Hitting the Road: New Energy HDT’s Bright Future

Brian Collie, Gang Xu, Chen Yu, Nicholas Ge, Haixu Wang

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Executive Summary

The global new energy heavy-duty truck (HDT) market has a promising future, particularly the battery electric HDT market. The battery electric HDT industry has prospered in both China and the US, and market players are diving in to offer a range of solutions. Battery electric HDTs will remain the major technology for new energy HDTs in the short to medium term. Meanwhile, the majority of HDTs are used for short-haul journeys in both China and the US. New energy HDTs, especially battery electric HDTs, are sufficient for most heavy-duty trucking use cases. As a battery electric HDT ecosystem of diverse policy support and accelerated infrastructure construction takes shape, the industry will predictably see growth at scale.

The new energy transformation from diesel HDTs represents both an opportunity and a challenge for the whole industry. We believe that, with the joint efforts of stakeholders across the industry, the mass production, commercialization, and high-level intelligence development of new energy HDTs will proceed at pace, driving both green economy and sustainable development.
1. New Energy HDTs Are the Future

With the increasingly pronounced effects of global warming and the depletion of conventional fossil fuels, industries across the board are exploring green growth and sustainable development. The commercial vehicle industry is no exception: companies are aggressively pursuing the research, development, and commercialization of new energy vehicles (NEVs), particularly for heavy-duty trucks (HDTs), a key fuel-guzzler and polluter. (See Exhibit 1.) As the total cost of ownership (TCO) of new energy HDTs drops, traditional OEMs and new forces are proactively entering the market, boosting its prospects for the future.

HDTs are characterized by high fuel consumption and heavy pollution due to their reliance on diesel fuel, high mileage, and a high fuel consumption rate. (See Exhibit 2.) In China, HDTs account for only about 3% of the national vehicle parc, but the carbon emissions of one diesel HDT are equivalent to those of nearly 100 passenger vehicles. Furthermore, diesel HDTs produce a large amount of nitrogen oxides (NOx) and particulate matter (PM), accounting for 85% and 65% of the total vehicle emissions respectively. According to the provisions of the United Nations Paris Agreement, the average global temperature increase should be limited to 1.5°C. The IPCC special report on global warming of 1.5°C further

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2. Innovation Center for Energy and Transportation (iCET).
4. United Nations Intergovernmental Panel on Climate Change (IPCC).
clarifies that, to achieve this goal, man-made carbon dioxide emissions should be reduced by 45% by 2030, and net zero emissions should be achieved by 2050. For its part, the Chinese government has enacted “dual carbon” goals and issued relevant policies, such as the China VI Emission Standard, to further restrict the emissions of internal combustion engine (ICE) vehicles, and it has continued to introduce zero-emission HDT incentives to reduce pollution. Therefore, the development of new energy HDTs will help bring about global net zero emissions and realize green, low-carbon, and sustainable development.

After years of unremitting efforts industry-wide, including battery cost reduction, battery energy density improvement, and infrastructure development, the TCO of new energy HDTs will continue to fall. In China, it is expected that the TCO of battery electric vehicles (BEVs) will reach parity with diesel HDTs by 2024–2025, while fuel cell electric vehicles (FCEVs) will not achieve parity until 2027–2028 and even then, will remain more costly than BEVs. In the longer term, after 2030, new energy HDTs will significantly outcompete traditional diesel HDTs on cost, both in China and the US. (See Exhibit 3.) However, TCO is not static; it is closely impacted by the global political and economic environment. For example, the higher diesel prices in 2022 resulted in an even better short-term TCO economy for new energy HDTs than that for diesel HDTs.

5 Carbon Peak by 2030 and Carbon Neutrality by 2060.
6 Incl. Limits and Measurement Methods for Emissions from Light-Duty Vehicles (CHINA VI), Limits and Measurement Methods for Emissions from Diesel Fueled Heavy-Duty Vehicles (CHINA VI).
Developing new energy HDTs has become the market consensus in both China and the US. Not only traditional OEMs have introduced new energy HDT products; cross-track players, such as passenger vehicle OEMs and autonomous driving technology companies, have also proactively entered the new energy HDT field. (See Exhibit 4.)

### Exhibit 3 | Total Cost of Ownership (TCO) Trends in China and the US

**Table:** TCO parity for battery electric and diesel HDTs in China and the US.

**Source:** BCG analysis.

**Note:** TCO is calculated based on the data of large fleets. Under the standard operation of large fleets, the average diesel cost per kilometer for HDTs in China is close to that in the US.

