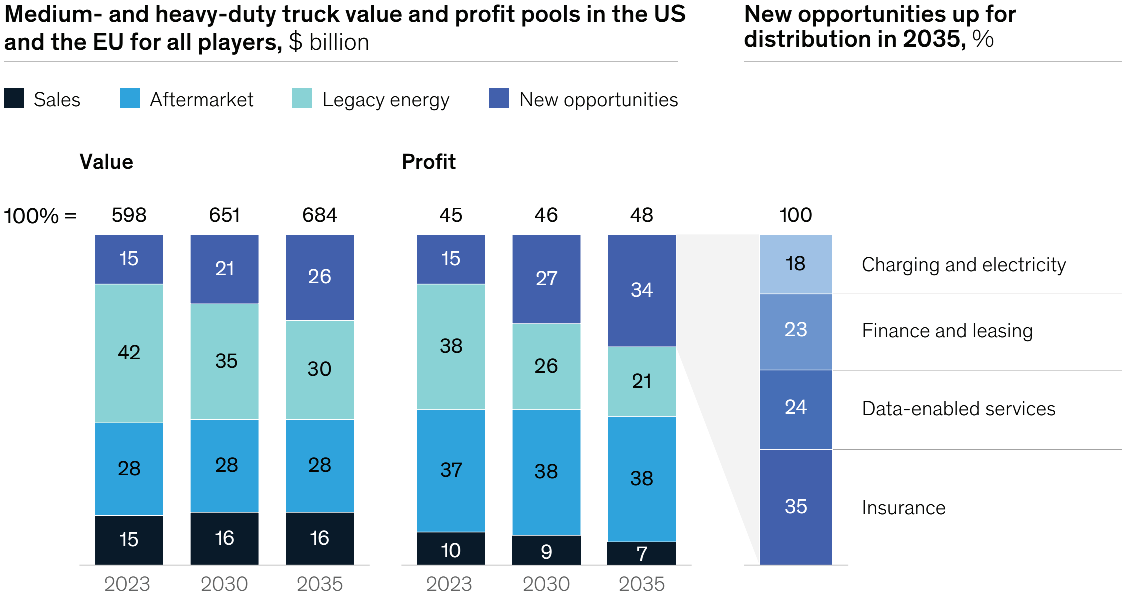
Scaling up zero-emission-truck sales at the speed required by current regulatory targets is a very ambitious goal and poses a wide variety of challenges. While none of these challenges is unsolvable on its own, the short timeline for the required ramp-up will push industry players fighting on their own to their limits and beyond.

Given how intertwined the challenges in infrastructure and vehicles are and how many different players, from regulators to consumers, must bring their capabilities to the table to resolve them, cooperative efforts appear to be the only way to work toward a resolution. Fortunately, these cooperative efforts are emerging on global, regional, and local levels, driving different types of conversations and progress.

Global. Some of the major challenges require collaboration on a global scale. Technological improvements and cost reductions of key components such as batteries and fuel-cell systems can be best addressed by bringing together engineers from different companies and across the globe. Several battery factories are already being built in partnerships. Similarly, solving the huge financing challenge for zero-emission trucks, charging infrastructure, and hydrogen refueling networks requires multinational collaboration among infrastructure investors, OEMs, and logistics players. The goal is to jointly develop new financing and ownership

Exhibit 6

The penetration of zero-emission trucks will create new opportunities, resulting in major growth in profit pools by 2030 and beyond.



Note: Figures may not sum to 100%, because of rounding.
Source: McKinsey Center for Future Mobility

McKinsey & Company

approaches, some of which are already being tested on the market.

Regional. On the regional level, the predictability of regulatory targets and incentive schemes is paramount to allow players to plan the transition to zero-emission road transport. At the same time, consistency in regulations and incentives across neighboring markets is key for multinational operations to develop consistent fleet and powertrain strategies. Industry cooperation will be pivotal in driving adoption and addressing the real constraints in the market. Pushing infrastructure buildup along key freight corridors will help increase expected reliability and confidence in the technology for longer-haul applications across more than one country. If enough fleet buyers get together and share requirements, charging capacity buildup can be funneled to the most important areas. Fleet electrification coalitions are forming across Europe and driving toward such ecosystem-level impact.

Local. Some of the required challenges can also be addressed on the local level. Bringing charging capacity to each fleet hub will put a strain on infrastructure resources, but public charging along main corridors will be insufficient to cover more local use cases best suited for electrification. In areas with multiple existing logistics sites (such as the center of Germany and ports in the United States), cooperation in building shared charging infrastructure can be a solution to this problem, but it will require a form of "coopetition" among competing entities for the greater good. Also, local cooperation with authorities can have a major impact; a great example can be found in the case of a European OEM's finished-vehicle logistics. By working with local authorities, its electric trucks were exempted from certain length restrictions, allowing them to transport one additional vehicle per trip, thereby entirely erasing the trucks' TCO disadvantage on paper.

The traffic jam holding back progress in reaching zero emissions in the truck industry is complex, with many participants and moving parts. While industry players have created a strong buzz around the use of lower-carbon fuels, the drive toward true zero-emission trucks is stalling due to a lack of sufficient cooperation among stakeholders. Furthermore, the trucking ecosystem faces an imbalance in incentives.

OEMs are the only players that fully bear the risk of not complying with regulatory CO_2 emission-reduction targets. The fines they face could threaten their survival if they fail to meet CO_2 targets.

All other elements of the system, including fleets, infrastructure, and financing, have weaker incentives and more time to wait. For example, the main challenge facing fleet operators is uncertainty regarding how zero-emission trucks will fit into their business models. Infrastructure players seek assurances that their investments in fueling and charging stations will pay off, while energy providers contemplate smaller profit pools than in the past. And the finance and insurance industries face new challenges that may force them out of their comfort zones.

Governments are eager to move forward but need to recognize the limited power of emissions regulations such as those imposed on OEMs to create a thriving zero-emission-truck ecosystem. While the issues facing this extended ecosystem call for an integrated response, each group of players often seems resolved to go it alone. Increased cooperation, partnerships, and collaboration across industries, sectors, and regions can provide a compelling way to make zero-emission trucking a reality much sooner than expected.

Anders Suneson is a partner in McKinsey's Stockholm office, **Anna Herlt** is a senior partner in the Munich office, and **Malte Hans** is a partner in the Cologne office. **Christian Begon** is a consultant in the Düsseldorf office, and **Henrik Becker** is a consultant in the Zurich office.

The truck industry is entering a phase of fundamental transitions. The following articles outline specific challenges (including industry ecosystems, charging infrastructure, commercial vehicle batteries, and electrical/electronic architecture) and describe possible solutions.

"Preparing the world for zero-emission trucks," McKinsey Center for Future Mobility, November 17, 2022.

"Decarbonize and create value: How incumbents can tackle the steep challenge," McKinsey, October 24, 2023.

For more information on McKinsey's capabilities in green business building, see "Decarbonize and create value: How incumbents can tackle the steep challenge."

Automotive & Assembly Practice

Truck as a service: The next step en route to zero-emission fleets

Commercial vehicle decarbonization requires changes to the ways fleet trucks are financed and serviced. The truck-as-a-service model is the next logical step toward zero-emission trucking.

by Anna Herlt and Tobias Schneiderbauer
with Eric Morden and Lena Bell

Today, more than 95 percent of trucks on the road around the world run on diesel or gasoline.[1] The traditional truck ownership model of combining purchasing or leasing with selected add-on services is a proven model for both OEMs and customers. Large-fleet customers have a strong understanding of vehicle life cycles, including the expected residual value when vehicles leave their fleets. They know how to arrange for emergency engine repairs and are on a first-name basis with aftermarket agents.

However, the shift to zero-emission (ZE) trucks—driven by regulatory requirements, long-term benefits of total cost of ownership (TCO), and end-customer demand for greener products—will necessitate new business models for OEMs and other truck ecosystem participants. The transition is approaching now; EU regulators, for example, are calling for 45 percent reductions in road transport CO_2 emissions in 2030 compared with 2019.[2]

To reach regulatory decarbonization targets, 15 to 20 percent of new medium- and heavy-duty truck sales globally will have to be ZE by 2030. This profound shift will affect sources of growth and profits across the commercial vehicle ecosystem. Nearly half of industry profits in 2030 will come from opportunities beyond vehicle and aftermarket sales that do not exist today, McKinsey analysis suggests.

OEMs can position themselves to capture this value by focusing on business models that encourage ZE adoption and improve margins. Although service bundles and solutions are already well established in the commercial vehicle ecosystem, the shift to ZE truck fleets (and, eventually, autonomous trucks) propels OEMs to offer a next-generation "truck as a service" (TaaS) business model.

However, capturing this value can be risky for OEMs. Already, we have seen some OEMs lose market share because they have not offered the mix of services needed by their customers in different segments or have not priced them correctly. TaaS models can result in more debt as OEMs need to finance more assets that are held on their balance sheets. In a few extreme cases, OEMs have even declared bankruptcy, either because they were unable to orchestrate the needed product and services ecosystem or because investors canceled their support.

This article explains one pathway to the TaaS model, explores the benefits and challenges of TaaS for multiple stakeholder groups, and discusses TaaS success factors—timing, investment, and partnership strategy—that can help in avoiding costly missteps.

Service bundles and solution offerings have already changed ways of doing business

Leasing and financing commercial vehicles has been a critical alternative to vehicle purchasing, especially in Asia, where up to two-thirds of vehicles are leased rather than purchased (compared with about one-third in Europe and North America), according to McKinsey analysis. These shares have remained stable since 2016, although total revenues have increased during that period. European and North American revenues from leases and finance grew from $20 billion in 2016 to $30 billion in 2024; in China, they grew from $22 billion in 2016 to $27 billion in 2024. For OEMs, the operating lease in particular, with a fixed monthly rate plus options for services, is an important financing product. These service options typically come in one of two forms: bundles or solution offerings (Exhibit 1).

Service bundles. OEMs frequently bundle additional services with the core truck vehicle product and associated lease agreement. They typically target bundles to large-fleet customers with a model partially based on optimizing TCO to share the upside. They also often have their own repair shops on-site, especially in today's world, which is dominated by internal combustion engine (ICE) vehicles.

Customers may choose from among a menu of services covering traditional components such as insurance, aftermarket services such as parts and maintenance, and fleet management services (for example, telematics) as well as newer services such as fleet transition consulting, component financing (for example, for batteries), and charging-infrastructure provisioning.

Customers configure their own bundles based on their perceived needs, paying for each additional element they add. More crucially, high variability in customer configurations increases complexity for OEMs and their ecosystem partners.

1 McKinsey Center of Future Mobility analysis of IHS Markit (S&P Global) data.
2 "Reducing CO_2 emissions from heavy-duty vehicles," European Commission, accessed August 23, 2024.

Exhibit 1

Truck fleet offerings have evolved over time and present a variety of benefits and challenges.

	Vehicle-centered services Customers select services in addition to paying a fixed price	**Service bundles** Services are bundled in tiers Customers mix and match services	**Solution offerings** Services are fixed and offered in line with use case Customers pay one monthly rate
View of (fleet) customers	⊕ Full price transparency ⊖ Limited support in choosing best option ⊖ Low consistency in customer service	⊕ Bundles include most relevant services, easing selection process ⊕ More stable financial planning with fixed monthly fee ⊖ Potential higher monthly fee compared with self-selection of services ⊖ Low consistency in customer service	⊕ Improved, use-case-specific service offering with single point of contact ⊕ Reduced asset risk (eg, through secured buyback) and downtime risk (eg, through compensation) ⊖ Potentially higher monthly fee compared with service bundle
View of OEMs and ecosystem players	⊕ Reduced business complexity ⊕ Multiple departments enabled to realize different margins ⊖ Customer relationship normally ends ~5 years after purchasing	⊕ Extended customer relationships due to improved service levels or contract terms ⊖ Higher management complexity due to partnerships and buildup of ecosystem	⊕ Balances out services with different profitability levels within the solution ⊕ Higher profit pools with zero-emission vehicles due to more efficient back end ⊖ Higher complexity and potential financial risk

McKinsey & Company

Solution offerings. Solution offerings are the next evolutionary step after bundling services. They are designed for smaller-fleet customers, a group that includes the majority of European fleet owners. Solutions typically provide customers with three options—vehicle purchase financing, leasing, or rental—with a set monthly payment that also includes an integrated package of services. Solution offerings are curated for customer segments—such as long-haul trucking, regional distribution, construction, or urban delivery—based on their distinct characteristics (Exhibit 2).

For example, OEMs may promise uptime compensation payments[3] to logistics providers operating on low margins of 3 to 5 percent. Urban delivery vans, by comparison, may benefit from access to charging infrastructure and instant parking assistance. Meanwhile, fleet owners of special construction trucks may need mobile, on-site repair assistance from qualified service centers.

Solution offerings can be attractive to fleet customers because they offer a suitable financing product (for example, an operating lease) and appropriate, segment-specific services that can help mitigate risk. Risk mitigation comes in many forms:

— A leasing offer that includes vehicle buyback helps reduce asset risk; ZE trucks still have rather uncertain residual values, and customers are often not prepared to take on risks for new, unproven assets.

— Uptime compensation can transfer utilization risk from customers to OEMs.

— Predefined packages of services (for example, insurance, fleet management, and maintenance) reduce complexity risk

[3] A payment to customers if the OEM fails to meet its vehicle uptime commitments.

(compared with managing components separately with multiple vendors) and allow integration across vehicles from multiple OEMs.

— Paying a monthly fee rather than making a sizable up-front investment substantially reduces capital risk, especially because ZE trucks not only cost more per asset than ICE trucks but also add significant cost and complexity (to reconfigure depots and install charging infrastructure).

— By effectively outsourcing fleet optimization, repair, and maintenance to a solutions provider, customers reduce labor risk; customers often lack the experience needed to integrate ZE trucks into operations.

How the TaaS model works

Despite the appeal of solution offerings, they are an intermediate step en route to the TaaS model, which requires additional organizational redesign. OEMs and other ecosystem participants can apply a TaaS approach to capture value in ZE and autonomous fleet truck segments—if they avoid repeating missteps taken by some providers (Exhibit 2).

TaaS front end

On the front end (from the customers' vantage point), the TaaS model is the same as solution offerings. OEMs offer financing combined with a "carefree" package of services designed with the needs of customer segments in mind. Potential services could include insurance, fleet management services (for example, telematics

Exhibit 2

Few OEMs have successfully implemented truck-as-a-service models.

[1]Joint venture.

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and dynamic routing), repair and maintenance, charging infrastructure, and energy services (for example, depot electrical upgrades).

Customers pay a fixed monthly rate but have the option to contract for a more advanced, usage-based arrangement (for example, paying per kilometer traveled). Equipment utilization, uptime, and asset risk are covered by OEMs (or a captive bank or other bank), which takes ownership off customers' balance sheets, thus reducing residual value risk for customers and creating potential upside for the OEM.

TaaS back end

Where TaaS differs, however, is on the back end. Several critical factors can increase chances of success.

Organizational structure and operating model. OEMs embracing TaaS would need to reorganize their profit and loss (P&L) from the traditional approach with multiple profit centers to a single profit center in which full P&L responsibility (by geography) is bundled and relevant cost centers report to a single senior sponsor. Some incumbents and fleet rental companies have already made this shift. Additionally, a separate, dedicated owner manages asset and recycling value risk including the remarketing strategy. By reimagining the current operating model and breaking down internal silos (for example, between sales and aftermarket), they can support the shift in focus from volume to margin. Meanwhile, new processes and systems can help evaluate risks and mitigation options. An integrated operating model also supports stronger risk management at the customer level.

Customer centricity. The model is highly dependent on OEMs shifting to a customer-centric mindset with a single, integrated interface with the customer, a single contract person per customer across the entire lifetime of the relationship, and a single monthly rate for the full TaaS offering. Making the shift will require OEMs to set up a scalable IT and service architecture to support end-to-end customer management and a system for gathering and monetizing customer insights. This can build on OEMs' existing customer relationship management (CRM) systems, which may be oriented toward the hardware sales pipeline, with a shift toward a more TaaS-like approach.

Services strategy. OEMs can carefully assess which services to acquire, which to outsource, and which to offer directly, based on their existing capabilities. Leaders will need to evaluate complex make-versus-buy decisions as part of the transition to TaaS. They will develop an extensive service network with a strong ecosystem of partners in the right locations to offer best-in-class services at the best price. Skilled leaders can define the partnership strategy for the solutions ecosystem and create fixed solution packages for industry subsegments with a clear understanding of the asset life cycle management for each.

Pricing strategy. New pricing processes, supported by access to larger data sets and analytics, will be needed along with new dealer incentive programs and new rules of engagement to support the TaaS transition and accrue benefits from network effects.

The model will require OEMs to reassess their talent strategies—including training, reskilling, and recruiting—to get the skills they will need (for example, in M&A and portfolio management and ecosystem partner management). A well-orchestrated change management program should support the transition across the company and ensure it sticks.

TaaS delivers benefits to multiple stakeholder groups

The TaaS model has the potential to create substantial financial value for OEMs throughout the vehicle life cycle, especially in the European Union and the United States, where ZE truck transition is projected to ramp up more quickly.

According to McKinsey profit pool analysis, by 2035 the OEM commercial vehicle profit pool in the United States and Europe will be $13.6 billion, including $10.4 billion (76 percent) in recurring profits from services throughout the life cycle and $1.0 billion in recurring potential profits from TaaS (Exhibit 3).

Due to adjusted back-end processes in the TaaS model, margins could increase more than 5 percent compared with both service bundles and solution offerings and more than 10 percent compared with the older vehicle-centered services model based on operating leases.

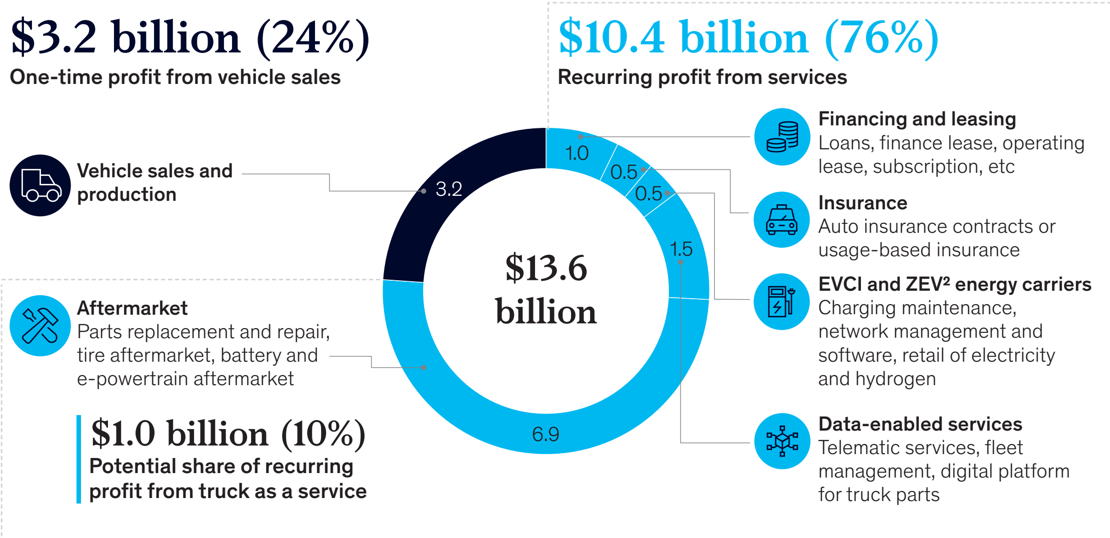
Additionally, TaaS helps OEMs gain a deeper understanding of customer needs and unlocks upselling opportunities. It creates new revenue streams from sales of supplementary services, improves margins through economies of scale, and helps optimize vehicle usage.

OEMs also traditionally lose customers to the independent aftermarket, where maintenance and spare parts are less costly, after roughly five years. With TaaS, customers stay directly connected to OEMs for reasons including the single rate and

Exhibit 3

In 2035, OEMs could earn up to 75 percent ($10.4 billion) of profits from recurring life cycle services.

OEM-relevant profit pool for medium- and heavy-duty trucks (including new-truck sales, aftersales, and new opportunities[1]) in US and EU, $ billion



[1]Finance, insurance, charging and energy, and data-enabled services considered as new opportunities.
[2]Electric-vehicle charging infrastructure and zero-emission vehicles.
Source: McKinsey Center for Future Mobility

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longer contracts, and have higher satisfaction through better services, a carefree package, and reduced asset risk. Last, the appeal of the TaaS model could accelerate the ZE truck transition and thus decarbonization of the commercial vehicle and transportation industry.

Based on a proprietary McKinsey survey of more than 400 fleet managers and owner-operators in five countries (France, Germany, Italy, the United Kingdom, and the United States),[4] customers have expressed high interest in the TaaS model because it offers better services in a carefree package with reduced risk (Exhibit 4).

The road to autonomous driving and the continued evolution of TaaS

Laying the TaaS foundation today will also help position OEMs and the wider ecosystem for the next mobility phase: autonomous driving at SAE Level 4 and above.[5] With autonomous driving, two new "as a service" business models could emerge.

Driver as a service (DaaS). Fleet customers purchase or lease trucks from an OEM and pay either the OEM or an AI company for "virtual drivers" on a per-mile basis at a projected cost of $0.30 to $0.50 per mile. The OEM or AI company is responsible for operating the trucks and earns revenues from truck sales or leasing (autonomous trucks cost $50,000 to $100,000 more than nonautonomous trucks) and recurring revenues per mile.

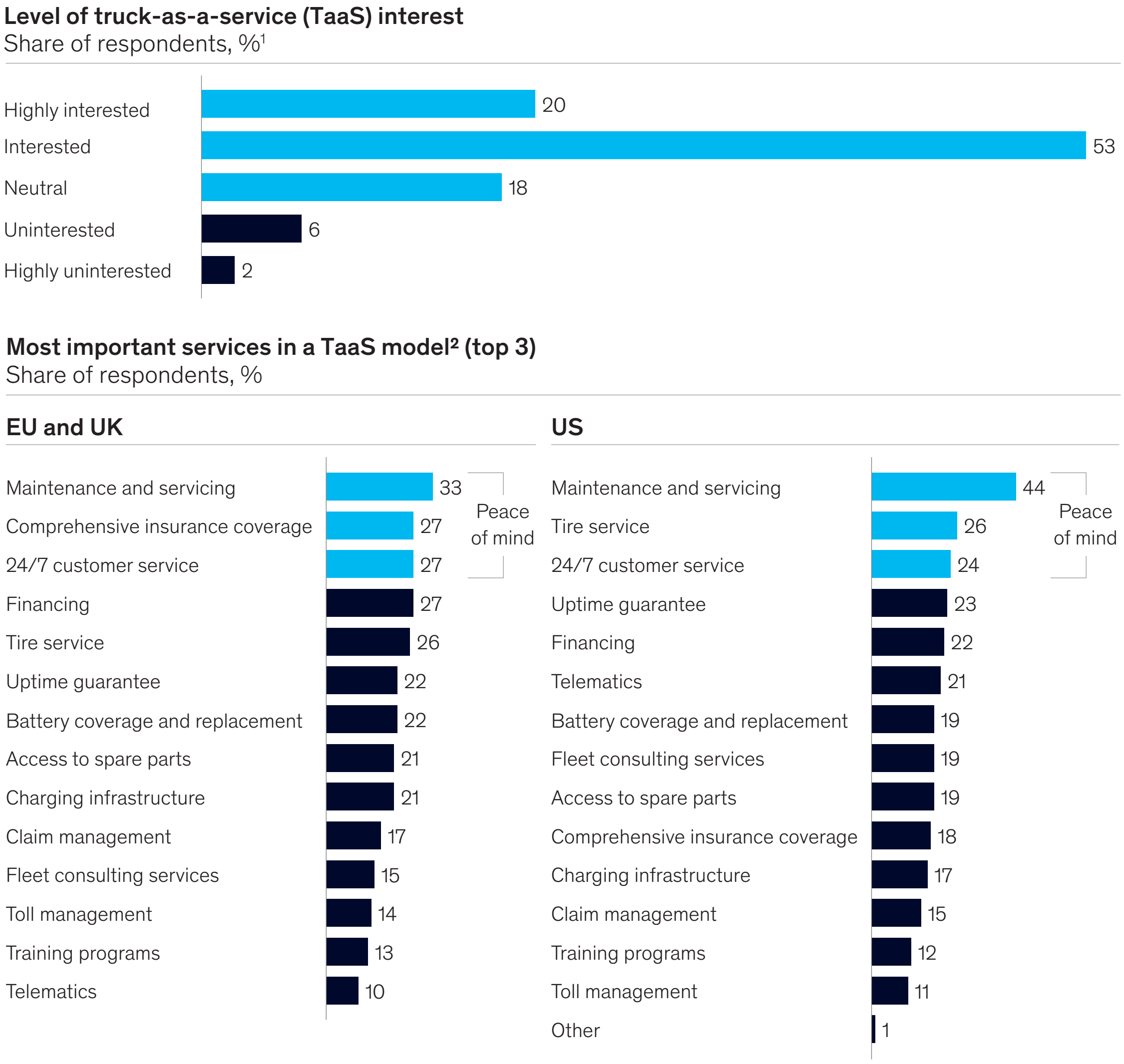
In this model, fleet customers such as freight or e-commerce companies still plan their distribution routes, organize truck freight and capacity, engage with end customers, and otherwise manage day-to-day activities. They outsource only the autonomous operation of trucks.