1. Assume the average annual mileage in both China and the US is 160,000 km.

### Exhibit 4 | New Energy HDT Players in China and the US

**Source:** Public information; BCG analysis.
In China, in contrast to the highly concentrated diesel HDT market, the new energy HDT market, especially the battery electric HDT market, is thriving and fragmented, and no dominant players have yet emerged. Several new force players plan to develop battery electric HDT platforms, whose competitiveness should not be underestimated.

In the US, not only established commercial vehicle manufacturers like Daimler, Paccar, and Volvo, but also new force players such as Nikola and Tesla, have launched battery electric HDT products. The diversification of the player landscape will further drive large-scale development of the new energy HDT industry.

The penetration of zero-emission HDTs in China is set for a rapid increase. In 2021, new energy HDT sales in China exceeded 10,000 units, although the penetration rate remained below 1%. By the end of 2022, new energy HDT sales reached over 25,000 units. BCG projects that 30% of the medium- and heavy-duty trucks sold in China by 2030 will be zero-emission trucks (battery electric and hydrogen fuel cell electric trucks, of which battery electric trucks will account for about 90%). (See Exhibit 5.)

**EXHIBIT 5 | China New Energy MHDT Penetration, 2020–2030**

- **Drivers**
  - **China VII Emission Standard** is likely to further restrict emissions and set standards for carbon emission
  - Government promotes zero-emission truck adoption by subsidizing infrastructure construction and granting favorable right-of-way
  - **OEMs** are proactively seeking opportunities in the zero-emission truck market, and are preparing for mass production in the near future

<table>
<thead>
<tr>
<th>Year</th>
<th>Penetration of zero-emission trucks</th>
<th>Zero-emission trucks (BEV and FCEV)</th>
<th>ICE trucks (diesel and natural gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>&lt;1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>~30%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: BCG analysis.*  
*Note: MHDT includes medium-duty trucks and heavy-duty trucks.*
2. Battery Electric HDTs Are Gaining Traction

Battery electric HDTs have recently gained traction, with a promising future ahead. Globally, several manufacturers announced SOPs for flagship battery electric HDTs as early as the second half of 2022, and scale-up is expected to follow. In China, battery electric HDTs already accounted for over 90% of the new energy HDTs sold in 2021 and 2022, while the proportion of fuel cell electric trucks remained very small.

We believe that battery electric HDTs will remain the major zero-emission technology for HDTs in the short to medium term, for the following reasons:

- **BEV technology for HDTs is currently more mature than FCEV technology.**
- **Falling costs and improved performance of lithium-ion batteries (LiBs) will accelerate the TCO parity for battery electric HDTs.**
- **The introduction of longer-range products, along with the deployment of battery swapping and fast charging, is expected to resolve the bottleneck of driving range and expand the use cases of battery electric HDTs.**
- **Most HDTs in both China and the US are used for short-haul journeys. Compared with China’s point-to-point delivery, drop-and-pull transportation is more common in the trucking industry in the US, meaning an even shorter average distance per trip. Therefore, the range of battery electric HDTs is sufficient for most use cases.**

1) **In the short to medium term, BEV technology for HDTs is more mature than FCEV technology.**

There are two mainstream zero-emission propulsion technologies for HDTs. **Battery electric vehicles (BEVs)** use rechargeable battery packs, with no secondary source of propulsion. **Fuel cell electric vehicles (FCEVs)** use a fuel cell that generates electricity using oxygen from the air and compressed hydrogen—in combination with a small battery, or a supercapacitor—to power the motor. (See Exhibit 6.) Hybrid vehicles are not considered zero-emission as they are more of a transitional solution still using ICEs, so this report will not discuss hybrid technology.

Battery electric HDTs and fuel cell electric HDTs have both advantages and limitations in terms of technical features and application readiness. **Fuel cell electric HDTs** theoretically deliver longer ranges and can sustain higher payloads. However, hydrogen fuel cell technology is not yet mature, and the current lifespan of fuel cell stacks cannot
cover the vehicle life cycle. The hydrogen supply chain—hydrogen production, transport, and refueling—is also in the initial stage, which raises the adoption barrier of FCEVs. **Battery electric HDTs**, by contrast, enjoy the benefits of a mature lithium-ion battery supply chain, with products of better safety, stability, and cyclicity performance. Although battery electric HDTs suffer from limited ranges and payloads, the deployment of battery swapping and fast charging can partially address these pain points, making the adoption of BEVs in trucking easier than for FCEVs. Hence, we expect **BEV technology to be the most adopted new energy technology for HDTs in the short to medium term**.

2) **The declining costs and improved performance of lithium-ion batteries will accelerate the development of battery electric HDTs.**

Driven by booming electric vehicle demand, battery shipments have grown, and lithium-ion battery prices have fallen by nearly 90% in the past decade. Although recently there has been a short-term rebound due to rising prices of lithium-ion battery raw materials, **falls in battery prices are set to continue in the longer term**—with potentially another two-thirds cost reduction by 2035. (See Exhibit 7.) The declining battery price will significantly improve the TCO for battery electric HDTs, which are likely to achieve TCO parity with diesel HDTs in the near future.

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7 BloombergNEF.
Cost reduction driven by scale-up and technology improvements: this logic also holds true for other key components of NEVs as much as for lithium-ion batteries. Falling costs are thus driving maturity across the whole electric vehicle and intelligent vehicle value chain. (See Exhibit 8.)
3) The range of battery electric HDTs already meets a significant proportion of use cases in China and the US.

The use cases of HDTs in China are not limited to inter-regional long-haul transportation; they are very diverse, and a significant proportion can be covered by the range of battery electric HDTs. According to the Research Institute of Highway, Ministry of Transport of China, the average daily mileage of freight vehicles in China for 2020 was 305 km. A BCG survey also found that the majority of heavy-duty semi-tractors in China are used for short-haul (under 200 km per trip) and medium-haul (200 km to 500 km per trip) journeys, while only a small proportion is used for long-haul transportation of beyond 500 km per trip. (See Exhibit 9.)

A similar pattern was observed in the US. A survey conducted by the US Department of Transportation in 2018 indicated that the largest portion (>50%) of cargo in trucking transportation was on short-haul (under 100 miles or around 160 km per trip) routes, followed by long-haul (beyond 250 miles or around 400 km per trip) and medium-haul (100 miles to 250 miles or around 160 km to 400 km per trip) routes. Another survey conducted by the US Department of Commerce, which calculated vehicle inventory

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and driving range by cargo weight, came to a similar conclusion that the majority of HDTs (payload capacity exceeding 11.8 tons) are used for short-haul (under 100 miles or around 160 km per trip) journeys, just like medium- and light-duty trucks. Furthermore, the average transportation distance per trip for HDTs in the US is shorter than that in China because drop-and-pull transportation is more common in the trucking industry in the US, compared with point-to-point delivery normally in China. Therefore, the range of battery electric HDTs is sufficient for most of the use cases in the US. (See Exhibit 10.)

Developments in lithium-ion battery technology are gradually resolving the challenge of driving range for battery electric HDTs. The range of currently available BEV truck models approaches 300 km on average, which is sufficient for short-haul use cases, especially the drayage for ports, mining areas, and other semi-enclosed environments. Several flagship battery electric HDTs with ranges of over 500 km are expected to address even medium- and long-haul transportation. They include the Nikola TRE BEV, which started delivery in 2022, and carries a 733 kWh battery pack with a range of up to 330 miles (around 530 km); the Tesla Semi also claims to offer choices of 300 miles (around 480 km) and 500 miles (around 800 km). In addition to longer-range products, the deployment of battery swapping and fast charging further lowers barriers to adoption for battery electric HDTs by expanding their feasible use cases. Battery electric HDTs will no longer be limited to usage in small-scale pilots, but will gradually become a viable and economical option in daily operations soon.

3. Two Technology Trends: Zero Emissions and High-level Intelligence

We envision two major trends in the future development of HDT technology: one is zero emissions, which achieves carbon neutrality through the adoption of new energy technology; the other is high-level intelligence, which boosts productivity through smart and autonomous solutions. Both trends together are pushing HDTs towards their ultimate form—autonomous, highly intelligent, and zero-emission vehicles. R&D efforts address each of these aspects, but the two also facilitate each other. (See Exhibit 11.)

**EXHIBIT 11 | The Development of HDT Technology**

1) **Zero emissions**

Due to the immature technology and limited volume, the currently available battery electric HDTs are mostly “retrofits” of diesel trucks. In the long run, however, developing purpose-built platforms for battery electric HDTs is necessary for performance optimization, which is a consensus of leading HDT players. (See Exhibit 12.)