For fleet customers, the recurring DaaS fee is significantly lower than the cost of paying drivers, although it is partially offset by the labor cost of loading and unloading.

4 McKinsey Off- and On-Highway Equipment Customer Insights Survey, fourth quarter 2023. Question answered by respondents with neutral or higher level of interest in TaaS.
5 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 seated in the driver's seat. The driver is not expected to take over driving at any time.

Exhibit 4

Surveyed customers across the board place high importance on maintenance and servicing and 24/7 customer service.



[1]Figures do not sum to 100%, because of rounding.
[2]Question answered only by respondents with neutral or higher level of interest in TaaS.
Source: McKinsey Off- and On-Highway Equipment Customer Insights Survey, Q4 2023

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Moreover, OEMs could develop the pay-per-usage model so that they share in those savings with slightly higher payments from customers. The DaaS model also strengthens their value propositions because fleet customers face high barriers to adoption of autonomous trucks and can use DaaS to smooth their ZE transitions and reduce capital and uptime risk.

Capacity as a service (CaaS). The OEM or AI company provides CaaS with full-service leasing or financing. In this model, the OEM or AI company assumes complete control (and risk) of trucks and all aspects of daily service operations, including route planning and deliveries, effectively disintermediating fleet customers and working directly with end customers. Both incumbents and new entrants actively adopt CaaS.

CaaS offers similar benefits as DaaS to OEMs and AI companies. However, it also entails additional risks, including entering the full-truck-load market, in which they have little expertise; direct competition with current customers; and the financial and operational risk of an asset-heavy business model. The role of external investors or other banks thus becomes more important than ever.

Challenges of TaaS implementation

Although customers express high interest in adopting TaaS, OEMs first need to overcome two key challenges.

Implementation challenges. Having substantially more assets on their books for longer periods of time significantly increases financial risk. However, OEMs can mitigate this risk with special-purpose financing to remove assets from the balance sheet or transfer them to another corporate entity, which can also attract external investors. Doing so would necessitate restructuring the organization and forming a separate entity dedicated to TaaS.

Additionally, they may need to adapt their go-to-market approaches, including redesigning pricing processes (facilitated by analytics against much larger data volumes) and retraining commercial teams. Furthermore, they will need to manage more complexity because although customers have a single point of contact, a broad array of stakeholders—including departments, IT systems, partnership networks, a profit center and multiple cost centers, and potentially investors—are operating behind the scenes.

Operational challenges. Because there is not yet a mature aftermarket for ZE trucks, OEMs may have difficulty assessing the residual value of vehicles, thus increasing asset risk. Moreover, integrating the back end into one TaaS profit center could obscure sources of value and create an unwelcome cycle of internal analysis that does not serve end customers; therefore, the integration must be carefully sequenced and managed.

Considerations for CEOs

To master TaaS and enable the ZE truck fleet transition, CEOs can start by answering three key questions.

Which customer segments and geographies offer the best starting point? OEMs can identify pain points with the ZE fleet transition for customers in different segments and geographies (for example, based on their fleet size or location). Next, they can define a clear customer segmentation model, prioritizing customers (for example, according to their willingness to pay and expected margins) and a higher likelihood of accepting the new business model based on their electrification needs, company size, and financial strength.

What business model should an OEM initially adopt to start the shift to TaaS? CEOs can start with a basic TaaS offering that their sales forces and end customers can easily understand and that clearly resolves known pain points with the ZE transition. They can clarify their competitive positioning compared with others in the services ecosystem and select partners, ensuring they have the size, capabilities, customer proximity, physical footprint, and risk appetite to align with and execute the OEM's strategy. The OEM can also develop a new sales strategy by adopting a multibrand approach to appeal to different customer segments. In addition, the OEM can design an effective asset management strategy centered on three questions: Who is the best owner of the truck? Which investors, insurance providers, and asset management companies should we involve? What is the residual value of the ZE truck and the battery at the end of the contract?

How can the organization get off to a strong start? OEMs can ensure their board members and relevant leaders throughout the organization are aligned with the TaaS vision and secure their commitment to the venture and acceptance of the risk/return profile. Next, they can assemble a core team with a mix of internal and external talent representing all the key knowledge areas required for TaaS and, most important, with an entrepreneurial mindset and a strong bias for action. Last, a new organizational pilot to test front- and back-end dynamics of TaaS can be helpful. It could include one TaaS offering with P&L accountability and a single profit pool, enabled by end-to-end IT infrastructure connecting different cost centers.

This approach could generate insights from pilot customers and team members to inform a lighthouse case to help ensure acceptance of the change throughout the organization.

Anna Herlt is a senior partner in McKinsey's Munich office, where **Tobias Schneiderbauer** is a partner. **Eric Morden** is an associate partner in the London office, and **Lena Bell** is an associate partner in the Cologne office.

Automotive & Assembly Practice

A new era: Trends shaping China's heavy-duty trucking industry

As the heavy-duty-truck market begins to stabilize, what does it mean for OEMs strategizing their next moves?

This article is a collaborative effort by Anna Herlt, Dominik Luczak, and Thomas Fang, with Alexander Will, Allen Zhuang, and Danhua Ouyang, representing views from McKinsey's Automotive & Assembly Practice.

The Chinese heavy-duty-truck (HDT) market has faced a variety of challenges. Nearly a decade of rapid growth gave way in 2022, with sales plummeting 45 percent year over year.[1] As the market finds its footing, several new trends are at play: the emergence and rise of new powertrains, partnerships exploring autonomous driving, an increase in exports, and customer pressure on pricing. What does it all mean for HDT OEMs in China? This article explores these trends in depth and in the context of the current market and suggests opportunities for Chinese OEMs both within the country and outside it.

The HDT market in China today

Several factors are contributing to the current state of China's HDT market.

A stabilizing market

In 2023, sales in China's HDT market rebounded somewhat from a dramatic dip in 2022 to about 900,000 trucks (including exports), driven by the recovery of the domestic market and an increase in exports.[2] Excluding exports, the domestic market achieved 616,000 truck sales in 2023,[3] benefiting from the rebound of key sectors, such as logistics, and the country's economic recovery (Exhibit 1). Indeed, China's GDP growth rate in 2023 was 5 percent compared with about 3 percent in 2022.[4]

However, the market is not expected to fully recover to 2020 levels, marked by nearly 1.6 million truck sales, in the near future.[5] Instead, growth will likely stabilize at around 800,000 trucks, excluding exports, based on McKinsey analysis of various economic scenarios. This is because of the slowing growth rate of China's economy and the downstream market, a trend away from road and toward rail in China to improve the overall efficiency of logistics sectors, and the longer replacement cycle of HDTs with the improvement of product maturity.

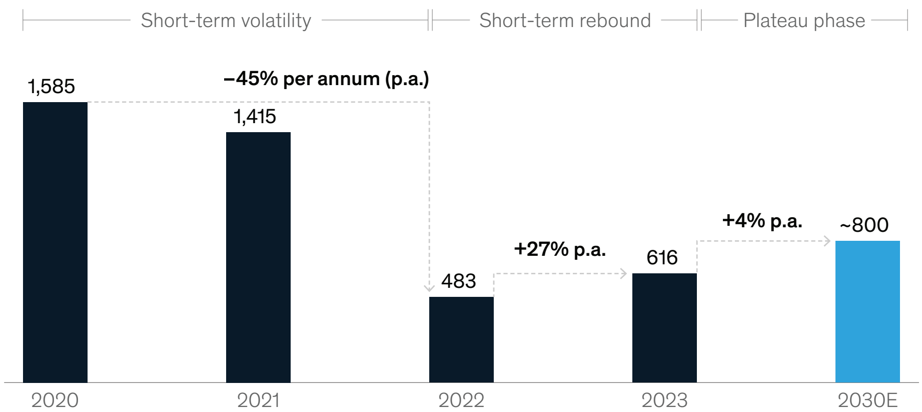
But exports are an increasingly critical factor. In 2023, they contributed about 30 percent of the total market, or 269,000 trucks,[6] representing a significant increase over previous years (Exhibit 2). Changes in both supply and demand contribute to this. And Chinese OEMs are shifting their strategic priorities to a global market in response to the intensifying competitiveness of the domestic market, which is influenced by current demand volumes and production capacities.

1 S&P Global.
2 Ibid.; "Customs Statistics Online Query Platform," General Administration of Customs of the People's Republic of China, accessed August 26, 2024.
3 Ibid.
4 "Growth rate of real gross domestic product (GDP) in China from 2013 to 2023 with forecasts until 2029," Statista, May 30, 2024.
5 "China's heavy-duty truck industry: The road ahead," McKinsey, August 9, 2023.
6 Based on data published by the General Administration of Customs of China (269/884 = 30 percent).

Exhibit 1

Domestic retail sales of heavy-duty trucks in China are stabilizing after peaking in 2020.

Domestic heavy-duty-truck sales in China, thousands of vehicles



Source: China New Vehicle Insurance Registration Database; McKinsey analysis

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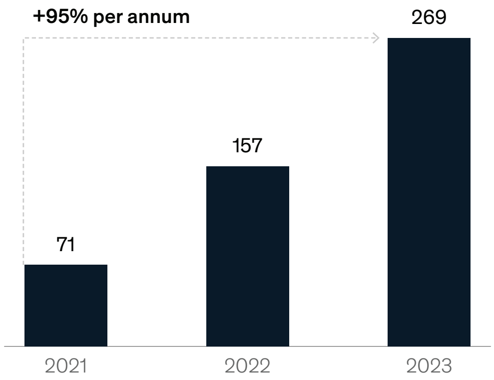
Exhibit 2

Chinese OEMs are rapidly increasing exports of heavy-duty trucks.

Heavy-duty-truck exports from China, thousands of vehicles



Source: General Administration of Customs of China; company reports; McKinsey analysis

McKinsey & Company

Emergence of new powertrains

Tractors are still the most popular type of HDT in China, accounting for about 43 percent of HDTs sold in the country in 2021, 48 percent in 2022, and 53 percent in 2023.[7] Meanwhile, powertrains other than diesel are emerging, accounting for about 30 percent of market share in 2023 (Exhibit 3).

Compressed natural gas (CNG) and liquefied natural gas (LNG) accounted for the largest share (25 percent), boosted by low gas prices.[8] In 2023, the diesel-to-NG price ratio rose to 1.9 times from 1.4 times in 2022,[9] which improved the total cost of ownership (TCO) for drivers given the relatively weak macroeconomic outlook. Major truck OEMs have also increased their focus on gas trucks and developed competitive new products.

Battery electric vehicles (BEVs) achieved about 5 percent of domestic sales, with battery swapping taking about 48 percent of the total.[10] Battery swapping has several benefits for players across the market.

- *For drivers and fleet owners,* battery swapping provides a flexible purchasing option that lowers the threshold for truck ownership. For instance, drivers can buy the chassis alone (excluding the battery) and obtain the battery through a leasing agreement. It also allows for shorter charging time compared with charging HDTs, which leads to higher uptime. Currently, the single recharge time for battery-swapping HDTs is around five minutes in China, comparable to that of a diesel truck.
- *For battery owners,* centralized battery management at swapping stations can enhance battery life cycle, leading to increased profitability.
- *For OEMs,* battery-swapping HDTs are usually easier to promote than charging HDTs because of their cost competitiveness.
- *For infrastructure builders,* reducing the number of ultrafast-charging stations means fewer challenges to the grid; the charging capacity of an HDT ultrafast-charging station typically exceeds 1,000 kW.

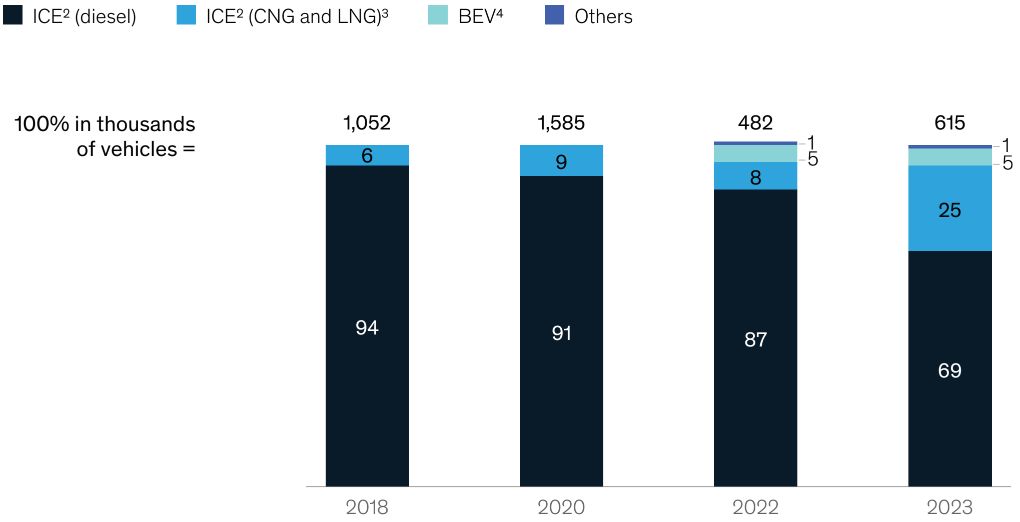
Fuel-cell electric vehicles (EVs) accounted for only about 0.6 percent (or 3,612 trucks) of China's domestic HDT retail sales in 2023.[11] The successful operation of battery-swapping electric HDTs will delay mass adoption of fuel-cell HDTs, given their efficiency and cost advantages.

7 Based on insurance data from China New Vehicle Insurance Registration Database.
8 Ibid.
9 McKinsey analysis of data from Bloomberg, CEIC, China National Development and Reform Commission, FGE, JLC, and S&P Global.
10 Based on McKinsey analysis of China New Vehicle Insurance Database (for volumes); Price Monitor Center of National Development and Reform Commission (for prices).
11 McKinsey analysis of China New Vehicle Insurance Registration Database.

Exhibit 3

Non-diesel powertrains are becoming more prominent in China.

Share of domestic heavy-duty-truck retail sales in China by powertrain,[1] %



[1]Figures may not sum to 100%, because of rounding.
[2]Internal-combustion engine.
[3]Compressed natural gas and liquefied natural gas.
[4]Battery electric vehicle.
Source: China New Vehicle Insurance Registration Database

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Changing prices

The average transaction price of domestic HDTs rose about ¥42,000 (about $5,800) from January 2018 to August 2023.[12] This can largely be attributed to the rising proportion of CNG/LNG trucks and BEVs,[13] given that the transaction price for CNG/LNG trucks is about ¥80,000 higher than for diesel trucks and the transaction price of BEVs is about ¥300,000 to ¥400,000 higher on average.[14] The transaction price for diesel internal combustion engine (ICE) trucks has remained flat, McKinsey analysis reveals, despite increasing costs associated with new emission and safety regulations as well as overall truck improvements (for example, engine performance, cabin setup, and features such as displays).

Factoring in producer price index—which saw a 6 percent increase in 2023 compared with 2018—as an estimate for inflation or producer prices, diesel ICE prices decreased, perhaps because of intensifying competition in times of low demand.[15]

High market concentration

Market concentration remains high, with the top five OEMs accounting for about 88 percent of the market.[16] This is expected to continue over the next

12 Ibid.; Price Monitor Center of National Development and Reform Commission; McKinsey analysis.
13 Based on comparisons of prices from Price Monitor Center of National Development and Reform Commission, accessed June 2024.
14 Ibid.
15 Chinese National Bureau of Statistics.
16 McKinsey analysis of China New Vehicle Insurance Database data.

The effect of driver numbers on battery swapping

As in most other countries, China's laws and regulations require that drivers take regular breaks. However, according to a McKinsey focus group with six major fleets operating more than 27,000 trucks—and contrary to the practice in many European and North American countries—fleet owners often operate trucks with two or three drivers for daily driving distances of more than 400 kilometers.[1] As a result, drivers can take breaks without vehicle downtime. Battery swapping, then, is an attractive value proposition for many fleet operators in China for trucks used for long-distance logistics operations.

1 McKinsey focus group conducted June 2024. Question: How many drivers does your company employ for each driving range? (Short range: <300 kilometers (km); midrange: 300–400 km/day; long range: >400 km/day.)

The shift toward electrification could help new players step into new markets with an attractive incentive scheme.

five years.[17] The largest players are also expected to gain market share at the expense of smaller players, which have lost market share in the past few years. Multinational OEMs captured about 1.0 percent of the domestic market, and localized products accounted for 0.4 percent in 2023.[18]

Domestic market share growth is lagging behind projections,[19] as trends toward premiumization are unfolding more slowly than anticipated and business owners feel uncertain about the economy. However, more multinational OEMs are localizing their offerings, and the cost competitiveness of these localized products will likely improve over time. As a result, the market share of localized multinational products is expected to increase.

Trends that may shape the HDT market in China going forward

The current state provides context for where the HDT market is headed. OEMs could consider focusing on trends that are shaping the future outlook.

Expansion of new powertrains

The new powertrains explored above will likely soon account for a substantial share of the market. CNG and LNG will remain significant in the short term, given their lower cost of fuel compared with diesel and their better emissions performance. The share of BEVs is expected to grow rapidly and reach 15 to 25 percent penetration in 2030, driven by government initiatives and incentives; advanced e-truck models launched by local OEMs; improved battery, e-powertrain, and autonomous driving (AD) technology; better charging and battery-swapping networks; and increasing competitiveness in TCO.[20] Battery swapping will likely be the main type of BEV in China, accounting for 60 to 70 percent of BEVs in 2030 (see sidebar, "The effect of driver numbers on battery swapping").[21] While infrastructure has been a key barrier to uptake, ecosystem players are investing heavily in infrastructure.[22]

Autonomous driving

Chinese HDT OEMs are pursuing high levels of autonomous driving through partnerships with tech and logistics companies, starting with specific use cases—for example, closed areas such as harbors and on-highway point-to-point long-haul transportation. For example, one of China's leading AD truck companies authorized the commercial deployment of its AD pilot for HDTs along the Beijing–Tianjin interprovincial logistics route. This truck was codeveloped through a strategic alliance with a Chinese logistics firm and a domestic truck OEM. In addition, a Chinese truck OEM has been operating an AD pilot for HDTs commercially for about four years in a point-to-point use case at the port in Shanghai. This pilot was codeveloped with the AD technology subsidiary of the OEM's parent corporation.

However, the road ahead presents considerable challenges, particularly in terms of achieving profitability, establishing regulations (especially for long-haul AD applications), and overcoming technological hurdles, which collectively have the potential to decelerate the development of autonomous HDTs in China.

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17 Ibid.
18 Ibid.
19 Based on analysis of 2023 IHS forecasts compared to actuals.
20 China New Vehicle Insurance Database (for actuals) and McKinsey analysis (for forecasts).
21 Ibid.
22 Ibid.

Increasing exports
Leading Chinese HDT OEMs are actively seeking to capture additional growth opportunities and have announced ambitious goals for exports in 2024. This is due to several factors. First, there is currently large overcapacity for ICE trucks in existing plants given the significant drop in the domestic market size compared with 2020. Players may have an opportunity to capture more market share in other markets with price-sensitive customers. Second, the shift toward electrification could help new players step into new markets with an attractive incentive scheme (for example, localizing e-truck production in some Southeast Asian countries). Last, similar to trends observed in passenger vehicles, electrification creates additional export opportunities as leaders in other markets potentially lose their value proposition (for example, leading fuel consumption), possibly leading to new players entering the market.

Pricing pressure
Fleet owners are experiencing intense profitability pressure coming from downstream customers. Since 2020, express logistics companies in China have had to lower their prices to compete because of intense market competition triggered by low-cost e-commerce parcels.[23] However, this pressure is expected to diminish and stabilize. And express players are diversifying their revenue streams instead of relying solely on a single e-commerce platform.

Strategic implications for OEMs

Given today's context and emerging trends, OEMs could consider a few strategies both within and outside China.

China drivetrain strategy for all HDT OEMs
Based on new realities—such as current natural gas prices and trends toward battery swaps—both local and multinational OEMs (either those already present or those planning to enter the Chinese market) may need to reevaluate their portfolios and powertrain strategies to adjust to new market realities and get a head start on trends such as electrification.

Global strategy for Chinese HDT OEMs
Chinese OEMs have gained market share in selected export markets and increased exports significantly. For example, from 2021 to 2023, exports to the Middle East and North Africa grew an average of 73 percent annually, while exports to Latin America increased 46 percent.[24] Chinese OEMs are capturing market shares in other regions from other players to offset the ongoing downturn in the domestic HDT market. OEMs may consider adjusting their localization and production footprint strategies based on available incentives. For example, Indonesia offers incentives for EV factory setups and reduced value-added tax for EVs with about 40 percent local components.[25]

OEMs could have broader market opportunities for new-energy-vehicle (NEV) HDTs in developed markets similar to recent developments in passenger cars (for example, Chinese OEMs are gaining market share in Europe and Southeast Asia). NEVs are a category of vehicles that rely on alternative energy sources and include BEVs and fuel-cell EVs. The rapid growth of China's NEV truck market, coupled with a mature EV supply chain and ecosystem, creates potential opportunities for Chinese OEMs. This also opens up opportunities for suppliers: established global suppliers can attract a new group of OEM customers, and Chinese suppliers can partner with Chinese HDT OEMs to broaden their offerings.

China ecosystem for multinational OEMs
Market restructuring, driven by autonomous, connected, electric, and shared/smart vehicles, creates openings for emerging entrants. It could allow smaller players to expand their market share and enable new technology players to enter the market (for example, for fleet connectivity and AD solutions). To ensure success in China, multinational OEMs need to review potential China-for-China ecosystem developments (similar to current trends in passenger cars) to keep up with developments by leading local OEMs on connectivity and AD, which are expected to bring significant benefits to large fleet customers.

The Chinese HDT market is undergoing significant change. As the market stabilizes and OEMs adjust to the new normal, there are opportunities for those that think strategically about their portfolios, powertrain strategies, and localization and production strategies.

[23] Barry van Wyk, "China's express delivery price war is finally over," TheChinaProject.com, July 6, 2022.
[24] McKinsey analysis of General Administration of Customs of China data.
[25] Melissa Cyrill, "Indonesia market prospects for EV sales and manufacturing," *ASEAN Briefing*, October 18, 2023.

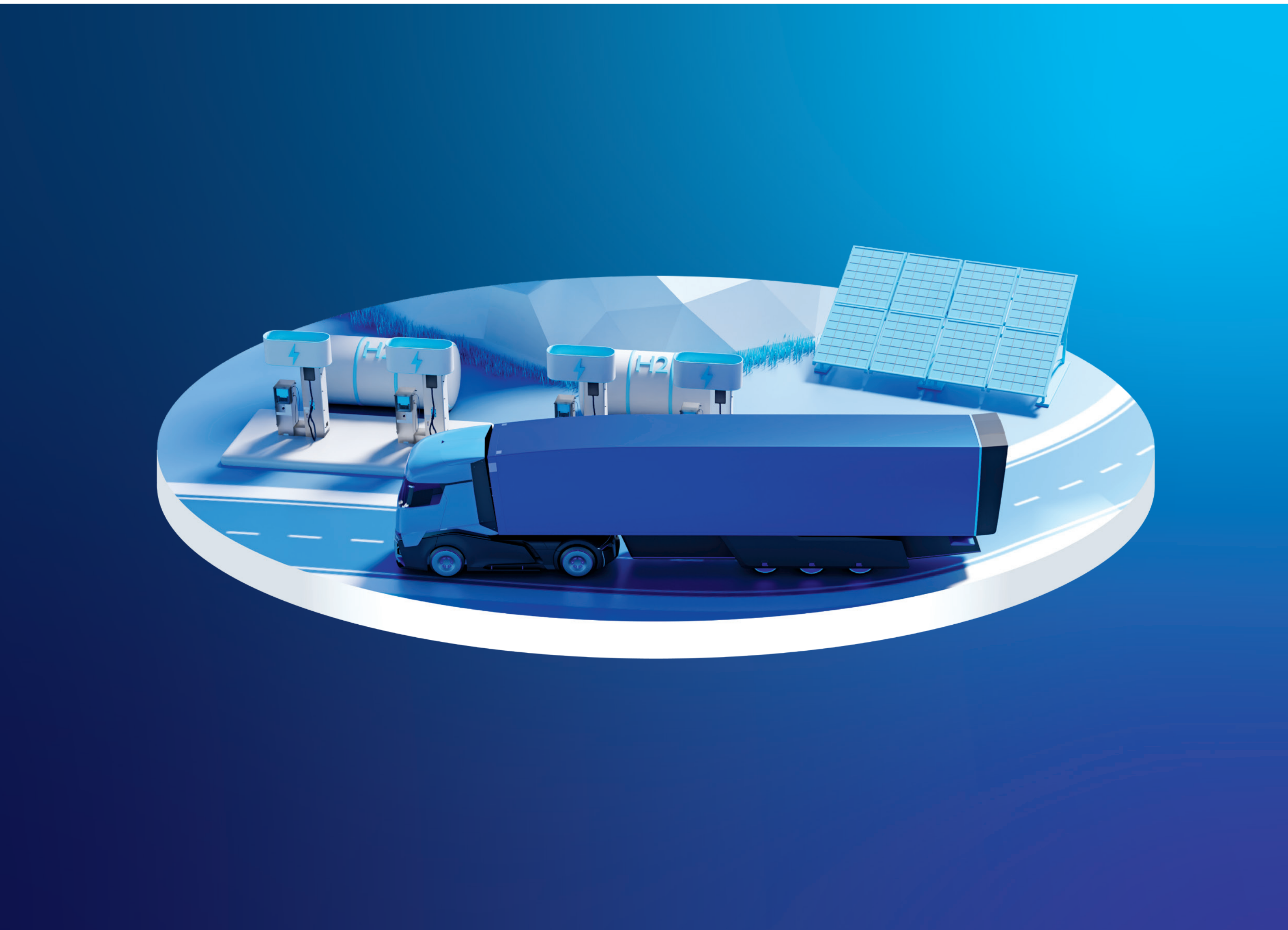
Anna Herlt is a senior partner in McKinsey's Munich office, **Dominik Luczak** is a senior partner in the Tokyo office, and **Thomas Fang** is a partner in the Shanghai office, where **Alexander Will** is an associate partner and **Allen Zhuang** is a consultant. **Danhua Ouyang** is a consultant in the Beijing office.

Automotive & Assembly Practice

Building Europe's electric-truck charging infrastructure

Rolling out the right kinds of charging networks to support the continent's zero-emission trucks will be a major challenge. But a wide range of players have significant opportunities to create value.

by Anna Herlt and Eugen Hildebrandt with Henrik Becker



The expected global mass rollout of electric trucks is going to require a dense charging network to keep these zero-emission vehicles moving. For Europe, McKinsey estimates that, by 2030, more than 300,000 public and private charge points will be required across the continent for medium- and heavy-duty trucks, up from roughly 10,000 today.

The creation of this new infrastructure represents a significant challenge. Building out robust networks of chargers will require approximately €40 billion of capital investment until 2040. Of this, €7 billion of investments are needed until 2030, less than a quarter of which has been publicly committed today.[1] Charging-network build-out will also be energy-intensive, consuming 20 terawatt-hours of electricity annually by 2030, roughly 0.5 percent of Europe's total electricity demand. Gaining access to all this energy will often mean securing additional capacity on an already congested grid.

At the same time, the possibilities are wide open. With no incumbent players fully established in the electric truck–charging market, companies from a variety of arenas have an opportunity to shape the ecosystem of market participants, creating new businesses or forging strategic collaborations.

This article is based on charging-infrastructure research from the McKinsey Center for Future Mobility and McKinsey's EV Charging Infrastructure service line.[2] We look at how Europe's charging network will evolve over the next decade and beyond, identifying major challenges players will need to solve for. Our analysis also details the steps fleet operators will need to take as they develop strategies for a successful scale-up of their truck charging infrastructure—efforts that will inevitably require collaborative actions from fleet operators; truck manufacturers; turnkey engineering, procurement, and construction (EPC) firms; finance providers; and energy and infrastructure players.

How will electric trucks be used across Europe?

Europe's first wave of commercial electric trucks will be those used for single-day travel. This includes distribution from a central facility, municipal routes, intermodal shuttles, and short hub-to-hub trips. The regular and predictable operating patterns of these trucks will allow them to recharge overnight at their depot with a low-power charger or to top up with a fast charger during, for instance, loading or unloading duties. Many of these trucks will not necessarily require public charging. Until 2030, these use cases will cover more than 50 percent of the continent's electric trucks.

Another 40 percent of Europe's electric trucks will do single-day, hub-to-hub transport of industrial or consumer goods on highways.[3] Daily distances for these trips will vary—ranging from 250 kilometers to more than 800 kilometers—but are typically regular for each vehicle. Given the longer distances involved, many of these trucks will need to supplement their depot charging with stops at public charge points.

Multiday, long-haul travel makes up the remaining 5 percent of trucks. This category of vehicles will be the slowest to electrify. Because they typically travel beyond their home base, drive long daily distances, have highly varying trip distances and destinations, and do not have many natural loading or unloading breaks in fleet depots, these electric trucks will be heavily reliant on public charging. Over time, this share of both single-day and multiday long-haul electric trucks will increase significantly as public charging becomes more available.

For each use case, fleet operators will have to navigate multiple trade-offs to define their optimal vehicle specifications. While larger batteries offer a longer driving range, they are expensive and heavier and thus have a reduced payload capacity. The more fast-charging stations available, the smaller (and lighter) truck batteries can be while still offering sufficient operational flexibility. Fast charging to top up the battery during mandatory driver breaks can be an attractive option for trucks with regular usage patterns, such as line-haul or private fleets (Exhibit 1).

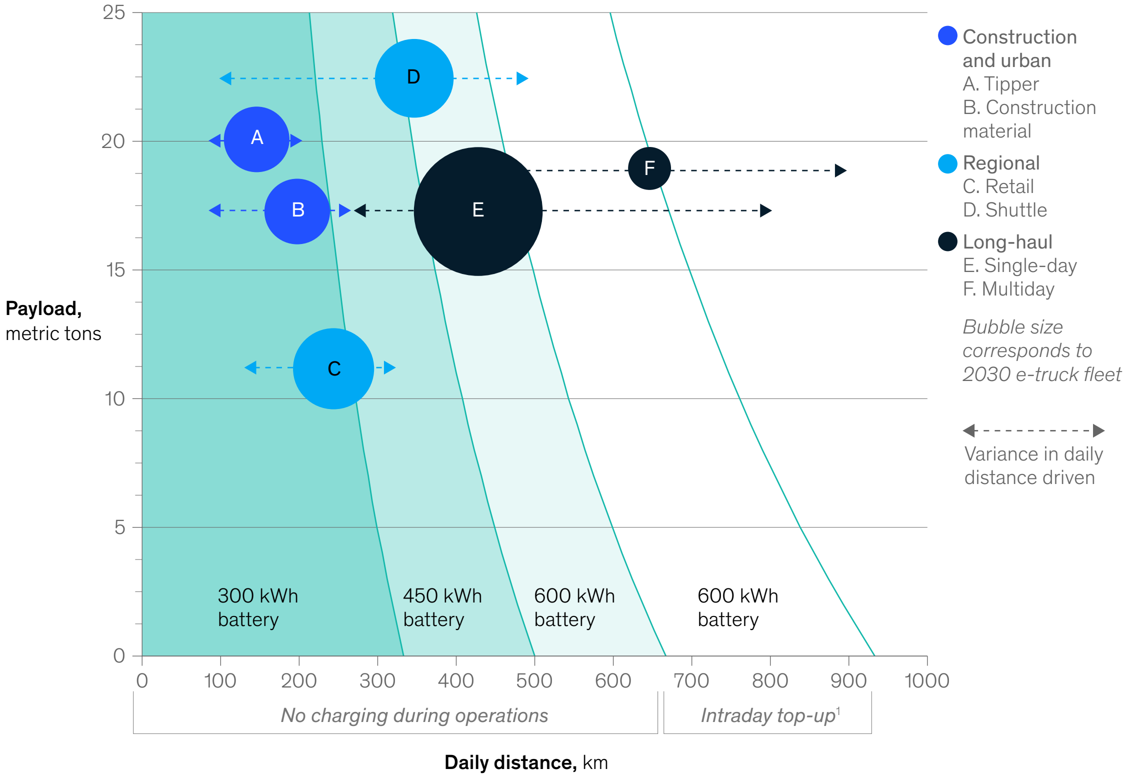
In practice, such optimization is often complicated by the structure of Europe's logistics industry. Much of the road transport market does not consist of private fleets used on specific, predictable routes, but is typically deployed in ad hoc setups for individual trips or as part of short-term contracts with durations of less than three years. As such, when optimizing their vehicle specifications, most fleet operators will need to allow for a high degree of flexibility in their operations, making the planning for charging infrastructure more challenging.

1 Based on McKinsey analysis from the McKinsey Center for Future Mobility and the EV Charging Infrastructure service line Charging Infrastructure Outlook. The €7 billion of investments includes funding for direct-charging hardware, planning, engineering, and installation, while excluding potential grid or site upgrades.
2 Unless otherwise noted, all data is from the McKinsey Center for Future Mobility.
3 Includes the 27 EU member countries, the United Kingdom, and four European Free Trade Association countries (Iceland, Liechtenstein, Norway, and Switzerland).

Exhibit 1

Charging infrastructure, driving patterns, and battery sizes have to be optimized in concert to efficiently electrify truck operations.

2030 view, use cases



[1]Assumes charging during mandatory break of 45 minutes at 400 kW DC charger.

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Europe's charging infrastructure deployment will happen in two phases

Mirroring these truck electrification trends, Europe's first phase of charging infrastructure will be installed in private fleet depots or semipublic hubs. After 2030, a second phase will allow the scaling of public charging infrastructure, given the expected additional access and capacity upgrades of medium- and high-voltage grid locations.

Between now and 2030, charging installations close to major industrial sites or logistics hubs, or even within private hubs, including directly at loading docks, will represent more than 90 percent of all charging infrastructure, requiring a total investment of €5.5 billion, and expected to cover 75 percent of the electricity demand for trucks by 2030. These chargers will serve the distribution or hub-to-hub use cases that will account for most of the first-generation electric trucks in operation. Depending on the operational requirements, fleet hubs will leverage a mix of chargers (including AC 40 and DC 50 to 400 or more kilowatts), with lower-power, slow chargers fueling vehicles overnight and higher-power, fast chargers providing top-up charging during operations, such as while loading or unloading at the ramp or during driver shift changes. This infrastructure can be deployed incrementally to synchronize with the growth of an operator's electric-truck fleet. However, the speed of rollout may also be dampened by local grid constraints for larger installations, especially in the short term.

For fleet operators that maintain their own logistics operations, the development of depot-based infrastructure offers a solid business case, given the predictable routes of short-haul trucks and the visibility operators have. For outsourced logistics operations, shared charging parks located close to hubs can help to facilitate truck electrification while also limiting the investment and operational risks for each player. Across the continent, an EBIT profit pool of €200 million is expected between now and 2030. This represents profits from turnkey solutions or from the combination of distinct charging-hardware sales, design, engineering and installation, and charge point management software on 300,000 chargers, plus wholesale energy profits.

[4] Including functionalities such as asset management, load management, and fleet dispatching.

Compared with depot-based charging, Europe's public charging infrastructure will be slow to develop. By 2030, the continent will have just 4,000 public charging points for slower, overnight charging and 12,000 fast-charging points, requiring a total investment of €1.5 billion. With an expected higher average power rating and utilization, public charging stations are expected to account for 25 percent of the electricity dispensed by 2030.[5] After 2030, however, as more and more long-haul electric trucks hit the market, public-infrastructure development will scale up. By 2040, we expect a total of 100,000 public charging points installed at locations along European highways, providing 45 percent of the total electricity used by electric trucks. These charging networks, which will be shaped by regulatory targets such as the European Union's Alternative Fuels Infrastructure Regulation or various national subsidy programs, are likely to be built and operated by specialized charge-point operators (CPOs).

We expect that public fast chargers will be the most profitable type of infrastructure, with a profit pool valued at €500 million between now and 2030. This is because fleet operators are expected to be willing to pay a premium for fast charging, such as during drivers' mandatory breaks, thus minimizing downtime. In addition, when fast chargers are being sufficiently utilized, they draw high volumes of daily energy, allowing CPOs to sell substantial quantities of this premium-rate electricity.[6] Conversely, public fast chargers carry significant commercial risk given the slower initial adoption of long-haul trucks and the larger geographic area that has to be served. CPOs may want to cover their investment risk by making some fleet operators anchor customers that guarantee a certain utilization of energy. CPOs could then charge a premium to à la carte customers.

Public overnight charging represents the smallest profit pool (€30 million), given the small number of use cases that will require this type of charging (Exhibit 2).

These projections assume that European truck manufacturers continue to develop batteries that are tailored to a given truck and not meant to be swapped between vehicles. This alternative approach of battery swapping, in which a discharged battery can be replaced with a fully charged one within a few minutes, is already popular in China, where roughly half of electric heavy-duty trucks are capable of battery swapping. Although this approach offers advantages (such as even higher vehicle uptime than current fast-charging protocols and the extension of a battery's total lifetime due to slower charging while the batteries rest in the swapping stations), bringing it to Europe would require not only a shift toward standardized (and not differentiated) battery packs but also new business models for battery financing and battery-swapping networks.

Setting up the optimal charging infrastructure means being in the driver's seat for every aspect

When planning to electrify fleet hubs, operators will need to consider a number of constraints, such as operational requirements and available grid capacity. To optimize costs and vehicle uptime for both fleet hubs and public locations, operators can follow five sets of activities.

Creating a blueprint for a cost-optimized charging infrastructure. To determine the types (size and power rating) and number of chargers needed, as well as their placement, fleet hub operators need a detailed understanding of their future electric-fleet operations. Ideally, this entails a detailed analysis of every specific truck use case, including the daily distance a truck travels, its battery size, whether charging on the go is needed, the payload the truck will be carrying, and the number of stops it will make throughout the day. Depending on the planned charging patterns, available space, and truck specifications (width, length, and turning radius), chargers can be installed at loading docks, in waiting areas, or at parking spaces. For outsourced logistics operations, charging-infrastructure needs are best evaluated in collaboration with relevant transport providers. To maximize both operational flexibility and charger utilization, these setups will often skew toward higher-power chargers in shared locations.

To avoid operational complexity, operators may want to consider installing only a limited number of different charger types at a given location. In addition, exploring changes in driver shifts or other operational patterns may help operators optimize their charging-infrastructure utilization and reduce the total number of chargers needed. All designs will need to be checked for compliance with applicable building or safety regulations (for example, insurance or fire safety) and initiated with enough time to acquire the necessary approvals.

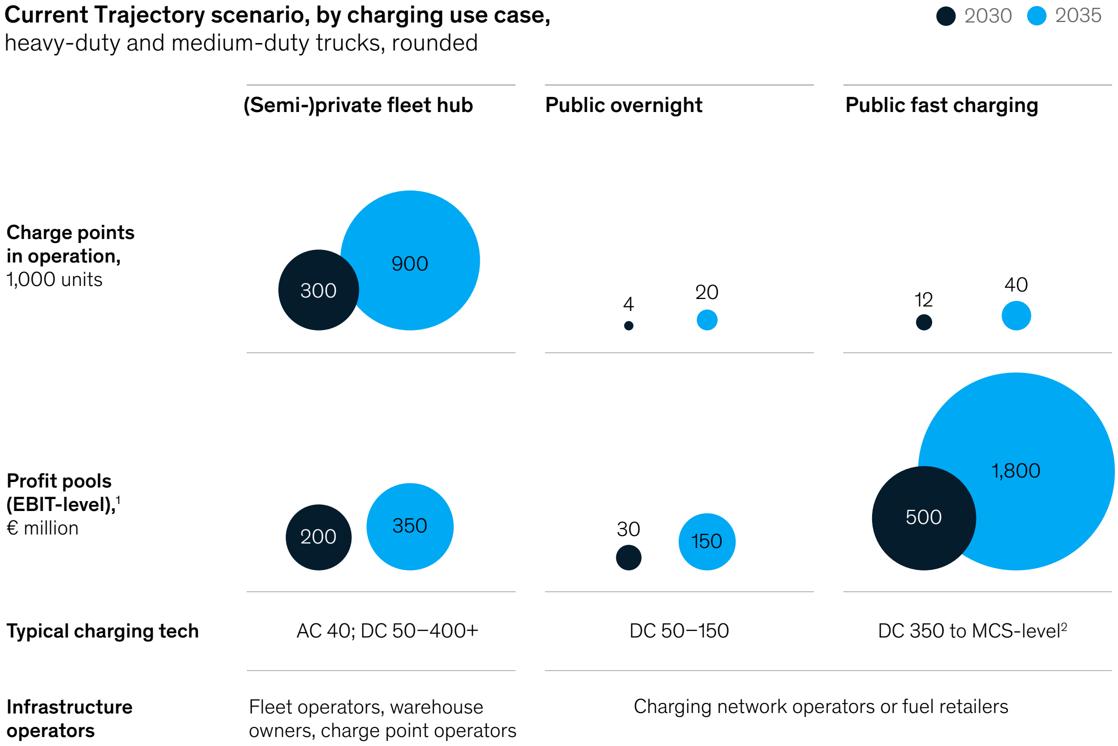
[5] Although the European Automobile Manufacturers' Association predicts 40,000 public chargers by 2030, its analysis does not consider the business case behind the rollout. Our analysis assumes 20 percent utilization of public charging infrastructure in 2030, with CPOs aiming for profitable network operations by this time. The more comprehensive the charging network becomes, the more it supports large-scale uptake of electric trucks, including across long-haul operations.

[6] An announced tender for electrification of parts of the German highway truck stop network aims to limit energy resale profit opportunities by introducing an option to leverage a fleet operator's commercial electricity rates ("Durchleitungsmodell").

Exhibit 2

Between 2030 and 2035, the number of charge points and profit pools is expected to greatly increase.

Current Trajectory scenario, by charging use case,
heavy-duty and medium-duty trucks, rounded



[1]Includes EBIT pools for hardware, software, installation, energy resale, and charge point operator business.
[2]Megawatt charging system.
Source: McKinsey Center for Future Mobility; McKinsey EV Charging Infrastructure service line

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Estimating power requirements. Most fleets of electric trucks will require sizable loads of electricity. By understanding their total power demand and its distribution throughout the day, fleet operators can determine the size of the connection they will need to the electricity grid. Operational adjustments, such as changes to truck ramp times and driver schedules and breaks, can result in a more balanced distribution of power demand throughout the day, potentially reducing the costs associated with upgrades to the existing grid connection and with the total number of charging points required.

Buffer (or backup) batteries—which are charged when fewer trucks are at the station and then discharged to refuel trucks during peak demand times—can also help shave off power requirements from the grid. In addition, by avoiding expensive peak-demand charges, they can help to reduce the average cost of electricity. Such local microgrids can be further complemented with local power generation, such as through solar or wind.

Establishing grid access. Depending on a fleet operator's location and power requirements, new electricity capacity may not be available from existing grid connections and contractual frameworks. Fleet operators will need to know what's involved in upgrading their grid connection. Is it simply a commercial negotiation to change power contracts (if sufficient overhead capacity is still available), or does it take actual construction work and additional deployment of power equipment? Will they need to upgrade the substation or connect directly to the transmission network?

Grid upgrades can be costly and time-consuming, with timelines ranging from months to years, depending on the type of upgrades required. Due to these long lead times, fleets will want to develop their electrification and charging infrastructure road maps multiple years ahead of any meaningful deployment of trucks on the road. Requesting grid upgrades early could potentially lead to preferential access to any available unused capacity, reducing costs and shortening timelines.

Offering end-to-end charging-infrastructure solutions will be key for the electrification of fleet hubs.

Planning for implementation. Fleet hub operators will typically follow a step-by-step approach to installing their charging infrastructure. Determining the right ramp-up sequence and timeline will depend on the expected rate of truck electrification and the level of operational disruptions that can be tolerated during the construction phase. Operators can mitigate the costs and impacts on daily operations by selecting construction firms that specialize in the installation of charging infrastructure.

Defining the operating model. Executing on the above steps will require a variety of skill sets. These include in-depth technical expertise on charger hardware and a market understanding of permitting, standards, and energy sourcing. In addition, setting up and running charging infrastructure will mean establishing local networks to do the planning, engineering, and construction work, as well as developing the capabilities for maintenance protocols, electricity sourcing, and potentially pricing and payments for public chargers.

Some fleet operators may choose to develop these capabilities in-house, owning their chargers and building their entire value chain of electric-truck charging infrastructure themselves. Most, however, will want to consider other operating models, including outsourcing their charging infrastructure and operations to specialized CPOs or turnkey solution providers that support the operations with dedicated servicing agreements. This arrangement allows fleet hub operators to focus on their core business and avoid a capital expenditure investment. However, CPO contract durations can be lengthy, and careful partner selection is necessary because partner capabilities are frequently overestimated and service-level agreements are not always properly constructed. Another option is a collaboration among various partners, such as utility companies, charging-hardware players, and CPOs, each of which provides a particular part of the value chain.