Currently, most battery electric HDT products are “retrofits” of diesel trucks: with as slight change as possible to the existing diesel truck layout, an electric truck is built by replacing the ICE with an e-motor and adding one or multiple battery packs behind the cabin or by the sides of the vehicle frame. Given the lack of a mature supply chain and
the limited scale of battery electric HDTs, retrofitting makes sense for OEMs to accelerate BEV product launches at a reasonable cost. However, as a transitional solution, retrofitting stands in the way of more optimal product performance. For example, chassis space utilization and transmission efficiency are low; available cargo space is squeezed by the battery behind the cab; the range is impacted due to the limited space for the battery pack. These issues thus compromise the productivity of retrofitted electric HDTs, leading to poor economics under working conditions.

To address the wide-scale electrification of commercial vehicles, leading players are developing **purpose-built platforms for battery electric HDTs**, working on the e-drive layout, chassis construction, and cabin design in a systems-engineering approach to fully unlock the potential of battery electric HDTs. Below are the key aspects of innovation.

- **E-drive system**

  Electrified diesel models typically use a central e-drive, replacing the ICE with an e-motor, while retaining a traditional longitudinal drivetrain. This kind of central-direct drive solution is easier to implement, but it also has noticeable disadvantages, including heavy weight, large size, and low transmission efficiency. By contrast, the purpose-built battery electric platforms allow for deeper optimization of the e-drive system.

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**EXHIBIT 12 | A Comparison of ICE Platforms, Electric Retrofits, and Purpose-built Battery Electric HDT Platforms**

<table>
<thead>
<tr>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A conventional diesel truck</strong></td>
<td><strong>An electric retrofit of diesel trucks</strong></td>
<td><strong>A purpose-built battery electric HDT</strong></td>
</tr>
<tr>
<td>A flat-front cab over truck design with high drag coefficient</td>
<td>A slightly streamlined cabin shape with lower drag coefficient</td>
<td>The bullet-head cabin with a lower center of gravity and further reduced drag coefficient</td>
</tr>
<tr>
<td>Cargo space is squeezed by the battery behind the cab, and driving range is impacted due to the limited space to place the battery pack</td>
<td>Integrated e-axles or distributed e-drives are more compact and have higher transmission efficiency</td>
<td></td>
</tr>
</tbody>
</table>

Exhibit 12: A Comparison of ICE Platforms, Electric Retrofits, and Purpose-built Battery Electric HDT Platforms

Source: BCG analysis.
The e-drive system of commercial vehicles is evolving towards integrated and compact solutions, such as integrated e-axles and distributed e-drive systems. E-axles for battery electric HDTs have been launched by companies such as Dongfeng Dana, ZF, AVL, AxleTech. Distributed e-drive solutions (wheel-side motors and wheel-hub motors) are still in the early stage of development.

Currently, purpose-built battery electric HDTs tend to use e-axles, which integrate e-motor, gear reducer, and driveshaft all in one axle. Compared with the central e-drive, the e-axle provides more compact packaging and lower efficiency loss. For battery electric HDTs, an integrated e-drive system leaves more room for battery packs and reduces vehicle weight, boosting power performance and energy efficiency. (See Exhibit 13.)

Another significant trend in e-drive development is the application of high-voltage platforms. At present, electric vehicles mostly run on either 400V platforms (passenger vehicles) or 600V platforms (commercial vehicles), while the next generation of electric vehicles is shifting towards 800V to 1000V high-voltage architectures. Running at such high voltages makes fast charging possible: with DC fast-charge piles, an 800V electric vehicle can enjoy unmatched charging speeds. Battery electric HDTs usually carry a large-capacity battery pack, so fast charging is particularly critical to improve
their operational efficiency. In addition, the high-voltage platform also **improves the overall efficiency of the e-drive system**: in a high-voltage architecture, the currents are lower, thus reducing the power loss of the entire system. In this way, the driving range is extended with the same battery capacity, and the power performance can be enhanced.

The 800V platform was initially launched on Porsche Taycan in 2019 and then added to a handful of recent passenger vehicle models. Commercial vehicle OEMs and suppliers also have 800V products in the pipeline. For example, BorgWarner launched an 800V electric motor for hybrid and electric commercial vehicles in 2021 and is expected to kick off production in 2024. *(See Exhibit 14.)*

In addition to high-voltage platforms tailored for vehicles, high-power fast charging also requires the deployment of **extreme fast charging (XFC) piles** as the essential infrastructure.