The market for fleet hub charging is still nascent

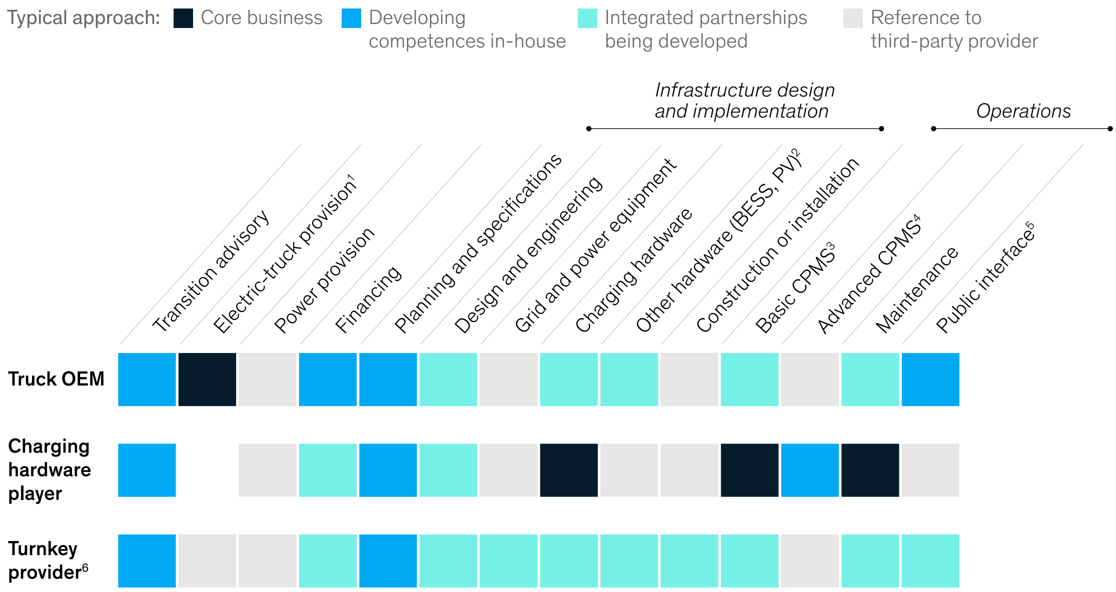
Few fleet operators have all the capabilities necessary to address each step required to deploy truck charging infrastructure in-house. Most will need support for a variety of skill sets—for example, in-depth technical insights on the interoperability of charging hardware, an understanding of permitting and energy sourcing, or the development of local networks for engineering and construction.

Truck manufacturers, utility companies, turnkey EPC firms, charging-hardware players, and CPOs can all offer value here (Exhibit 3). Yet, with the truck-charging ecosystem still evolving, protocols still maturing, and technologies still not standardized, only a few players are currently able to provide convenient, plug-and-play offerings. Offering these end-to-end charging-infrastructure solutions will be key for the electrification of fleet hubs.

A significant growth opportunity exists for players that are able to construct an attractive value proposition. The key success factor is the ability to combine subject matter expertise, power sourcing, access to financing at a national or regional level, and local networks for implementation (construction, installation, operations, and maintenance). Given the complex implementation path, a strong offering

Exhibit 3

Player types have different core competencies as starting points for integrated offerings.



[1]In many cases, charging infrastructure in fleet hubs will mainly serve subcontracted truck fleets. In such cases, there typically is no direct link between individual truck sales and charging infrastructure deployment.
[2]Battery energy storage system; photovoltaic.
[3]Basic charge point management system (CPMS) includes asset management.
[4]Advanced CPMS includes dynamic load management, grid services, and fleet management.
[5]For semipublic or public hubs: e-mobility service providers and payment solutions.
[6]For example, engineering, procurement, and construction firms; passenger car charge-point operators; utilities; and oil and gas players.
Source: McKinsey EV Charging Infrastructure service line

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in advisory, planning, and financing will be a major differentiator in attracting customers. In addition, excellence in implementation and high charger uptime will be key drivers to create sticky customer relationships, especially given the long lifetime of charging infrastructure. Both elements can create a significant first-mover advantage. Multiple players, such as truck manufacturers, utilities, hardware players, and CPOs, have a right to win in the space.

Players will need to solve for key challenges

Before any significant value can be created or momentum achieved, players will need to solve several significant challenges. In addition to the energy-sourcing issues mentioned above, fleet operators and other players face challenges related to grid upgrades, financing, approvals for charging stations, physical-space constraints, and market structure.

Grid upgrades. While pilot-scale deployment of up to ten electric trucks is often feasible with existing grid connections, most fleet hubs will require some degree of upgrades to their grid connection to charge larger numbers of electric trucks, especially when relying on fast charging. With lead times of multiple months or even years for the approvals alone, these additions are typically not only costly but also time-consuming. Additionally, there is often limited transparency about how much capacity is available at the substation and transformer level, as well as what investments and upgrades distribution system operators (DSOs) have in the works. A fragmented landscape further limits visibility. Some countries, for instance, have hundreds of different DSOs.

In a phased rollout of electric trucks, operators can kick-start the transition with a small subfleet of electric trucks and then scale up once an upgraded grid connection is available. To minimize the amount of grid upgrades needed, players could take several actions. In addition to employing smart-charging strategies that take advantage of lower time-of-use electricity rates, fleet operators and other solution providers could consider implementing battery storage systems that would allow them to store cheaper electricity for later use. Installing microgrids of solar panels or instituting station-level load balancing could also help shave off peak power demand from the grid.

For the deployment of electric trucks at scale, most fleet operators will need strategic upgrades of transmission and distribution grids. As a first step, a centralized database of available grid capacity would significantly help accelerate and improve the energy planning process.

Financing. Charging infrastructure is a significant capital expenditure investment that many fleet operators, especially smaller ones, will be unable to shoulder on their own. At the moment, financing options are limited. Truck manufacturers and OEMs could participate via their financing arms, but infrastructure financing is far from their normal business model. Green investment funds can supply capital but will likely struggle to identify opportunities large enough to fit their typical requirements. Local banks could step in, but they typically lack the market understanding to correctly appraise the risk and long-term return profile of charging-infrastructure investments.

To support the broad rollout of charging infrastructure, new public or private funding is needed. Such schemes will need to be tailored for long-term return profiles and be able to manage relatively small investments for individual fleet locations. Additionally, aggregator players such as CPOs, which own and manage charging infrastructure at multiple sites, may achieve sufficient scale to attract interest from private sector investors. To attract the participation of financing focused on different asset classes, they could offer portfolios of varying sizes, configurations, and risk profiles.

Approvals for charging stations. Getting a new charging station up and running typically requires approvals from multiple local and country-level authorities first. Currently, lead times for these go-aheads range from three to 18 months, which can cause significant delays in implementation. Requirements that vary both by country and by local jurisdiction further complicate processes and delay rollouts. To quickly achieve scale in Europe's charging infrastructure, approval processes will need to be standardized and accelerated. Governments may also want to consider proactively identifying and preapproving potential locations.

Physical-space constraints. Many truck stops along highways, as well as fleet hubs, already face challenges in accommodating the current numbers of diesel trucks. Electric charging will exacerbate this. Significant amounts of additional space are required not only for the infrastructure itself but also for trucks that will need to be parked for longer periods of time. A first-step solution can be an integrated planning system that is used to identify and reserve additional space for both on- and off-highway truck charging. This intelligent reservation system could also help increase the utilization of available charging infrastructure. As electric-truck charging begins to scale, however, significant spatial extensions of truck stops along highways and near fleet hubs will be required.

Market structure. With most of Europe's fleet operators outsourcing their logistics operations, several practical challenges arise when designing cost-efficient charging infrastructure. For example, while slow overnight charging in a private fleet hub is a favorable option for distribution, it may not be feasible when the fleet hub and trucks belong to different companies. In addition, the short-term contract durations between freight buyers and truck operators make it hard for truck operators to tailor their vehicle specifications to specific use cases because they risk losing the ability to serve other customers efficiently.

Solutions that can help give fleet operators more visibility into the demand for their electric trucks include extending the contract durations for logistics services and using freight forwarding platforms that specialize in green logistics. In addition, shared charging parks next to private fleet hubs can offer the benefits of slow overnight charging near the trip's starting location. Such shared charging parks would require cooperation between different fleet hub operators that may be competing logistics players.

Truck manufacturers have a unique role to play

Truck manufacturers have a daunting mandate. Complying with the European Union's CO_2 emissions standards for new heavy-duty vehicles will mean aggressively introducing electric trucks into the market. For the average manufacturer, missing these targets by 1 percent could trigger fines of approximately €90 million.[7]

Yet without sufficient charging infrastructure, electric-truck sales are at risk. In addition, customers perceive charging infrastructure to be part of a differentiated electric-truck product and expect manufacturers to treat it as a core part of their offering. As a result, electric-truck manufacturers have started to enter the charging business. Recently, some companies have set up stand-alone organizations, allocated dedicated budgets, and created competence centers for charging infrastructure. This includes a group of large European truck manufacturers that formed a joint venture to collaboratively build out a core network of public truck-charging infrastructure along major highway corridors, as well as several manufacturers that have announced their own services for depot-based charging and fleet hub electrification.

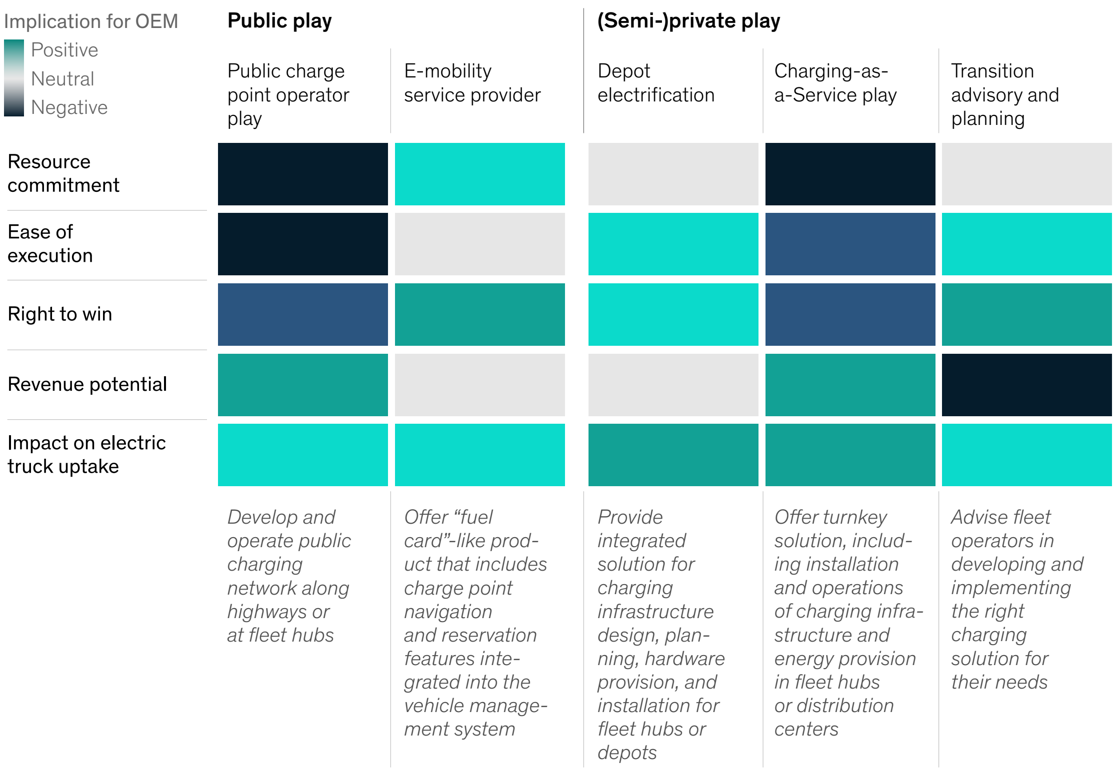
Necessary elements for a depot charging solution are planning, design, engineering, hardware procurement, financing, and business development. Beyond these table stakes, truck manufacturers can create a competitive product with differentiators such as load and energy management and e-mobility services. In the electric-bus space, for instance, electricity sourcing and vehicles sales are sometimes packaged into a bundled offering.

While there is tremendous value in offering an integrated solution, not everything has to be available in-house. A network of partnerships with local engineering firms, hardware players, and perhaps software providers can also be an effective way to address the market. The level of integration can range between a mere consulting-type approach all the way to a full CPO play (Exhibit 4). These strategies come with different risk/return

[7] Eamonn Mulholland, *The revised CO_2 standards for heavy-duty vehicles in the European Union*, International Council on Clean Transportation (ICCT), May 2024.

Exhibit 4

Truck manufacturers have a number of options to play in charging infrastructure.



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profiles, and the choice will depend on a company's ambition: is the goal to enable electric-truck sales and generate additional revenues, or is it to potentially build a whole new business?

Charging for commercial electric trucks is poised to become a fast-growing market with significant opportunities to capture value. Yet this growth could be held back by difficult challenges, including a dramatic lack of funding and a complex market structure, which would then imperil electric-truck sales.

To support the expected adoption of zero-emission trucks, €40 billion of capital investments will be required through 2040 to build up sufficient truck charging infrastructure across Europe. Until 2030, most of this infrastructure (90 percent) will be located in or near fleet hubs, supporting the electrification of distribution and hub-to-hub use cases. However, players also need to start the process of building public charging networks now to be ready to meet the fast-growing demand from long-haul use cases expected after 2030. These public charging networks offer the largest profit pools going forward.

Taking a basic infrastructure investment approach won't be enough. As players build their charging networks, they will have to navigate uncertainties about demand (given the complex market structure in logistics services) and technology risks (given how quickly charging technology is expected to advance). In addition, unlocking the full future potential of truck charging infrastructure is going to require smart approaches in new areas, such as local microgrids, energy management, and digital reservation systems.

Now is the time to create integrated solutions for truck charging that will also include financing offerings, support for electricity access, hardware, implementation, and operations. Players that enter the truck-charging market will do so with different motivations—for example, to boost vehicle sales, to create a stand-alone business, or to provide a stepping stone for an integrated offering that includes electricity solutions such as load management, energy management, and energy storage.

Regardless of motivation, all players will benefit from having both a short-term plan to start creating a product from their offering and a long-term plan to scale their offering across regions or even countries, customized to local environments. Such a go-to-market strategy also needs a clear understanding of the market dynamics that will inform what a differentiated customer offering looks like and which elements should be done in-house versus through partnerships.

Rewards exist for those who can solve today's formidable challenges. The prize is not only more electric-truck sales but also a whole new business opportunity. Once a sufficiently large fleet of electric trucks is on the road, charging players can boost utilization and tap into a more than €700 million profit pool that will be available by 2030—in a market with significant early-mover advantages and no natural incumbents.

Anna Herlt is a senior partner in McKinsey's Munich office, where **Eugen Hildebrandt** is a partner. **Henrik Becker** is a consultant in the Zurich office.

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Automotive & Assembly Practice

How batteries will drive the zero-emission truck transition

Battery electric vehicle technology will be key to reducing road freight emissions and achieving global climate targets.

by Jakob Fleischmann
with Lena Bell and Patrick Kroyer

Road freight vehicles[1] account for a significant share of global CO_2 emissions. Hence, minimizing their carbon footprint is a vital step toward achieving global climate targets. Over the past decade, governments, fleet operators, and truck OEMs have realized this need for action and have gone to significant lengths to make this positive change happen. Today, the only effective way to reduce these emissions is by switching from combustion engines powered by fossil fuels to zero-emission propulsion systems or other carbon-neutral fuels.

Several potential carbon-neutral alternatives to diesel combustion engines exist, including hydrogen engines and biofuels or synthetic fuels (synfuels); however, for most truck applications in the short term, battery electric propulsion systems are the most promising option, both technologically and economically. Battery electric vehicles (BEVs) are considered suitable propulsion systems for most commercial vehicle use cases and are expected to dominate the market, especially in the short term.

This publication discusses why investing in battery electric trucks is key to capturing the truck market and how OEMs can think strategically about pursuing battery technologies with a consideration for circularity.

Why batteries are the way forward for trucks

Regulators across the globe have encouraged truck OEMs to consider using alternative technologies to meet their emission targets as the most direct route to reducing emissions quickly. In 2024, the Environmental Protection Agency in the United States emphasized this by stating that its "standards are performance-based, such that manufacturers are not required to use particular technologies" to meet the standards.[2] The European Commission has set some of the tightest emissions regulations, requiring a 45 percent emissions reduction in new-vehicle sales by 2030 compared to 2019 levels and a 90 percent reduction by 2040.[3]

The alternatives to diesel

Currently, the most viable alternatives to diesel are BEVs, hydrogen fuel cell electric vehicles (H_2-FCEVs), hydrogen internal-combustion engines (H_2-ICEs), and renewable fuels. For BEVs, on one hand, truck OEMs can build on more than a decade of innovation in battery technologies in the passenger car and bus segments. Battery pack prices have also dropped by more than 80 percent over the past ten years, making battery electric powertrains an attractive option for trucks.

On the other hand, hydrogen fuel cell powertrains are still a more nascent technology due to lower uptake in the passenger vehicle space. To make H_2-FCEVs competitive, therefore, truck OEMs and suppliers would need to invest in further innovation and production scale-up. Hydrogen combustion requires fewer changes to the powertrain platform because existing combustion engines can be modified to suit the technology. But H_2-ICE vehicles have only recently gained more attention; regulators have started to consider them as zero-emission powertrains that are eligible to meet emissions targets.[4]

Last, renewable fuels can typically fuel existing diesel or gas combustion engines without further modifications and are already used to decarbonize certain fleet operations. But these fuels do not count toward heavy-vehicle emission targets for OEMs in major markets such as Europe or the United States because they still produce emissions.

In their practical application, alternative powertrains have specific sets of advantages and disadvantages (Exhibit 1).

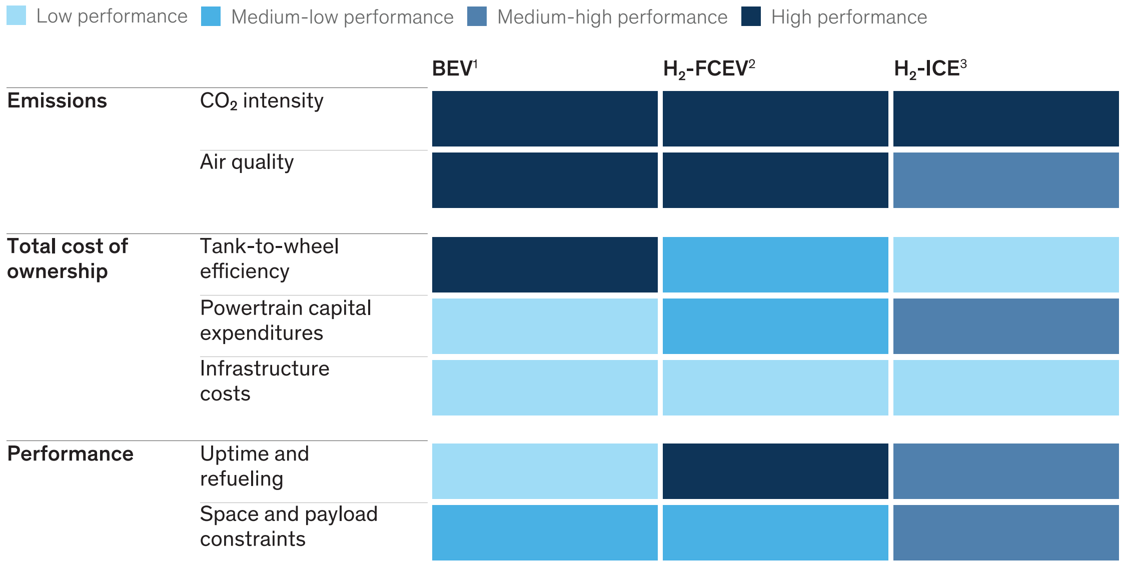
Emissions. When considering CO_2 emissions and air quality (including nitrogen oxides [NOx] and particulate matter), only BEVs and H_2-FCEVs[5] truly have zero emissions. While H_2-ICE vehicles have no tailpipe CO_2 emissions, they do emit NOx. Bio- and synfuels are holistically carbon neutral, but locally they emit CO_2, NOx, and particulate matter comparable to diesel engines. Thus they are not considered zero-emission technologies by regulations and do not contribute to meeting emission-reduction targets.

Total cost of ownership. The total cost of ownership (TCO) for a truck depends on the investment in and costs of truck R&D, infrastructure, and technology. Achieving desired TCO requires a stable and attractive supply of alternative fuel and affordable electricity. BEVs may require substantial up-front capital because of the significant R&D investments needed to develop novel battery cell technology and build

1 Road freight vehicles include heavy-duty trucks (HDTs), medium-duty trucks (MDTs), and light-duty trucks (LDTs).
2 "Greenhouse gas emissions standards for heavy-duty vehicles: Phase 3," US Environmental Protection Agency, April 22, 2024.
3 "Questions and answers: Revised CO2 emission standards for heavy-duty vehicles," European Commission, May 13, 2024.
4 Eamonn Mulholland, *The revised CO_2 standards for heavy-duty vehicles in the European Union*, International Council on Clean Transportation (ICCT), May 2024.
5 Zero-emission H_2-FCEV assumes the use of green or blue hydrogen and renewable power.

Exhibit 1

Three alternatives to diesel are most viable for road freight vehicles.



[1]Battery electric vehicle.
[2]H_2 fuel-cell electric vehicle.
[3]H_2 internal-combustion engine vehicle.

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charging infrastructure for both fast-charging, high-powered stations and depot charging stations. Battery manufacturing also requires building new production facilities and overhauling existing vehicle assembly lines to adapt to new vehicle architectures. At the same time, BEVs can achieve well-to-wheel efficiencies of 75 to 85 percent, reducing operational costs over time.[6]

The well-to-wheel efficiencies of H_2-FCEVs range between 30 percent and 50 percent, depending on the type of electron used, while the well-to-wheel efficiency of H_2-ICE vehicles is between 30 percent and 40 percent.[7] H_2-ICE vehicles are also more efficient in terms of capital expenditures because traditional engine technology can be modified to burn hydrogen rather than fossil fuels.

Performance. In addition to TCO, factors such as refueling time or payload constraints affect the suitability of propulsion systems for different use cases. Depending on the type of charger, BEVs require up to 2.5 hours for a charge that can last 500 kilometers (km),[8] whereas H_2-operated trucks take just 15 to 30 minutes to refuel to an amount that can last the same distance. Long refueling times reduce the efficiency of a truck and increase the complexity of route planning because both mandatory driver swaps and refueling breaks must be accounted for, making BEVs less attractive for use cases that require high utilization or around-the-clock operations. But the performance of batteries has improved significantly in recent years following strong R&D investments, especially for lithium-ion (Li-ion) cell chemistries. By 2030, much R&D is expected to go toward improving BEV chargers so they can charge trucks in 45 minutes for a 500-km range.[9]

In addition to emissions, TCO, and performance, factors such as geopolitical dependencies and supply chain stability need to be considered.

So far, more than ten OEMs have launched or announced new medium- and heavy-duty zero-emission truck models. Among these are models for long-haul applications with ranges of up to 500 km in Europe and 700 km in the United States.

Battery electric trucks are expected to dominate in truck use cases with limited range requirements and predictable, regular usage patterns, such as distribution or line-haul operations. In such use cases, both vehicle specifications and

[6] Bernd Heid, Christopher Martens, and Anna Orthofer, “How hydrogen combustion engines can contribute to zero emissions,” McKinsey, June 25, 2021.
[7] Ibid.
[8] When using a 350-kilowatt charger (the standard type at most truck stops in 2024).
[9] When using a one-megawatt charger.

charging infrastructure can be tailored to specific operational needs to enable battery electric trucks to play out their full strengths on high energy efficiency. Battery electric powertrains are also expected to capture a sizable share of the market for long-haul use cases with very long ranges, limited predictability on use cases, or multidriver operations, but they will face competition from hydrogen powertrains, which are expected to offer longer ranges and faster refueling times and hence additional flexibility in their operations.

For OEMs to capture the BEV market, it is essential to offer technologically leading and commercially attractive vehicles. This will require them to master the battery, which is the key technological differentiator and the main cost driver (Exhibit 2).

The best short- and long-term battery technologies for trucks

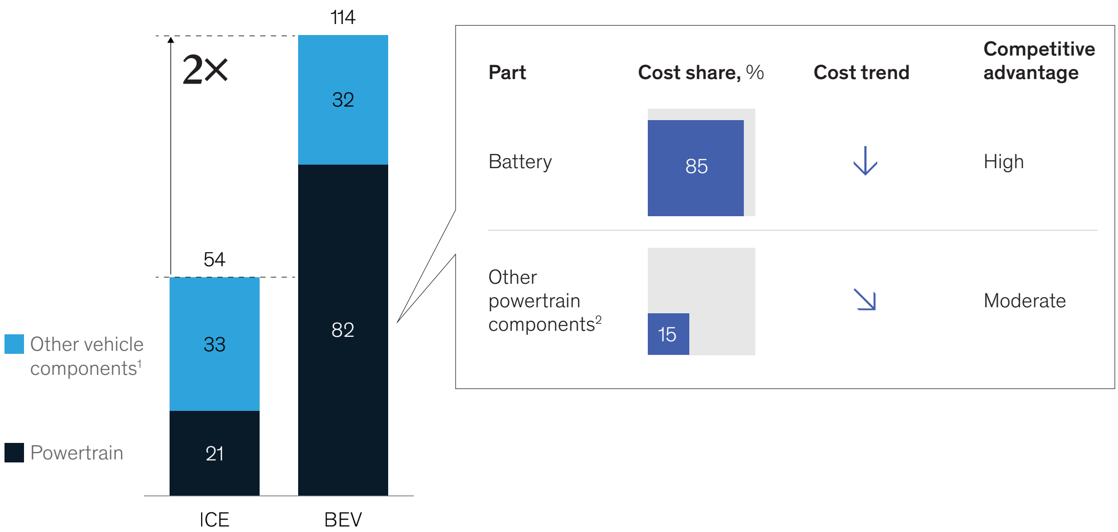
As the performance of batteries improves due to continuous advancements in Li-ion cell chemistries, truck OEMs can leverage these innovations to offer technologies that best meet the unique requirements of their vehicles. Truck battery performance is dependent on several factors, including energy density, battery cost, and cycle life—the most relevant factors in choosing a battery technology. Additionally, power density, thermal propagation, and sustainability should be considered for a holistic perspective.

The higher the weight and volume of a battery, the more constrained the vehicle's space and payload are. A high energy density of more than 210 watt-hours per kilogram (Wh/kg) is required to minimize the weight and volume of a battery while ensuring sufficient range, especially for use cases of more than 500 km. In a similar vein, high cycle life (3,000 to 6,000 cycles) is crucial to ensure the longevity of batteries. As fleet operators aim to maximize the uptime of trucks, freight batteries will experience significantly more charging cycles compared with passenger cars. Finally, because the battery makes up the largest portion of a truck's bill of materials, OEMs have a high sensitivity to cell cost, which affects commercial competitiveness and profitability.

Exhibit 2

The main expense for a battery electric vehicle truck is the battery, which accounts for 84 percent of powertrain costs.

Global average internal-combustion-engine (ICE) vehicle cost vs battery electric vehicle (BEV) cost for heavy-duty trucks, 2023, € thousand per vehicle



[1]Including chassis, electronics, interior, and exterior.
[2]Including electric drive, power electronics, and thermal management.
Source: McKinsey Center for Future Mobility

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With these considerations in mind, two types of battery will be the best option in the short term: nickel manganese cobalt (NMC) and lithium iron phosphate (LFP). In the long term, lithium manganese iron phosphate (LMFP) batteries will be the most promising battery composition, with an exceptional performance across all categories (Exhibit 3).

NMC technology's high energy density makes it an attractive option. However, the cost of NMC is relatively high and its cycle life is lower than that of other technologies because nickel chemistries are less durable than iron phosphate chemistries. Limiting NMC cells' operating window to improve a battery's lifetime is not a viable option because it can jeopardize its energy density advantage on both a cell and pack level due to the higher cooling and mechanical-stability requirements needed to comply with safety standards.

LFP cells have become an attractive option, thanks to adaptations that reduce the weight of packs and improve space efficiency, thereby increasing the batteries' energy density. Additionally, LFP chemistries have been advanced by adding manganese, which increases voltage and energy density to improve the performance of iron phosphate chemistries. LFP's cycle life is the highest of all three technologies; in addition, its total cost is relatively moderate and its makeup is cobalt-free, which makes it a significantly more sustainable and affordable option.

While LMFP has the highest potential across all categories, the technology is not yet fully developed, and its first market application is not expected to emerge until 2025 or later. In the meantime, LFP performs similarly to LMFP in most categories but has lower energy density. This has an impact on range, especially in long-haul use cases. Until LMFP is ready, LFP will be the best battery chemistry for trucks.

Implications of battery pack designs for trucks

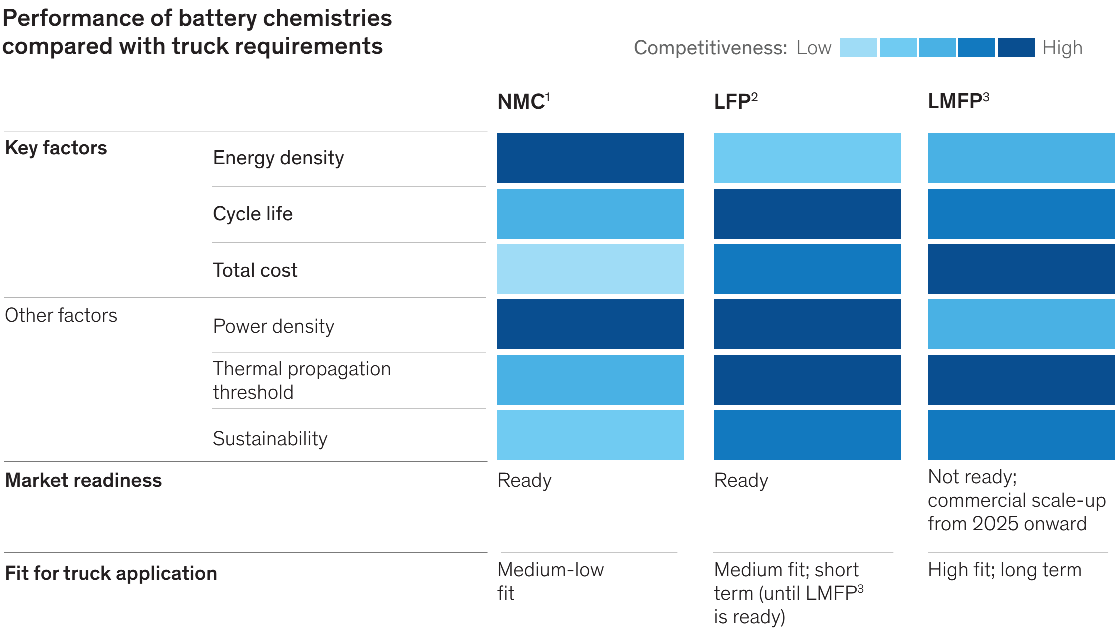
Pack design choices can also have a notable impact on the performance of a truck, including its range and charging speed.

Cell-to-pack and cell-to-vehicle designs

Traditionally, battery cells are arranged in modules and then combined into a pack. While modules have the advantage of better serviceability, a module-based pack design compromises energy density on the pack level and, thus, a truck's range.

Exhibit 3

Lithium manganese iron phosphate batteries perform exceptionally well across six key categories.



[1]Nickel manganese cobalt.
[2]Lithium iron phosphate.
[3]Lithium manganese iron phosphate.
Source: McKinsey Center for Future Mobility

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Battery swapping technology can reduce charging times for BEVs from several hours to less than five minutes, thereby eliminating a significant pain point.

Recently, the cell-to-pack design—which eliminates modules and assembles the pack directly from cells—has been discussed more widely because it offers a higher packaging density. A next potential step in integrating cells as structural battery components would be a cell-to-vehicle design, which would install the battery cells directly into the vehicle. But this approach would require rethinking trucks' platform design, and the design of heavy-duty vehicles is foreseen to remain as a frame-based layout due to rigidity requirements and the many superstructures built on truck frames by independent suppliers.

Another factor influencing pack energy density is the format of battery cells. The three most common cell formats are round, pouch, and prismatic. While pouch cells offer higher energy density on a single cell level, the efficient packaging of prismatic cells offers higher energy density at the pack level. Prismatic cells also offer a financial incentive for cell production, in terms of both operating and capital expenditures, because they can be used to create larger-format cells. Hence, the popularity of the prismatic cell format has increased.

Another highly relevant trend is the switch from 400-volt to 800-volt vehicle architecture. Among many benefits, 800-volt technology allows trucks to charge with up to twice the power, reducing the required charging time by up to 50 percent. In addition to many advancements related to performance improvement, OEMs have also been focusing on the safety aspects of this new architecture. With advancements in cooling systems and insulation for packs, they can reduce the risk of thermal runaway, enhance fire resistance, and ensure more-stable operating temperatures, thereby improving the overall safety and reliability of electric trucks.

The potential of swappable batteries

Traditionally, BEV design assumes that a battery pack is permanently installed and recharged if empty. However, time lost on battery charging is one of the most significant drawbacks of BEV trucks and can be especially challenging for fleet operators, whose business model is dependent on high utilization. Battery swapping technology can reduce charging times for BEVs from several hours to less than five minutes, thereby eliminating a significant pain point.

In contrast to permanently installed batteries, swappable batteries can be removed from underneath the truck or behind the wheelhouse and replaced with a fully charged one. Placing batteries behind the wheelhouse would require minimal additional investment and could be executed immediately, but this option would affect a truck's driving dynamics, braking distances, and, thus, driver safety. Alternatively, placing the battery below the truck would not affect driving dynamics, but this option might come at a higher cost because it may require adjustments to the vehicle architecture.

If implemented at scale, battery swapping could hold the potential to fundamentally change how the zero-emission-truck industry operates. In the Chinese market, most truck OEMs offer swappable battery concepts—almost half of all BEV HDT trucks sold in 2023 are battery swappable capable. In the short and midterm, this concept could be highly attractive. While not all trucks make use of this functionality today, individual cell players are pushing to establish battery swapping technology in the market and drive the development of the relevant infrastructure. If adopted, battery swapping technology could have far-reaching benefits across the freight trucking value chain:

Fleet owners. Fleet owners can increase fleet utilization resulting from reduced charging time while improving flexibility in route planning because there will be fewer constraints in terms of matching driver breaks with fixed charging points. Owners will also have access to new technology and business models, including a battery-as-a-service (BaaS) model that will reduce upfront capital expenditures.

OEMs. With the introduction of the BaaS model, OEMs can generate recurring revenues with batteries and increase the volume of unit sales because providing batteries via the BaaS model will reduce the sales price of trucks. If battery swap technology prevails, OEMs will need to capitalize on BaaS opportunities or may find it difficult to recover lost revenues from trucks sold without batteries. However, OEMs might face competition from other players in the value chain, such as battery pack manufacturers or swapping-network operators.

OEMs can also increase the residual value of batteries, as standardized battery packs make second-life applications and recycling more attractive. Furthermore, battery lifetimes will be extended, as battery swap stations would intentionally have lower charging speeds than megawatt charging systems (MCSs), putting less strain on batteries. Finally, trucks will be easier to service because battery packs can be separately serviced, eliminating the need for specialized battery services at OEM service stations.

Battery manufacturers. BaaS models will increase the volume of batteries required from battery manufacturers to cover demand, which will drive top-line growth. Additionally, as batteries become standardized, manufacturers will be able to increase the efficiency of their production and find more opportunities to partner with OEMs to develop the design of these standardized battery packs. Furthermore, first movers could position themselves strategically to develop this standardized technology with OEMs and capture additional market share.

Utility companies. For utility companies, a battery swap technology would reduce the load on the grid because swapping stations charge with lower power than MCSs, and operators can optimize charging patterns by taking peak times into account. Utility companies could also generate additional revenue by taking energy arbitrage opportunities in a battery-to-grid concept.

To make the BaaS model possible in the United States and Europe, OEMs will need to standardize battery packs across OEM platforms, which could present challenges with R&D complexity and funding. However, the Western truck market is dominated by a few large OEMs, which could be a substantial advantage because it will be easier to standardize packs, attain critical vehicle volume to make battery swapping attractive for all players along the value chain, and gain regulatory support. US and European OEMs may think proactively about battery swap strategies and financing needs, either jointly or individually, to ensure they're prepared. Otherwise, they might risk missing out on the potential next big thing.

Ways OEMs can source batteries

OEMs can source batteries in three distinctive ways: by directly purchasing batteries from battery suppliers; by partnering with battery players to develop and produce batteries in joint facilities; and by producing batteries in OEM-owned facilities with limited partner support. Leading truck OEMs typically deploy a mix of strategies. Some supplement long-term purchasing agreements with battery manufacturers with their own production capacities—mostly at the pilot stage—while others rely fully on partners using selected purchasing contracts or joint ventures.

Direct sourcing. Sourcing directly from battery suppliers can be beneficial for OEMs. It requires only limited battery expertise, takes less up-front investment in the form of capital expenditure, and allows for more flexibility in timing and volume.

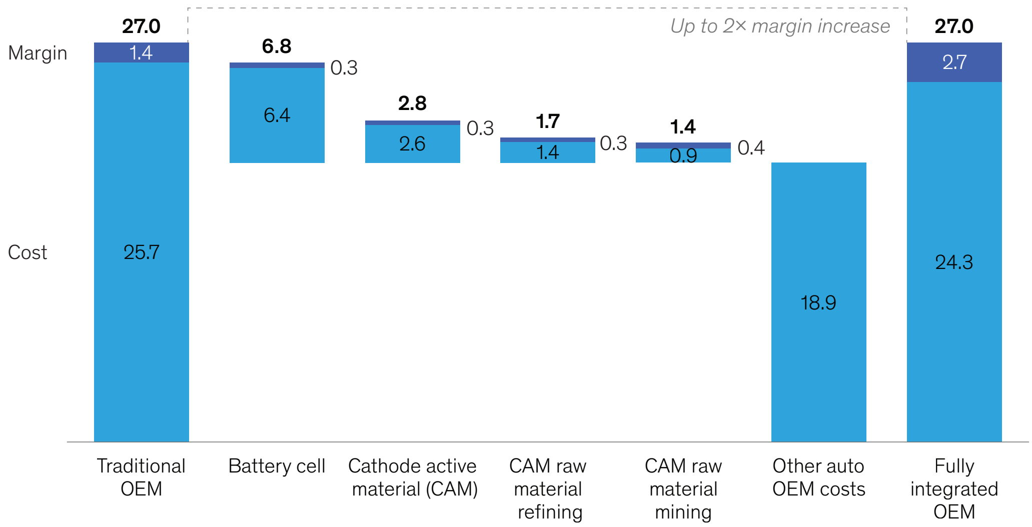
Partnerships. Partnerships allow OEMs to be involved in the battery value chain without having to build batteries in-house. They can help bridge the capability gap within companies while lowering the investment hurdle of becoming a manufacturer. For example, major truck OEMs that were focused on direct sourcing can increasingly integrate vertically through various partnerships to be more competitive.

By partnering along the value chain, OEMs can participate in additional value pools, which could double their margins, depending on their depth of involvement (Exhibit 4). However, this strategy is also subject to risks. Low interest rates in the market could lead to an increase in battery production capacity before 2030 because cheap capital will be available for investors to put into gigafactories. If so, more battery manufacturing could result in "build to print" processes, which could slash cell prices and squeeze margins along the value chain.

Exhibit 4

Backward integration along the value chain could double OEMs' margins and secure supply capacities.

Illustration of volume battery electric vehicle (BEV) cost vs margin along BEV value chain, € thousand



	Traditional OEM	Battery cell	Cathode active material (CAM)	CAM raw material refining	CAM raw material mining
Typical EBIT margin, %	5	5	10	15	5–40

Note: Figures may not sum to totals, because of rounding. Potential analysis based on upper range of margin observations in CAM mining, margin spread in mining given cyclicity, and large performance spreads observed across assets.
Source: McKinsey Battery Insights

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In-house production. Producing batteries in-house can give OEMs the upper hand: they can develop and produce tailor-made batteries at low cost while protecting their own battery intellectual property, allowing them to gain more upstream value. OEMs especially have an opportunity when it comes to developing LFP batteries because, despite potential demand, the supplier base in Europe and North America is still limited.

The involvement of truck OEMs in the battery value chain depends mostly on their competence in battery technologies, their willingness and ability to make large-scale investments, and their strategic considerations regarding the value to be captured in the future EV truck market.

Usually, OEMs that pursue this strategy will still involve selected technology partners—but to a limited extent. Companies that choose to become independent will have to ensure that they have freedom to operate and that their end-to-end battery supply chain matches the regulatory environment.

Another important consideration is the market environment. EV car sales and investments have slowed down compared with the past five years, leading to overcapacities and making truck OEMs with smaller offtake agreements more attractive. Several Chinese cell suppliers have decreased their prices as much as 50 percent, falling below €60 per kilowatt-hour (kWh)[11]—levels that cannot be met by European OEMs, even with in-house cell production. Producing cells in Europe comes with a premium of roughly €10/kWh but can better withstand potential regulatory changes and the risks that come with longer, more complex supply chains. In North America, alternatively, the current policy environment puts significant import tariffs on Chinese cells, making local cell production the economically more viable option. Depending on the region and regulatory environment, the current buyers' cell market may delay in-house cell manufacturing plans or reduce the appetite of truck OEMs in the long term to invest in the battery value chain.

[11] Colin McKerracher, "China's batteries are now cheap enough to power huge shifts," Bloomberg, July 9, 2024.

Sourcing raw materials

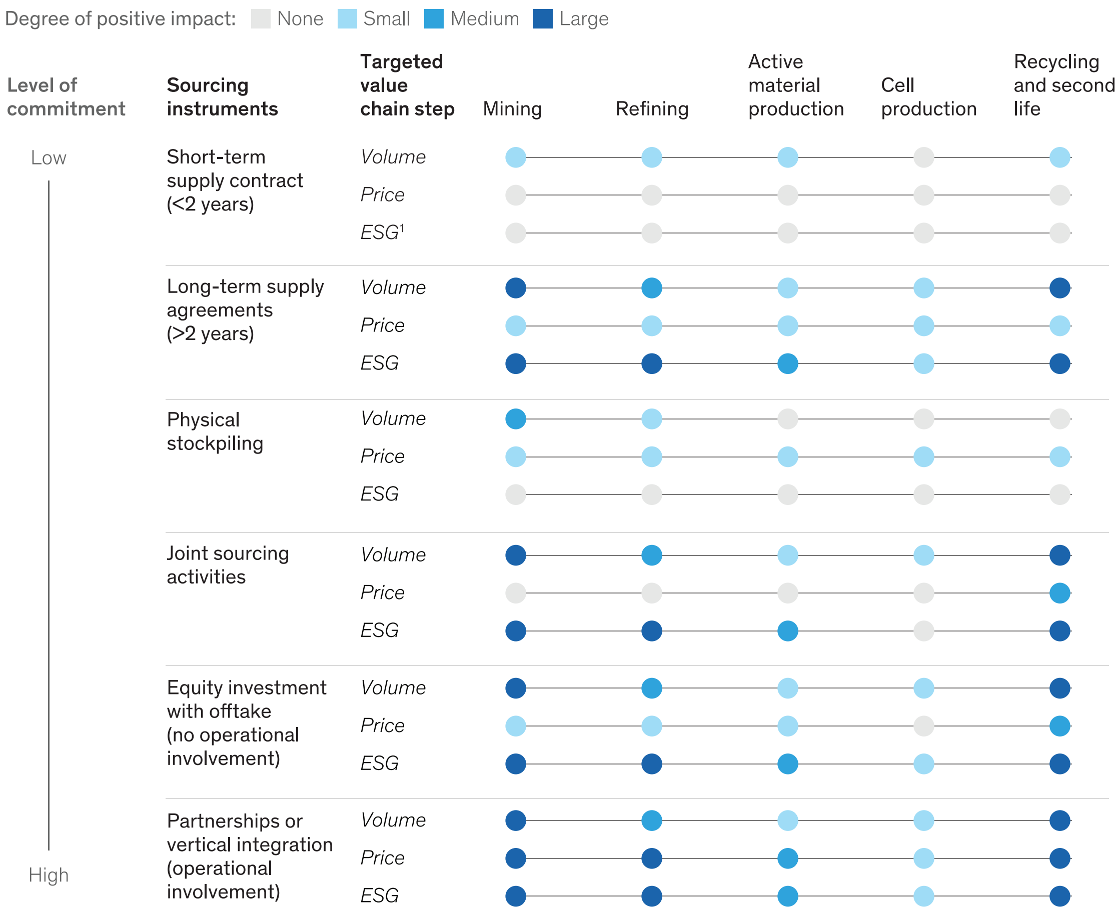
When sourcing raw materials for batteries—for example, for in-house battery production or to provide them to value chain partners—OEMs should consider whether the volume of available materials is sufficient, whether prices are low and stable, and whether the materials are compliant with internal and external environmental, social, and governance (ESG) regulations. Additional factors, such as geoeconomic risks and policies, should also be considered to develop a holistic sourcing strategy. Also, as the recent semiconductor shortage demonstrated, controlling critical parts of the supply chain can be considered a strategic and differentiating factor.

OEMs can choose among several sourcing instruments, each with a different level of organizational commitment (Exhibit 5).

Vertical integration may result in the most favorable position for OEMs in terms of volume, price, and ESG; however, poor operations could inflate costs, potentially above market price. For example, operational constraints and unforeseen complications in the development of an asset may raise the cost of producing it. In these cases, having a high level of organizational commitment through vertical integration does not necessarily result in a more favorable position for an OEM because inefficient operations could prevent them from realizing the price advantage. Moreover, investing in selected assets (one mine, for example) may make an OEM more dependent on certain suppliers, which increases supply risk and limits flexibility. For OEMs, risk exposure is high when investing in a limited number of assets compared with the lower risk when sourcing via one or multiple mining companies, which typically operate a portfolio of assets.

Exhibit 5

Long-term contracts to source raw materials may put OEMs in better, risk-avoidant positions.



[1]Environmental, social, and governance.

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Alternatively, well-negotiated long-term supply agreements can offer positive impacts similar to those of higher-commitment options, such as equity investments or vertical integration. These long-term contracts also eliminate the need for up-front capital expenditure investments, allowing OEMs to allocate capital elsewhere. Long-term agreements thus could be the best immediate option to put OEMs in a good position.

The current raw-materials market underscores this fact, especially for the lithium needed to make LFP battery technology for truck applications. Based on McKinsey's current demand-and-supply outlook, a global lithium shortage over the next ten years has become less likely, and sufficient volume will be available via contracts (Exhibit 6). But it's important for OEMs to be aware of the amount of material available in a given location and the materialization of projects currently in development.

Confirmed and currently operational projects cover lithium demand until 2026. With new recycling capabilities and further projects expected, lithium demand could be satisfied beyond 2030. Additionally, after years of strong fluctuations, lithium prices have been low since electrification has become more popular, offering the opportunity to negotiate favorable long-term contracts. As it stands, changes in the price of lithium are affecting contribution margins more significantly than potential supply interruptions, which makes the opportunity for long-term offtake agreements even more appealing for OEMs today.

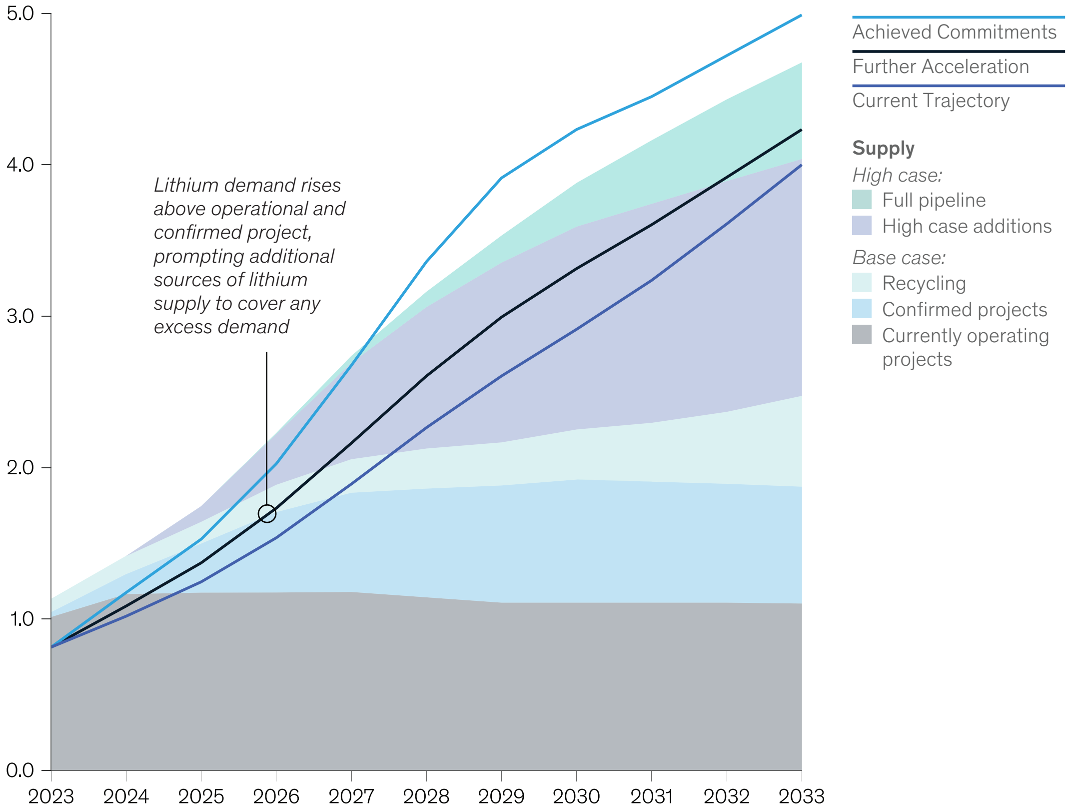
Battery circularity: Managing complexity with partnerships

Eventually, batteries reach the end of life (EOL) of their original application. Multiple EOL pathways

Exhibit 6

Global lithium demand is expected to be met by 2030 and beyond, making long-term contracts more attractive for OEMs.

Lithium mine supply and demand[1] balance, projected, metric tons of lithium carbonate equivalent



[1]Mined production volume. Forecast potential production accounts for historical utilization rates as a result of external disruptions and economic curtailments (7%), modeled at 93% of the available capacity. Production includes volumes that may not have been refined. These include stockpiling of direct shipping ore and spodumene concentrate.
Source: McKinsey Battery Insights; MineSpans

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exist[12]: batteries can be reused (following repair or refurbishment) for their initial purpose of powering trucks, used for second-life application in battery energy storage systems (BESS), or recycled to extract valuable raw materials. A battery's EOL pathway is determined by a situation-based cost-benefit analysis, primarily driven by the battery's state of health (SOH).

Batteries with a high SOH (more than 80 percent residual capacity) have a high potential of being reused in EVs, whereas those with a lower SOH (70 to 80 percent) can be repurposed in a suitable second-life application. The higher the SOH, the more value can be extracted from the battery during recycling, and the more emissions can be reduced.

Recycling represents the largest market in terms of mobility battery volume[13]: about 78 percent of global mobility EOL batteries are expected to go directly to recycling by 2030 (Exhibit 7). When a battery is recycled, its raw materials are reintroduced into the battery value chain to make new batteries, which reduces the amount of raw material that needs to be extracted from mines and avoids 15 to 40 percent of CO_2 emissions, depending on the material extracted.

To recycle batteries, trucking companies can choose among several business models, depending on their desired ownership of the recycled materials and control over the recycling process. In closed loop models, companies can retain ownership of the metals in the battery throughout the entire life cycle and can use them as input for their own battery production. Alternatively, open loop models release ownership by selling off batteries to third-party providers.

OEMs can choose between building fully owned in-house recycling divisions, relying on one preferred end-to-end partner (through a joint venture, for example) or selecting multiple service providers. Of course, pursuing fully owned in-house recycling requires OEMs to build recycling capabilities, manage recycling complexity, and invest capital expenditures. In the mid to short term, most large truck OEMs are likely to pursue strategic partnerships for recycling in a closed loop (with one or multiple partners) or open the loop to sell off batteries to third-party providers.

The potential value creation of battery recycling should also be considered. Value creation from battery recycling differs between NMC and LFP chemistries based on the cost of recycling and the worth of the materials extracted (Exhibit 8). For example, a company could lose nearly €1,000 from an LFP battery that is disassembled and recycled in Germany in 2030.[14] For NMC truck batteries, however, a company could gain €2,000 from the materials extracted. This difference in value is because the primary revenue drivers in NMC batteries are nickel, cobalt, and lithium, while

[12] "Battery 2030: Resilient, sustainable, and circular," McKinsey, January 16, 2023.
[13] "Battery recycling takes the driver's seat," McKinsey, March 13, 2023.
[14] 200-kWh battery energy density assumed.

Exhibit 7

By 2030, most end-of-life batteries are expected to be recycled, allowing their materials to reenter the value chain.

Circular pathway	**State of health,** %	**Value generated,** $/kWh[1]	**CO_2 avoided,** %[2]	**Share of global mobility EOL[3] battery volumes,** %, in 2030
Reuse	>80	135–154	100	4
Second life	70–80	4–30	33–50	18
Recycling	<70	0–6	15–40	78

[1]Each pathway generates different value. Reuse: cost of new batteries in 2030; 2nd life: willingness to pay for a 2nd-life battery based on a 15-year battery energy storage system business case; recycling: sales value of an EOL battery when sold to a recycler.
[2]Share of total emissions per battery produced.
[3]End-of-life.
Source: McKinsey Battery Insights

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the sole driver in LFP batteries is lithium. Having a larger share of valuable metals leads, on average, to 300 percent greater revenues. But the cost of NMC recycling is usually also higher because it is more complex to extract multiple metals.

Currently, the value creation for LFP batteries with traditional recycling technology is highly dependent on the price of lithium, especially in the West. Alternative innovations, such as direct recycling processes, could significantly improve LFP recycling economics. However, these innovations are still quite early in their development, and more time and investment will be needed for them to reach maturity. The business case for recycling LFP could potentially be further optimized by introducing the recovery of the iron-phosphate precursor and the graphite, a practice already introduced in China.

The value of adaptability

As trucks move toward zero-emission powertrains, investing in BEV trucks will be a key driver of the transition, especially in the short term. Within the BEV-truck industry, batteries have the potential to be the most lucrative investment, considering their high potential for technological differentiation and high innovation speed, and will be crucial for the future success of OEMs. While various degrees of involvement are possible, building in-house competencies and capacities is vital to assess and steer the supply chain and ensure a technologically competitive and profitable product, both for themselves and their customers. But as OEMs continue to invest in BEV technologies, they should keep in mind four uncertainties.

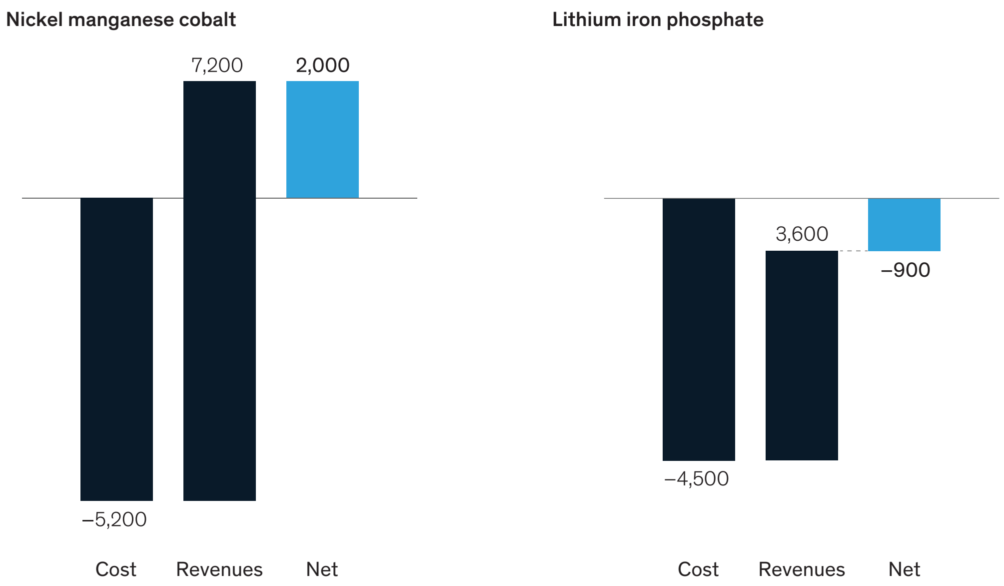
First, battery swapping may seem like a lucrative opportunity, but the technology's potential is more uncertain in the United States and Europe. At a minimum, OEMs can prepare for the option and foresee batteries' ability to be swapped in product design. More boldly, an OEM could aim to become a front-runner in the design of this technology or invest in the needed infrastructure, such as swapping stations.

Second, it's uncertain how much truck OEMs should invest in their own battery production capacities and upstream activities. The current buyer's market doesn't promote direct investment in cell manufacturing, but investing in this capability today could help OEMs prepare for

Exhibit 8

The materials recovered from nickel manganese cobalt batteries are more valuable than those reaped from lithium iron phosphate batteries.

Value creation of battery recycling in Germany in 2030 by cell chemistry, € per battery[1]



[1]~200 kWh battery assumed.

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future bouts of undersupply if too many capacity expansions are delayed or stopped.

Third, it's uncertain whether OEMs need to invest directly in raw materials. Doing so is a bold move that could bring high rewards—but it's also a greater risk. Nonetheless, OEMs should prepare to have a steady supply of raw materials, which could mean engaging in long-term agreements.

Fourth, the path forward for OEMs to enter recycling is mildly uncertain. The best options are for OEMs to enter partnerships with battery recycling facilities or for truck OEMs to source EOL batteries if they don't have in-house cell manufacturing capabilities.

OEMs can manage these uncertainties using the framework for battery mastery, which discusses how companies can approach cell component production and prioritize actions in a timely way.

There is enormous potential to reduce the emissions of road freight vehicles by implementing new technologies and updating and scaling current solutions. OEMs can manage the uncertainties that remain when it comes to investing in BEV technology by staying adaptable to react to potential technological, regulatory, and business model changes, especially over the next few years. Ultimately, taking steps to reduce emissions of heavy-duty trucks will get countries closer to meeting global emissions–cutting goals and pave a more sustainable road forward.

Jakob Fleischmann is a partner in McKinsey's Munich office, where **Patrick Kroyer** is a consultant. **Lena Bell** is an associate partner in the Cologne office.

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Drawing finance to the mobility transition

Two leading experts discuss why the mobility transition represents a new kind of asset class and outline the steps stakeholders can take to derisk investment opportunities.

by Tobias Schneiderbauer
with Max Grossmann

September 2024

The ongoing shift to zero-emission mobility is disrupting the entire transportation industry, a dynamic that creates both opportunities and challenges for companies across the ecosystem. Regulatory interventions, especially in Europe and North America, are pushing industry players to decarbonize their supply chains through 2030 and beyond. Specifically, Europe has one of the most ambitious targets, calling for as much as a 43 percent reduction in emissions for new-vehicle sales by 2030 and 90 percent by 2040.[1]

However, this transition to zero emissions faces substantial financial barriers. Despite the potential long-term savings from the transition, the deployment of private capital remains hindered by the fact that early-stage decarbonization projects have insufficient scale. Once projects attain scale, derisking mechanisms are not in place.

To discuss solutions on mobility transition finance, with a focus on trucks, buses, and infrastructure more broadly, McKinsey's Tobias Schneiderbauer and Max Grossmann spoke with two experts. Uday Khemka is an investor, entrepreneur, and philanthropist focusing on climate change. He serves as the vice chairman of SUN Group after previously leading Morgan Stanley's activities in India. Christoph Wolff is CEO of Smart Freight Centre, an international nonprofit focused on emissions accounting and reduction in freight. Prior to his current role, he was the global head of mobility and a member of the executive committee at the World Economic Forum.

Both shared insights on the hurdles that must be overcome to draw capital to the mobility transition.

McKinsey: Why are there so few large-scale projects in zero-emission mobility that can attract private capital at scale?

Uday Khemka: The existing system built around fossil fuels has been in place for more than 100 years. In response to climate imperatives, we need to implement a new system in ten years. This is extremely complex and challenging. Investors like simple routes to creating multiples and investment returns, and there is a fundamental contradiction between the interdependent complexity of a system in the midst of change and the simplicity required to derisk investment returns.

The capital has to flow from the private sector because the existing owners of transportation services, states, and federal governments just do not have that kind of capital. This is true in not only emerging markets, which require at least a trillion dollars of extra capital from developed countries every single year for decades, but also in Europe and the United States, where fiscal situations at the country level are not necessarily strong. The only way to replace an entire category of infrastructure is to move from an ownership model to a service procurement model.

That means somebody else has to own those assets—both transportation and charging infrastructure. So far, these assets have been funded in a very limited way, either by OEMs

'The only way to replace an entire category of infrastructure is to move from an ownership model to a service procurement model.'

–Uday Khemka

[1] "Europe sets the bar high and approves a 90% CO2 emission reduction target in new trucks by 2040," International Council on Clean Transportation, April 10, 2024.

themselves or by high-risk private equity investors. It's a question of the scale of capital as well as the cost of capital. If the cost of capital does not decline to a point where it more closely resembles infrastructure, it won't solve the third problem, which is total cost of ownership [TCO] and up-front costs.

Governments play a critical role in providing the right regulatory framework, incentives, and coordination functions to drive derisking and ensure attractive TCO levels for an increasing share of use cases.

We currently have bottlenecks where we don't have enough deals, the right economics, or strong demand signals. So it requires an intervention to accelerate what would occur naturally over decades to happen through structured interventions over a short period of time.

McKinsey: When it comes to convening large-scale private capital deployments in the transportation sector's mobility transition, who are the main stakeholders that need to be involved in developing a compelling value proposition for investors?

Christoph Wolff: It takes an entire village to move the needle, and the village consists of the following parties. On the supply side, manufacturers are currently producing diesel trucks. To transition resources and production systems, OEMs need to be convinced about the ramp-up and the scale of demand. So it's a chicken-and-egg challenge.

On the demand side, the carrier space is more or less fragmented. In North America, a significant share of the overall demand is handled by big carriers with thousands of trucks. In Europe, the share of those fleets is lower. Emerging markets have few fleets with more than a hundred trucks. In a market as big as India, you can count them on two hands.

The carriers act on behalf of shippers. Over the past ten years, shippers have increasingly outsourced their fleets to third parties. They're interested in reducing Scope 3 emissions, but at the end of the day, they know they have to bring their contractors on board in a competitive market.

The mobility transition requires a systemic shift: not just replacing fuels but moving to a different power base, which is electricity. Charging stations are the gas stations for electricity. That's a business model in its own right.

Grid operators are also part of the ecosystem. A charging station capable of accommodating 50 trucks at the same time is a massive factory. So you need to have the right power supply and the grid reinforcements in the right places.

All of these elements need financing. But for the finance sector, this is a new asset class. Investors don't quite understand it. They will look at the risk and say, "If things go wrong, we don't want to be at the end of the chain."

The policy makers are also a stakeholder because they need to put pressure on everybody to move to a different system. All need to work together to make this complete shift happen over the next 15 to 20 years.

McKinsey: Which mechanisms have proved to be effective in attracting finance to large-scale mobility transition projects and making them viable in the long run?

Uday Khemka: We see at least three key elements: the private sector, from OEMs to operators; government; and investors. These three groups have to coordinate deliberate, time-bound derisking efforts to accelerate this revolution.

I'd argue there are five stages in the derisking process. The first is for government to create extremely clear and consistent regulatory or fiscal signals. We've seen various governments change their targets.

The second stage is working with the private sector—transportation OEMs and fleet operators as well as investors. Take bus transportation: a public entity procuring long-term bus services is analogous to procuring power from an independent producer. Just as the independent-power-producer revolution was premised upon power purchase agreements based on pay-per-use models, mobility purchase agreements could be set up similarly. This could be facilitated by the creation of standardized instruments to diminish and quantify the risk in long-term procurement contracts.

The coordination of OEMs, operators, governments, and investors is necessary for actual deployment. For example, by bringing together power producers and distributors with transportation service providers, individual routes can be mapped. A freight transportation service provider using electric trucks knows there will be power on that route, and the infrastructure company investing in the route knows there will be demand for electricity. This coordination requires convening around individual large-scale project corridors down to the local level. Of course, government has a huge role to play by providing infrastructure, financial incentives, and permitting.

‘We need teams with a focus on transport electrification that understand the risk and see the opportunity. We can then move toward a core offering from the finance sector.’

–Christoph Wolff

The third stage is demand pipeline development. Operating players may not have the capabilities to build investment cases that are aggregated at sufficient scale in order to reduce their cost of capital. Assistance with pipeline development can be extremely important.

The next stage is blended finance, which can best be done when stages one, two, and three are in effect. The fifth stage is the syndication of the deal flow to project investors, corporate investors, programmatic investors, and investors in developed and emerging markets. No function currently exists to do this appropriately. All five of these stages could be complemented with a sixth stage focused on narrowing the gap between real and perceived risk, which is particularly relevant for developing countries.

In Scotland, a relatively small market, the government convened all sectors to coordinate policy for electric buses. Similarly, India brought together large-scale demand aggregation plus regulation for electric buses. Most important, it was done in consultation with the private sector, finance, and government at various levels. Such projects require an infrastructure mindset and a high degree of coordination to deliberately derisk. And they need to be done at a much greater scale and with a greater degree of ferocity.

McKinsey: In your time at the Smart Freight Centre, have you come across successful examples of convening mobility transition finance projects?

Christoph Wolff: We are trying to get to a level of projects with 100 trucks, 500 trucks, or 1,000 trucks. In India, for example, there was a joint announcement across 28 shippers and carriers to deploy roughly 10,000 e-trucks over the next five years. This agreement is divided into tranches of 500 to 1,000 trucks at a time. They collaborate with, among others, finance-as-a-service providers, truck-as-a-service providers, battery-swapping companies, and battery-as-a-service providers to address financial and technology risks. These arrangements have the potential to unlock this opportunity and mitigate asset risks for private companies.

In Europe and the United States, we have increased collaboration on more-sophisticated use cases. We are working with the Port of Rotterdam and some of the shipping lines on electrifying port drayage for transport between ports and nearby distribution warehouses. This requires large depots that trucks return to at night. It is actually a lot simpler than open-loop and corridor-based use cases.

The United States DOE [Department of Energy] supports the development of a network of heavy-duty-truck corridors, some of them with 10,000 trucks a day in both directions. The Smart Freight Centre is working with progressive shippers on selected e-truck corridor pilots, especially in the form of long-haul round trips, with the aim of achieving TCO parity with combustion-engine trucks. TCO is largely dependent on the circulation patterns, not only on the up-front capital. The aggregation of volumes to more than 1,000 trucks creates sufficient scale to attract asset owners and investors, which could offer e-truck fleets to shippers in the form of a truck-as-a-service model.

Any remaining risk should be covered by first-loss guarantees from specialized lenders or insurance companies. Overall, it’s less a technology challenge than an economic and coordination challenge.

McKinsey: What are three wishes you have for scaling promising use cases?

Uday Khemka: Well, my most important wish is a global multilateral institution around systemic derisking. It would be a global body with branches in individual countries that are trying to derisk in emerging countries.

For instance, a Senegalese sustainable transport derisking center would report to the office of the prime minister of the president because it would need to coordinate across ministries of transportation and power and many others. These institutions would then be sponsored at the highest level by all governments that are committed to this journey. Government's function would be to coordinate these multistakeholder dialogues to create the right regulations, financial support, coordination of routes, sectors, projects, and aggregation of demand.

Another wish is then to figure out the kind of support required from the global community to provide financing for southern derisking efforts. Northern government support is very important if emerging countries, where the bulk of the world's population and infrastructure will be in the next 30 years, are to catch up. I'm going to limit my wishes to these two big ones.

Christoph Wolff: My first wish is for the finance sector to be more engaged. Transport contributes 25 percent of global CO_2 emissions, and heavy transport is around a third of that—about as much as the steel or chemical industry. We need teams with a focus on transport electrification that understand the risk and see the opportunity. We can then move toward a core offering from the finance sector.

The second wish involves the policy makers. In the European Union and United States, it's important for policy makers to stay on course and serve as an example for other leaders in huge countries.

The third wish is for the supply and demand sides to work together on concrete projects. When that happens, shippers could see that the necessary policy, finance, and technology are all there. Once we figure out where we have critical mass, we could actually work together on pilots and then use cases of scale. That could break the chicken-and-egg dilemma.

About Christoph Wolff

Christoph Wolff is the CEO of Smart Freight Centre, a globally active non-profit organization for climate action in the freight sector. Previously, he was the global head of mobility and a member of the executive committee at the World Economic Forum, where he led initiatives on autonomous, shared, and electric mobility. Christoph has also served as managing director of the European Climate Foundation, focusing on decarbonizing energy, transport, and industries across the EU. Leveraging his experience at McKinsey as global practice head in travel and logistics, he has held executive roles at Deutsche Bahn, DB Schenker, Ferrostaal, and ABB.

About Uday Khemka

Uday Khemka is an investor, entrepreneur, and philanthropist who has made significant contributions to the climate change sector in India. He serves as vice chairman of SUN Group, a diversified family-owned investment and industrial group based in India with interests in new and renewable energy, electric mobility, and natural resources, and leads the activities of the Nand & Jeet Khemka Foundation. Uday has more than 30 years of finance expertise: he served as head of Morgan Stanley's activities in India and as an infrastructure investor in transportation and contributed his philanthropic leadership of collaborative institutional investors on relevant themes for more than two decades.

Christoph Wolff is the CEO of Smart Freight Centre. **Uday Khemka** is the vice chairman of SUN Group. **Tobias Schneiderbauer** is a partner in McKinsey's Munich office, where **Max Grossmann** is a consultant.

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Automotive & Assembly Practice

Driving the future: How connectivity will shape the truck industry

Connected services can bring significant value to commercial vehicles—but industry stakeholders must work together to make it happen.

by Florian Garms and Tobias Schneiderbauer

Momentum around connected and data-enabled services in commercial vehicles is accelerating. Data-enabled services are critical for new opportunities in charging energy solutions, connected insurance, the automotive aftermarket, advanced financing solutions, and transport as a service [TaaS]. Their potential to solve complex problems for OEMs, automakers, and fleet managers is too enticing to ignore. And those possibilities could yield serious value creation. According to McKinsey research, data-enabled services could represent a more than $3 billion profit pool by 2035.

To get a clearer picture of the current connected-services landscape—and what's to come—McKinsey's Florian Garms and Tobias Schneiderbauer spoke with Rupert Stuetzle, general manager of EMEA manufacturing and mobility at Microsoft, and Frank Kaleck, automotive industry expert at Microsoft. Rupert and Frank have been working with commercial vehicle industry players for more than a decade and are experiencing the evolution of connected services firsthand. In this interview, they discuss the evolution of connected services for commercial vehicles, the transition to zero-emission vehicles, generative AI (gen AI) use cases, and why industry players must work together to reap the full value of connected services.

McKinsey: What trends are you seeing related to connected services for commercial vehicles, and what do you anticipate moving forward?

Rupert Stuetzle: Three trends will drive the relevance of connected services. The latest vehicle architecture and connectivity solutions will provide value beyond traditional telematics use cases in the short term. For example, we anticipate increased visibility into real-time logistics and correlating data from multiple domains, such as traffic or weather. Examples of these applications in practice include tracking and fleet management services, intelligent cruise control, eco-driving capabilities, and predictive diagnostics.

We've also observed a growing interest in integrated transport system solutions and as-a-service business models. Connected services are a prerequisite for these offerings because they ensure profitable service provisioning for the operators and enable efficient transport management. When we look at full logistics-as-a-service solutions, connected services could support higher-level services beyond road transport. This trend will likely fuel demand for connected services in trucking in the midterm. Virtual-freight-forwarding players are already offering TaaS-like services, which could increase the use of connected services in fleets.

The zero-emission vehicle transition could also heighten demand for connected trucks as various use cases emerge that provide substantial value to customers, such as charge planning. As this transition gathers momentum, we expect a significant uptake of connected services in the mid- to long term. Autonomous trucks will likely make connected services even more relevant, though this is a bit further out, even with assisted driver functionalities integrating into the connected-services landscape.

McKinsey: Frank, what use cases have you observed among key players in the field?

Frank Kaleck: First, we need to distinguish between commercial vehicles and passenger cars, and there is a clear business case for commercial vehicles. In such a margin-critical industry, fleet managers earn money only if a truck is on the street. Therefore, with commercial vehicles, it's all about reliability and efficiency, which provide significant opportunities for monetization and value creation.

Business-critical services have a higher demand for near real-time capabilities, such as vehicle tracking. Several large retailers already claim they can reduce diesel consumption by up to 8 percent by leveraging a fleet management system. Nearly all the commercial vehicle OEMs that provide guidance on efficient consumption in their vehicles incorporate gamification. For example, OEMs can identify drivers with the lowest diesel consumption on a specific route and generate daily high scores.

However, the most sophisticated use cases for connected services are intelligent driver-assistance systems, which some OEMs have in the market or are announcing. For example, a truck can develop a route plan by incorporating maps, route profiles, road conditions, and traffic data to guide the driver. And if the driver approaches a speed reduction zone, the truck can tell the driver to take their foot off the accelerator.

McKinsey: Those are some impressive use cases. What do you think is next? If we consider TaaS, for example, how will connectivity shape that model?

Frank Kaleck: The TaaS model is meant to reduce logistics companies' total cost of ownership [TCO]. As we know, TCO is related to vehicle asset management, which is driven by new-vehicle prices, maintenance, insurance, and, eventually, depreciation. By leveraging TaaS offerings, logistics companies pay only for the core purpose of a truck, meaning the transportation of goods and people from A to B.

There isn't just one flavor of TaaS; we have logistics as a service, mobility as a service, and electric vehicle [EV] charging as a service. For connected fleets, task providers rely heavily on data and advanced analytics to optimize routes, manage the fleets, proactively maintain vehicle health, and match supply with demand. All these examples illustrate the movement toward TaaS models.

McKinsey: The biggest transition in commercial vehicles is the shift toward zero-emission vehicles. Depending on the forecast, estimates suggest that by 2030, 20 to 25 percent of new-vehicle sales in the US and 40 percent in Europe might be zero emission. Rupert, you mentioned that the zero-emission transition could help connected services become more relevant and differentiated. Could you elaborate?

Rupert Stuetzle: We see two drivers of connectivity services through zero-emission vehicles: shorter innovation and R&D cycles in product development, and broader use cases for efficient EV operations. In general, the automotive market expects significantly shorter development cycles. Tier-1 suppliers and commercial vehicle OEMs are under pressure to iterate on EV technology within an extremely short period. To do so, they need a fast digital feedback loop. Engineers can use connected services to capture real-time signals from any vehicle module, such as engine control units, a human–machine interface, a battery, or sensors. They can then analyze the information to identify anomalies quickly, make data-driven decisions to solve problems, and optimize performance.

Connectivity can also support efficient operations for zero-emission vehicle truck fleets. Example use cases include route optimization, route charge planning, battery and truck condition monitoring, depot charge planning, and even bidirectional charging. However, achieving efficient zero-emission vehicle truck and fleet operations requires significantly more connected and linked data domains than traditional telematics. Range optimization and charging, or refueling planning, will also be crucial in reaching TCO targets.

McKinsey: What implications do you think the evolution of things such as connected trucks, charging infrastructure, and transport solutions will have on system and business architecture?

Frank Kaleck: The automotive industry has been on a disruptive path over the past two or three decades. As more vehicle capabilities become software-based, the industry is adopting recognized technology patterns from mobile app or cloud application development, such as observability.

However, to effectively monitor, log, and trace data, automakers need a mature, reliable, performance-optimized, and secure vehicle telematics and data analytics platform. Automakers already have machine learning and analytics capabilities to gather insights and extract valuable information from vast data. This approach helps them identify anomalies in vehicle performance and proactively adapt vehicle configurations to reduce unplanned maintenance events.

Automakers must also consider the electrical and electronics [E/E] domain. In addition to cloud and backend capabilities, they need to increase the power of the high-performance computer within the vehicle. Therefore, technology patterns such as cloud computing, hybrid infrastructures, and data processing at the edge and in various domains are becoming more important. Connectivity modules are an essential component of this puzzle.

Another interesting dimension is the impact of connectivity on large fleets. For example, if you look at large fleets, you will see multiple brands and vehicles of different ages. Managers currently rely on retrofitted OEM-agnostic solutions to get a holistic view of their fleet. This situation paves the way for a new digital services and data-related business model. Tech companies are already helping collect fleet data and enriching it with other data sources, such as weather or traffic information. They are also establishing marketplaces so that OEMs, fleet managers, and other players can exchange data, creating a new pathway for data monetization. Of course, this business model is not just for tech companies—it's an opportunity for all commercial vehicle OEMs.

Rupert Stuetzle: We're also seeing significant changes in backend infrastructure. From our perspective, a standard harmonization layer can enable data analytics across a fleet with different OEMs and vehicle ages and provide a cost-efficient way for providers and ecosystem partners to participate in connected services without bearing the development cost.

Open-source initiatives and alliances—such as Eclipse SDV and COVESA—are already working to establish data format standards and common ontologies related to vehicle data and signals. Competitors are also teaming up to create a common software-defined vehicle platform and dedicated truck operating system that offers advanced digital features and services to enhance customer efficiency and experience. By pooling resources and expertise, stakeholders can accelerate the development of new platforms and systems, increase scale, and reduce material costs and R&D costs per unit.

McKinsey: One technology on everyone's mind right now is gen AI. Where do you see gen AI operating or evolving in the current vehicle ecosystem?

Frank Kaleck: There's huge pressure to improve efficiency in the new vehicle life cycle, generating interest in gen AI among OEMs and Tier 1s and leading to rapid adoption. At the same time, the complexity of vehicle engineering is growing exponentially because automakers are producing zero-emission vehicles alongside combustion engines.

So how can AI help drive efficiency in vehicle engineering? One option is to use gen AI to analyze regulatory documents, extract functional specifications, check consistency, and suggest test and validation cases. Automakers are already starting to use gen AI-based tools such as GitHub Copilot, for instance, to generate software code, identify issues, and automate repetitive tasks, such as testing software code, which shows proof of value.

Gen AI can also help with data literacy. In the past, you had two personas in automakers: a data analytics specialist and a domain expert (like an engineer) who knows about E/E mechatronics development. To gather insights from the vast amount of data at their disposal, they had to talk to each other and translate what they needed from each other.

Now, gen AI can help increase data literacy instead of having the engineer explain the question so that it makes sense to a data-literate analyst. Instead, the engineer can ask gen AI questions in natural language and get detailed insights. For example, engineers could tell gen AI to "plot a map where anomaly battery drains happened during the last test drive" and get a figure with all the information. OEMs and tech companies are working to provide similar capabilities to their fleet customers, tapping into another opportunity to monetize new digital services.

Automotive and commercial vehicle market players are deploying Gen AI as an intelligent driver companion or assistant. Some passenger car OEMs already offer ChatGPT-powered assistance, for example, providing a benchmark for commercial vehicle OEMs. These assistants can improve safety by ensuring the driver is not distracted by trying to retrieve information manually. Future applications on the horizon include asking the assistant to solve complex tasks. For instance, you could say "Get me from A to B, but make sure that there's a parking space with a DC fast charger available."

McKinsey: How can the industry maximize the value of connected truck services?

Rupert Stuetzle: Automakers, suppliers, and other commercial vehicle and transportation players need to address three critical challenges.

First, we need stronger ecosystem thinking around use cases that create the value customers expect. We receive many requests from traditional commercial vehicle ecosystem players, such as OEMs and fleet operators, on how to operate a competitive business model with appropriate governance, steering, and target setting. These requests indicate a desire to move away from conventional thinking. Interface standardization will be crucial to value generation because connectivity services need to work across various truck models, domains, and data sources. For this to work, however, industry players must be open to using standard APIs and common anthologies rather than closed solutions.

Second, stakeholders should invest in pilot projects and real-world deployments of autonomous-driving technology to gain practical experience and refine their business models. Partnerships with tech companies and regulatory bodies can also accelerate the deployment and integration of autonomous vehicles.

Third, automakers and OEMs must also establish clear policies and frameworks around data ownership, ensuring transparency and trust among all stakeholders. Specifically, they should implement robust data protection measures that comply with regional and international regulations and safeguard vehicle and customer data. Content management systems should allow customers, OEMs, and suppliers to easily control and manage their data-sharing preferences.

And finally, stakeholders should establish a data-driven engineering feedback loop. By sharing real-time vehicle data within a closed feedback loop, stakeholders can get the right information for requirements management and engineering, design, product engineering, production processes, and sales. This approach can accelerate continuous improvement and innovation through advanced analytics that capture and analyze customer feedback and vehicle signals.

Frank Kaleck is an automotive industry expert at Microsoft, where **Rupert Stuetzle** is the general manager of EMEA manufacturing and mobility. **Tobias Schneiderbauer** is a partner in McKinsey's Munich office, and **Florian Garms** is an associate partner in the Berlin office.

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Automotive & Assembly Practice

The big shift: Moving commercial vehicle OEMs to centralized E/E

A software-centric strategy can help commercial vehicle OEMs transition to electrical/electronic architectures with centralized computing and hardware–software separation, unlocking new opportunities.

by Anna Herlt, Johannes Deichmann, and Martin Kellner with Asif Khan

In an era marked by rapid technological advancements, the commercial vehicle industry stands on the cusp of a transformative evolution. The decentralized electrical/electronic (E/E) architectures that have long been the backbone of vehicle operations are now being redefined, and so is the software running on them. To master this evolution in E/E architecture and unlock customer value, commercial vehicle OEMs and their suppliers can take a software-centric approach to transforming their capabilities, operations, and organizations.

Modern trucks will soon be sophisticated digital platforms that integrate advanced E/E architectures with unprecedented efficiency, safety, and connectivity potential. These new E/E architectures are characterized by centralized compute units, high-speed data networks, and advanced software capabilities decoupled from hardware. The shift from a decentralized architecture to a central architecture will enable adoption of autonomous-driving (AD) technologies, connected and data-based services, real-time diagnostics, and over-the-air (OTA) updates at scale.

What does this mean at a practical level? Commercial vehicle OEMs have historically achieved great success in developing and offering highly modular variants of products to accommodate individual customer needs. In contrast, the rising complexity of a software-defined truck will require a more strongly harmonized E/E system with low hardware variance across derivatives to differentiate on a decoupled software level. OEMs will need to balance the need for customization with the complexity of integration, control, and security to seize the opportunities presented by this next generation of vehicle architecture. To drive value differentiation on the software level, OEMs will need to exert greater control over their software stack and accelerate innovations in response to market demand.

This article discusses implications and opportunities inherent in advanced E/E architectures for OEMs and suppliers. It offers a framework for developing and deploying software as well as insights to help OEMs and suppliers transform their offerings, operations, and business models to respond rapidly to demand for advanced E/E architecture.

OEMs and advanced E/E architectures: Challenges and implications

The commercial vehicle industry follows the principles of modularity to enable customers to customize vehicles according to their specific needs, such as construction, long-haul transport, or urban delivery. OEMs design and assemble vehicles using a wide array of components, mixing and matching them to create tailored solutions. In distributed architectures, each function of the vehicle—such as engine control, chassis controls (including trailer systems), and infotainment or telematics—operates with its own dedicated electronic control unit (ECU). These distributed systems have been built on captive elements: components and subsystems that OEMs source from specialized suppliers and then integrate into a cohesive vehicle platform, primarily at the hardware level.

In contrast, next-generation architectures consolidate control into a few high-performance computing units that manage multiple vehicle domains simultaneously. Integration in a centralized architecture is performed at the software level, with functional software building blocks integrated and deployed on one control unit. Customization can be achieved through specific software building blocks instead of through a customized set of ECUs. This approach requires OEMs to take stronger control of a standardized core software platform comprising middleware, an operating system, and communication interfaces.

While the advent of fifth-generation centralized architectures poses challenges to the modular approach that has been central to vehicle design, it also brings significant advantages. For example, centralization helps OEMs manage increased functional complexity, allows for more frequent development and update cycles—including OTA updates—and provides the ability to support advanced technologies such as AD, electrification, and enhanced connectivity.

The shift from distributed to centralized architectures brings OEMs into new territory, requiring them to reevaluate supply chains, internal capabilities, and product development processes. Customization, a straightforward process in modular systems, is more complex in centralized systems because changes to one part of the system can have widespread implications across multiple layers. OEMs' previous reliance on suppliers means they must build or acquire new competencies in areas such as software development, system integration, and cybersecurity to ensure compliance with evolving regulatory standards (see sidebar, "The evolution of electrical/electronic architectures").

Integrating advanced E/E: Key OEM and supplier considerations

To incorporate fourth- and fifth-generation E/E architectures into their business models and operations, OEMs and suppliers must build their capabilities to specify, develop, and integrate their own and other suppliers' software into one domain or central control unit. Managing this complex process with a large number of suppliers and internal stakeholders can present specific challenges, including a heightened need for cross-functional collaboration, because all domains share the same computer hardware in fifth-generation architectures. And because domain and central computers will need to be updated over many years, companies will need to forecast future demand for hardware resources.

The underlying motivations for the shift toward centralized E/E architectures[1] are largely similar for commercial vehicles and passenger cars—namely, the desire to enable OTA updates,

[1] "Getting ready for next-generation E/E architecture with zonal compute," McKinsey, June 14, 2023.

The evolution of electrical/electronic architectures

The transition to new electrical/electronic (E/E) architectures is driven by several key technological advancements.[1] These new E/E architectures are characterized by centralized computing power, high-speed data networks, and advanced software capabilities.[2] A significant milestone in this evolution is fifth-generation E/E architectures. Understanding the transition from traditional E/E architectures to fifth-generation architectures is crucial to grasp the advancements shaping the future of trucks.

— *Third-generation architectures.* In this decentralized approach to architecture, each domain—such as powertrain, chassis, advanced driver-assistance systems (ADAS), and comfort—consists of several electronic control units (ECUs) connected via a central gateway. Typically, each ECU is sourced from a supplier and integrated on a vehicle level.

— *Fourth-generation architectures.* In a typical fourth-generation architecture, each domain (such as powertrain, body, and chassis) is managed by domain control units (DCUs) usually connected via high-speed bus, an electronic pathway for data such as ethernet.

— *Fifth-generation architectures.* The substantial leap forward offered by the fifth-generation approach is enabled by its combination of central compute units and zonal architecture connected via high-speed bus that allows full virtualization of the functional software layer. Computing centralization enhances processing power, reduces latency, and simplifies the integration of new features. Instead of DCUs spread across different domains, electronic functions are consolidated into physical zones within the vehicle. Each zone manages local sensors and actuators, while one or two powerful central computing units handle data processing, decision making, and coordination among zones. The centralized computing unit can be realized via a rack-based design, several dedicated systems on a chip on one printed circuit board, or a fusion chip.

[1] Ani Kelkar, Timo Möller, and Felix Ziegler, "What technology trends are shaping the mobility sector?," McKinsey, February 14, 2024.
[2] "Advanced semiconductors for the era of centralized E/E architectures," McKinsey, June 19, 2024.

reduce system complexity, and increase the use of common software. In addition, most platform development processes for commercial vehicles and passenger cars are similar, including foundational aspects such as middleware, platform layers, and customer functions enabled through software features.

There are also notable differences between passenger car OEMs and commercial vehicle OEMs when it comes to centralized E/E architecture and software:

— In passenger vehicles, software is focused on enhancing driver safety, comfort, and entertainment. Advanced driver-assistance systems (ADAS) and infotainment are important but are generally considered value-added features. In commercial vehicles, on the other hand, software is an essential component of core, business-critical functions in the vehicle. For example, fleet operators rely on telematics for tracking, operational reliability, fuel efficiency, and more to conduct business operations in a safe, compliant, efficient, and cost-effective manner.

— Software features for commercial vehicles focus on reducing total cost of ownership via capabilities such as predictive maintenance, adaptive cruise control with efficiency enhancements, and energy recuperation for electric trucks.

— The complexity and scale of commercial vehicles necessitate longer development cycles in which architectural evolution happens much more gradually. In addition, OEMs partner extensively to bring the necessary capabilities onboard because the breadth of applications and requirements for commercial vehicles exceeds what can be developed in-house by OEMs.

Market potential for commercial vehicle players

As the trucking industry transitions to centralized E/E architectures, changes to onboard and off-board vehicle components—hardware, operating systems and middleware, the application layer, and the connected cloud environment—will add significant value for customers. OEMs will have the opportunity to drive customer value through new functionality, such as ADAS and AD, and by deploying additional functionality OTA throughout the vehicle's life cycle. Further, centralized E/E architectures can reduce the complexity of commercial vehicle hardware systems, making trucks more reliable and efficient—critical factors for fleet operators. For suppliers, the shift from multiple distributed ECUs to centralized hardware presents a chance to offer software independent of hardware, but it also bears the threat of potential margin pressure from standardized hardware and reduced business opportunities because of integrated ECUs. Standardized operating systems and middleware, meanwhile, simplify vehicle diagnostics, software updates, and system interoperability while enhancing cybersecurity for all players.

The potential of aftermarket services

The opportunity for growth associated with advanced E/E architecture extends beyond the sale of trucks and underlying components. There is also a burgeoning market for aftermarket services including software updates, connected services, and data analytics. Companies that can provide end-to-end solutions for managing these complex systems stand to achieve significant gains.

By providing software updates, maintenance services, and cloud-based solutions, OEMs and suppliers can maintain long-term relationships with their customers, ensuring ongoing revenue after the vehicle's initial sale. At the same time, customers benefit from extended vehicle lifespans and the ability to continuously update and improve their vehicles without the need for new hardware. This enhances the long-term value of the vehicle and ensures that it remains competitive with newer models.

Notable avenues for potential aftermarket growth include the following:

— *Software updates and subscription-based services.* As trucks become increasingly software-centric, the demand for regular software updates and upgrades will increase. This presents a potentially lucrative opportunity for OEMs and suppliers to offer subscription-based services and generate recurring revenue.

— *Data monetization.* The data generated by advanced E/E systems can be monetized in various ways. Fleet operators can leverage this data to optimize their operations, reduce downtime, and enhance safety. In addition, based on the combined potential value derived from various data-driven services and applications within the automotive industry—including connected car services, predictive maintenance, fleet management, and other innovative solutions that leverage vehicle data—the market for automotive data–enabled services could be worth $3 billion to $4 billion in the European Union and the United States by 2035, according to McKinsey analysis.

— *Predictive maintenance.* Predictive maintenance, enabled by real-time diagnostics and AI algorithms, can significantly reduce operational costs and improve vehicle uptime. This service can be offered as part of a comprehensive fleet management solution, creating additional revenue streams for OEMs and suppliers.

Growth estimates by market segment

The market potential for advanced E/E architectures in the commercial vehicle industry is vast amid mounting demand for the autonomous, connected, and electric vehicles that require such systems to operate effectively. As OEMs and suppliers transition from modular to centralized operating models to meet this demand, growth estimates for the global commercial vehicle E/E architecture market point to a 6 percent per annum growth rate from 2024 to 2030, when it could reach nearly $20 billion.[2]

The heavy-duty-truck segment is expected to lead the sector with about 50 percent of value ($10 billion) by 2030, followed by the bus segment capturing about 30 percent of value ($6 billion) and the medium-duty-truck segment with about 20 percent ($4 billion) of the total market.[3]

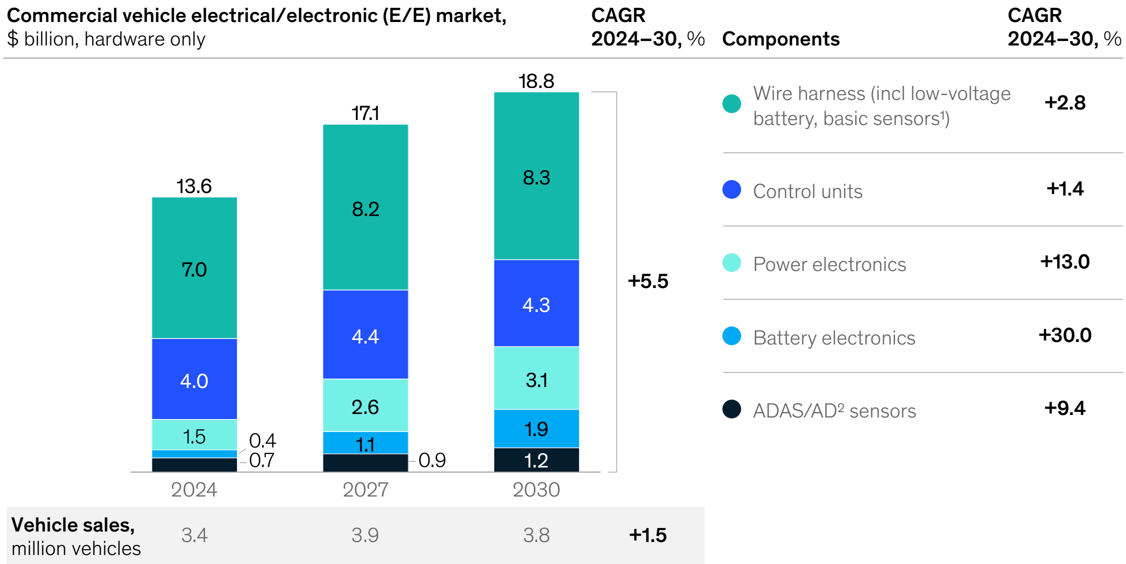
Truck electrification will drive high growth in power electronics such as inverters, converters, power distribution units, and battery electronics, while more-sophisticated ADAS and the introduction of autonomous driving AD will boost growth in the ADAS/AD sensor segment. Wire harness and control unit segment growth, meanwhile, is lower because of the cost savings expected from a reduction in the number of control units needed for fifth-generation architectures (Exhibit 1).

2 McKinsey Center for Future Mobility analysis.
3 Ibid.

Exhibit 1

The commercial vehicle electrical/electronic market is expected to grow at 6 percent CAGR until 2030.

Commercial vehicle forecast, incl heavy-duty trucks (HDT, class 8), medium-duty trucks (MDT, classes 3–7), and buses



Note: Figures may not sum to totals, because of rounding.
[1]Traditional sensors such as engine oil pressure, door position, temperature sensor, etc.
[2]Advanced driver-assistance systems and autonomous driving.
Source: McKinsey Center for Future Mobility

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To capture the identified market potential, suppliers will need to develop comprehensive go-to-market strategies that consider both the E/E architectural components and the software solutions deployed. For example, they might strengthen sales, marketing, and customer support strategies tailored to the unique features and benefits of the software solutions.

Preparing for the future of E/E architectures: Transitioning from modular to software-centric

Indeed, the evolving landscape of E/E architectures in commercial vehicles presents significant implications and opportunities for OEMs and suppliers. To thrive in this new era, companies must adapt their traditional modular approach to a software-centric development approach. This will require them to familiarize themselves with the various dimensions of software development and deployment.[4] We have defined a holistic framework to address the essential considerations within each of the four dimensions of software development (Exhibit 2).

Each of the framework's four dimensions focuses on a specific set of challenges and considerations:

— *What software is developed:* ensuring that software requirements address competing priorities while maintaining efficiency in development; for example, balancing user-centric design with streamlined hardware and software integration

— *Where software is developed:* creating organizational and operational structures that support new software development needs

— *How software is developed:* implementing agile and development practices to support innovation and efficiency

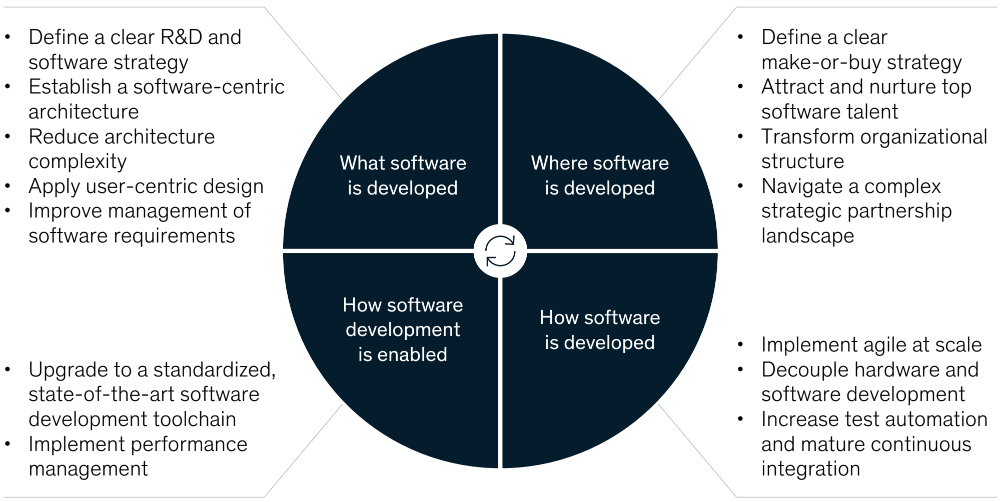
— *How software development is enabled:* enabling tools and infrastructure to track and guide progress toward efficiency, performance, integration, and quality goals

Companies must carefully consider the competitive and strategic implications of this change and the other organizational and operational transitions needed to support advanced E/E architectures and the smart vehicles they enable. The software development framework can serve as a foundation upon which OEMs can build a new approach, as exemplified below.

4 "When code is king: Mastering automotive software excellence," McKinsey, February 17, 2021.

Exhibit 2

The framework for software development outlines key considerations for each dimension of the process.



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What software is developed: Creating the right architecture

OEMs must invest significantly in R&D to remain competitive, developing new hardware as well as focusing on software innovations. Companies can position themselves for success in this critical realm by starting with the right road map and offerings, as discussed below.

— *Define a clear R&D and software strategy.* OEMs will need to adopt a software-centric development approach that places software at the center of vehicle functionality, updates, and customer experience. This can be achieved by prioritizing the development of software that enables OTA updates, real-time data analytics, and AI-driven features that enhance vehicle performance and user experience.

— *Establish a software-centric architecture.* OEMs should focus on enabling vehicles that are defined primarily by their software rather than their hardware. Developing a flexible and scalable software architecture can help facilitate continuous improvement and feature enhancement throughout a vehicle's life cycle. This approach can enhance the value proposition of vehicles and open up new revenue streams for software updates and enhancements.

— *Reduce architecture complexity.* Decoupling hardware and software and standardizing, modularizing, and adopting service-oriented architecture can help manage the intricate integration of an increased amount of software and hardware.

— *Apply user-centric design.* Limit software development to essential features valued by customers, focusing on usability and functionality.

— *Improve management of software requirements.* Adapt processes to ensure efficient management, prioritization, and end-to-end tracking of software requirements.

Where software is developed: Building the right organization

To ensure continued success, companies must establish organizational and operational structures conducive to innovation and collaboration in software development.

— *Define a clear make-or-buy strategy.* Defining a strategic make-or-buy decision framework entails identifying which software components should be developed in-house and which should be outsourced. Outsourcing areas that fall outside an organization's core strengths may enhance capabilities and speed up development cycles. Establishing a robust procurement process that ensures the quality and reliability of third-party software is also vital.

— *Attract and nurture top software talent.* To attract and retain critical top software talent, OEMs can consider investing in centers of excellence that focus on software development and delivery. Ideally, these centers would be strategically located in regions with access to skilled talent. Additionally, partnerships with universities and technical schools can create a pipeline of skilled professionals.

— *Transform organizational structure.* By transitioning away from developing functionality and software in fragmented silos and forming cross-functional teams dedicated to software projects with strengthened horizontal capabilities, OEMs can benefit from seamless integration between software and hardware development processes and promoting a culture of continuous learning and improvement. Overarching software development teams may need to be integrated into vehicle project organizations to promote cross-platform reuse and alignment with vehicle development timelines.

— *Navigate a complex strategic partnership landscape.* Given the decoupled software and hardware architecture and fragmented vendor landscape, strategic partnerships will become rather complex, and defining clear make-or-buy strategies and forging strategic partnerships with software vendors will be key. Joint ventures between OEMs could provide one path to lowering development costs.

How software is developed: Optimizing processes using best practices

Following the established software development principles discussed below is essential to ensure quality, reduce time to market, and realize process efficiencies.

— *Implement agile at scale.* Implementing agile methodologies at scale in the vehicle development process helps maintain operational efficiency by coordinating multiple teams, fostering collaboration, and enabling rapid adaptation. This approach delivers incremental value via fast software and hardware innovations and ensures cohesive progress across complex projects.

— *Decouple hardware and software development.* Managing the separation of hardware and software development processes poses a challenge because it requires overcoming technical and organizational barriers to enable independent innovation cycles and agile software updates. OEMs can adopt a two-speed development process in which hardware and software development cycles are decoupled, enabling faster software updates and iterations by removing any constraints posed by hardware timelines.

— *Increase test automation and mature continuous integration.* As hardware and software development processes are decoupled, the need for rigorous and efficient testing processes grows. Increasing test automation helps manage the expanded scope of testing required for both hardware and software components. It accelerates testing, improves accuracy, and ensures that all components meet high reliability and performance standards. Maturing continuous-integration processes is vital for integrating new software and hardware in commercial vehicles. Frequent updates and early issue detection facilitate smoother integration, enhance system performance, and ensure rapid deployment of new features.

How software development is enabled: Maximizing performance and infrastructure
Enabling successful software and hardware launches and deployment requires an advanced and robust software development infrastructure.

— *Upgrade to a standardized, state-of-the-art software development toolchain.* Fast-paced release cycles place immense pressure on the development toolchain. A key challenge is building a standardized, state-of-the-art toolchain that supports continuous integration and continuous delivery (CI/CD) practices, enabling seamless integration of software and hardware updates. This requires investment in new tools and platforms that can handle the increased complexity and volume of data generated by modern vehicles while also ensuring cybersecurity and regulatory compliance. Investing in modernization of the toolchain accelerates development, reduces errors, and improves software quality.

— *Implement performance management.* By setting metrics and benchmarks for productivity and quality, OEMs can monitor and enhance their development processes. Data-driven insights from performance management help address issues early, maintain high standards, and ensure the software meets the rigorous demands of commercial applications. This leads to more reliable and effective software solutions.

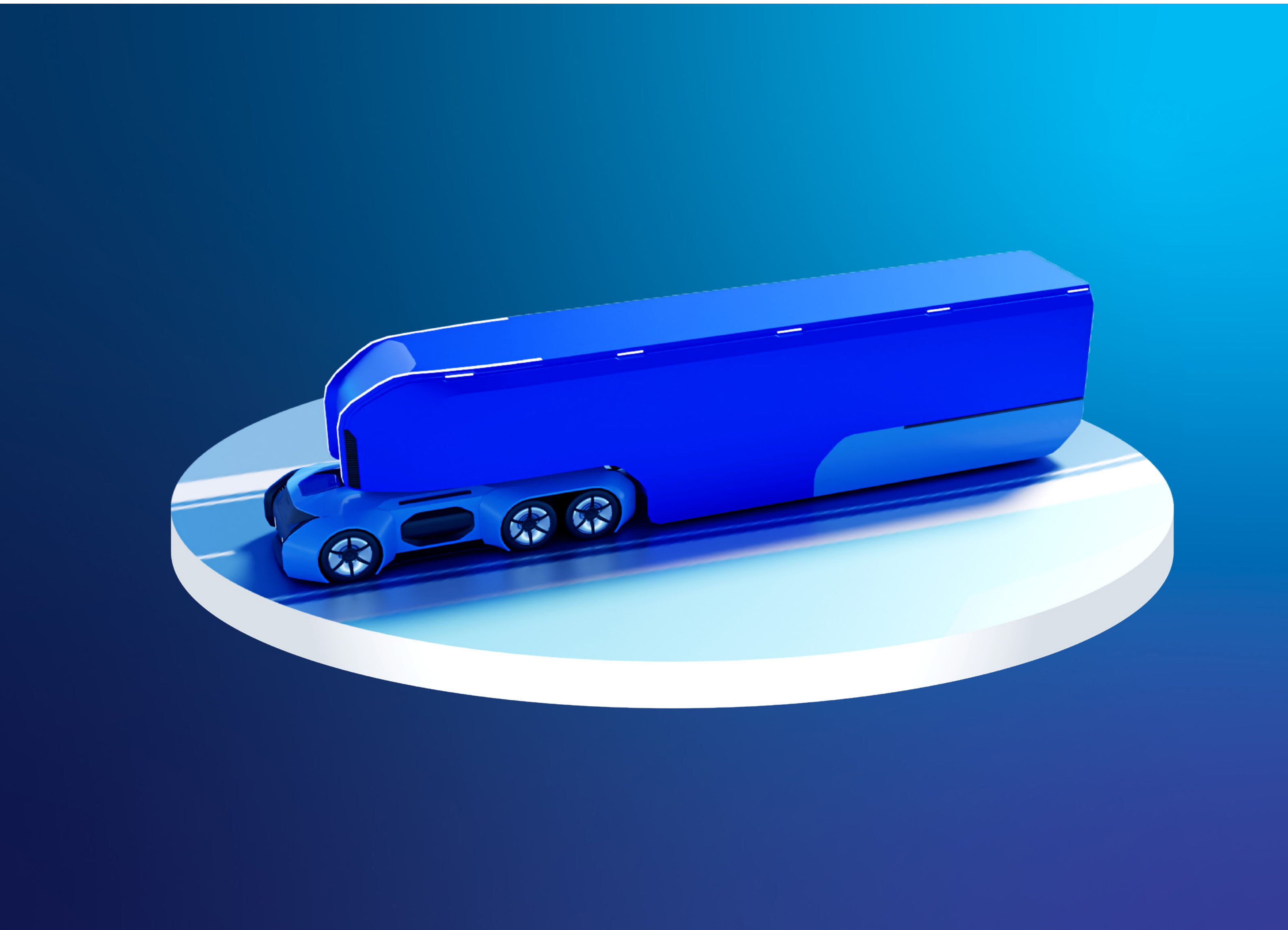
Shifting OEM and supplier processes, organization, and capabilities from a modular, hardware-centric approach to a software-centric approach with centralized E/E architectures is a complex endeavor. But given the growing demand for leading-edge commercial vehicles with best-in-class efficiency and performance, this shift represents tremendous economic potential for OEMs and suppliers. Leaders should focus on preparing their organizations today to maximize their competitive advantages tomorrow.

Anna Herlt is a senior partner in McKinsey's Munich office, where **Martin Kellner** is a partner; **Johannes Deichmann** is a partner in the Stuttgart office, and **Asif Khan** is an associate partner in the Stockholm office.

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).

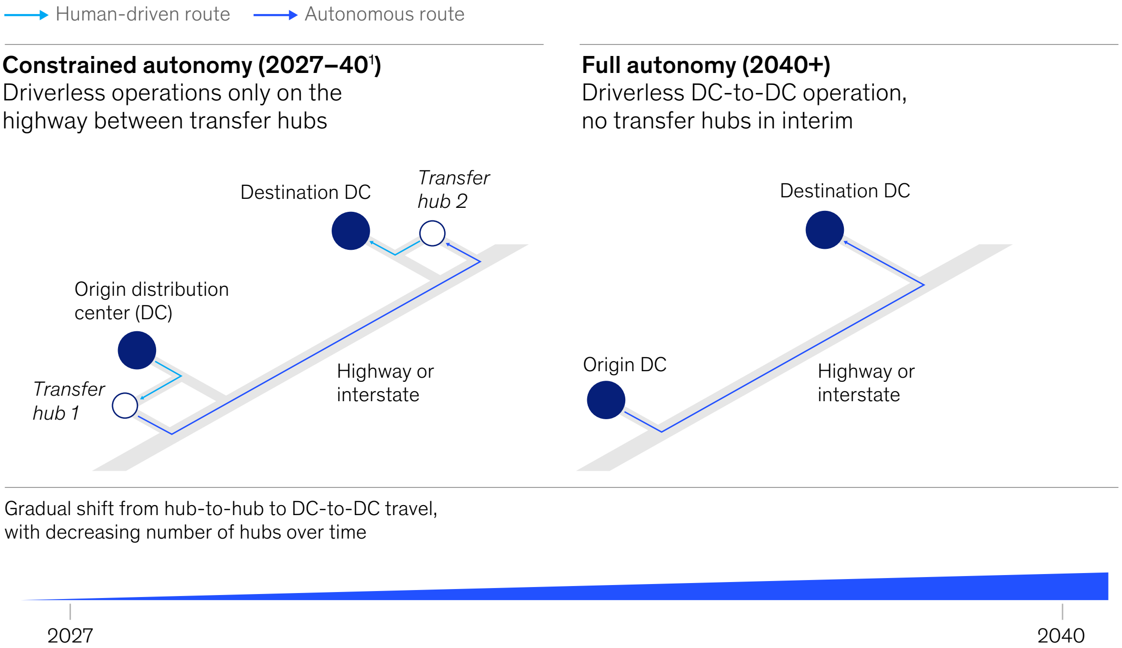
Full autonomy. The second use case is driverless DC-to-DC operation (SAE Level 4) with transfer hubs required only for recharging or refueling on longer routes or to swap trailers for deliveries to a location other than a DC that cannot be reached by autonomous trucks. Because some DCs are already so 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.



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

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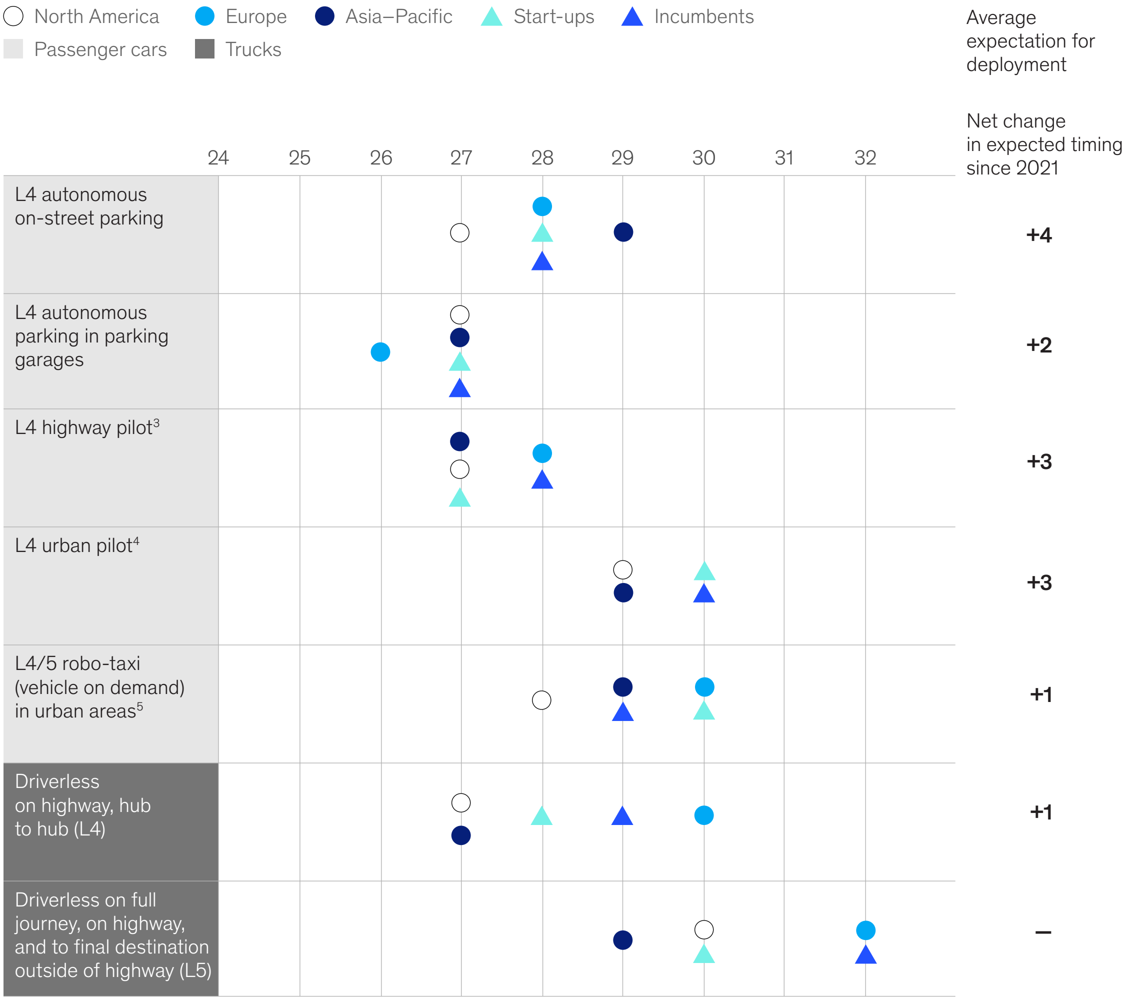
Exhibit 2

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

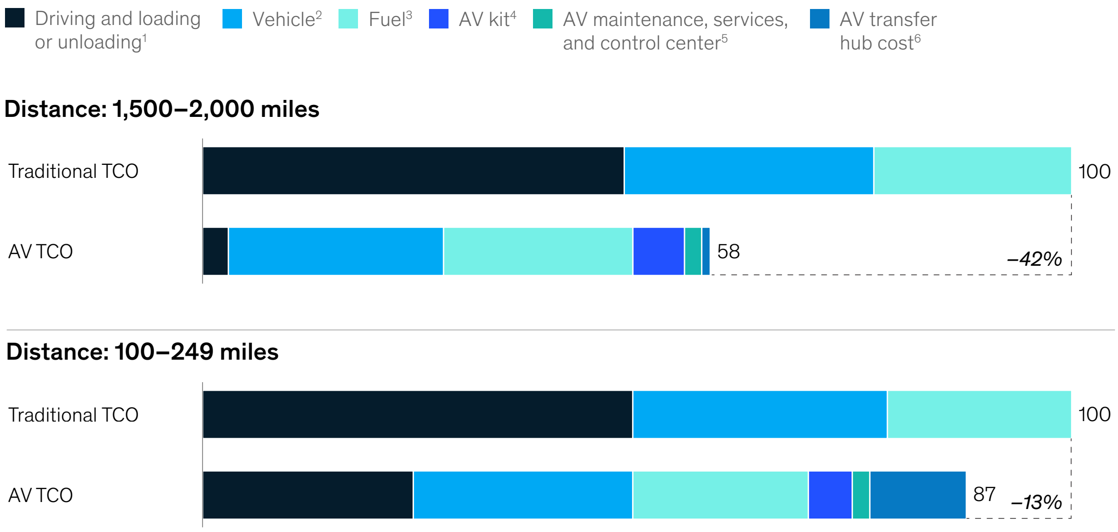
According to McKinsey projections, the autonomous heavy-duty trucking market could reach an aggregated $616 billion in 2035 in China (about $327 billion), the United States (about $178 billion), and Europe (about $112 billion) (Exhibit 4).[10]

[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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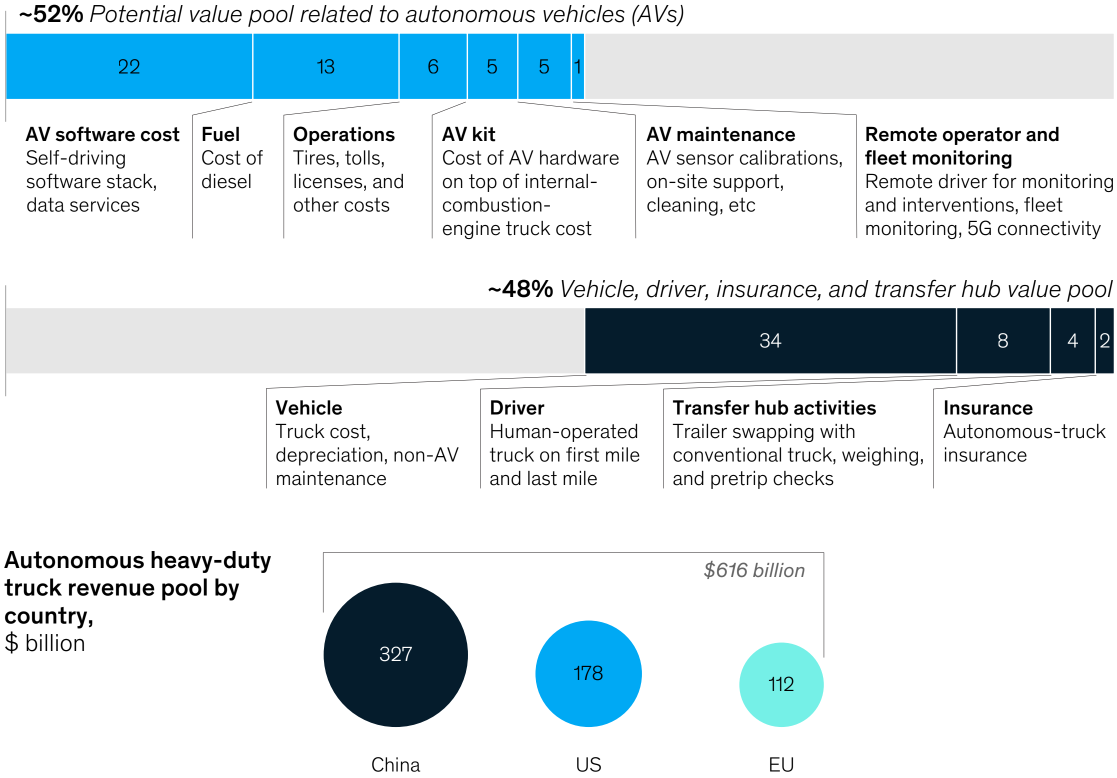
Exhibit 4

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



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 on a per-mile basis. OEMs or AV trucking companies are responsible for end-to-end uptime management of the truck, including maintenance and software updates. They earn revenue from truck sales or leasing (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 and e-commerce companies, still manage logistics. Despite higher up-front investments, DaaS lowers TCO because the human driver becomes obsolete. For the majority of truck customers, this could directly translate into higher margins.

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.

Ani Kelkar is a partner in McKinsey's Boston office, **Kersten Heineke** is a partner in the Frankfurt office, **Martin Kellner** is a partner in the Munich office, **Timo Möller** is a partner in the Cologne office, **Robert Brennecke** is a consultant in the Düsseldorf office, and **Saral Chauhan** is a consultant in the Detroit office.

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