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High-power XFC solutions that enable higher charging voltage (from 400V to 800V–1,000V) and peak power (from 120 kW to 480 kW) emerge with the development of high-voltage vehicle platforms. Pioneers in passenger vehicles, such as GAC Aion and XPeng, already launched 480 kW XFC piles, along with high-voltage vehicle models. For commercial vehicles, CharIN, a leading global association committed to developing and promoting standardized XFC solutions for commercial vehicles, unveiled a working prototype of the megawatt charging system (MCS) for heavy-duty vehicles in June 2022. XFC is expected to significantly improve charging efficiency by reducing the charging time to only a few minutes, on par with refueling.

Technological innovations are critical to XFC piles. On the one hand, to support the higher power outputs of XFC piles, a diversified portfolio of charger modules (for example, a combination of 20/30/40 kW, instead of a pure 20 kW solution) is necessary. DC charging piles typically consist of multiple charger modules that are connected. On the other hand, thermal management is essential for dealing with the massive heat during the fast-charging process, hence XFC piles shift to liquid cooling technology, instead of conventional air cooling, to ensure safety, reduce noise, and make maintenance easier. Liquid cooling technology is seen on Tesla’s V3 Superchargers (launched in 2019) and GAC Aion’s A480 Superchargers (debuted in 2021).

- **Chassis construction**

  To fit the central drive layout (also known as FR layout: front-engine, rear-wheel drive), diesel trucks are normally built on a “ladder frame” chassis consisting of two longitudinal beams and several cross beams. If battery electric HDTs were built on the same chassis design, it would be difficult to find adequate battery space. Consequently, retrofitted electric HDTs often place a large battery box on the frame behind the cab, which is an inefficient use of the chassis space and encroaches on the cargo space.

  The chassis construction of battery electric HDTs can also be further optimized by redesigning the e-drive system. For example, by getting rid of the longitudinal drivetrain and restructuring the frame structure, the battery pack(s) can be placed flat on the chassis. (See Exhibit 13.) This is an improvement on placing the battery pack behind the cab for several reasons:

  - By placing the battery flat, the vehicle can hold a larger pack, enabling a longer range and freeing up more space for cargo, ensuring crucial productivity for the HDT.
With a structural box-beam frame of the battery pack(s) placed inside, it makes the chassis structure stronger, which not only protects the battery box but also takes full advantage of the frame’s load-bearing capacity.

It lowers the center of gravity of the vehicle, reducing rollover risk and improving vehicle handling.

It makes a unified exterior design possible.

**Body/cabin design**

R&D improvements to purpose-built electric HDTs also include redesigning the vehicle body to optimize its aerodynamic performance. Without the legacy of the conventional cab-over style, purpose-built electric HDTs are able to further improve energy efficiency by adopting a cab shape with a low drag coefficient and utilizing lightweight materials for the vehicle body. (See Exhibits 15, 16, and 17.)

For example, at present, the drag coefficient of mass-produced cab-over trucks in China is typically 0.55 to 0.65. With a bullet head and one centered seat, a global leading OEM claims to have reduced the drag coefficient to 0.36.
**EXHIBIT 16 | Cabin Design—Exterior (Front View)**

1.0

- 1 driver seat + 1 passenger seat
- Equipped with a sleeper for the two drivers taking turns to rest
- Crowded cockpit

2.0

- 1 driver seat + 1 passenger seat
- Equipped with a sleeper for the two drivers taking turns to rest
- Crowded cockpit

3.0

- 1 central driver seat
- Equipped with a minibar and a folding sleeper
- Spacious cockpit

Source: Literature research; BCG analysis.

**EXHIBIT 17 | Cabin Design—Interior**

1.0

- 1 driver seat + 1 passenger seat
- Equipped with a sleeper for the two drivers taking turns to rest
- Crowded cockpit

2.0

- 1 driver seat + 1 passenger seat
- Equipped with a sleeper for the two drivers taking turns to rest
- Crowded cockpit

3.0

- 1 central driver seat
- Equipped with a minibar and a folding sleeper
- Spacious cockpit

Source: Literature research; BCG analysis.
2) High-level intelligence

Autonomous driving and intelligent vehicle technologies will significantly boost the productivity of freight transportation by achieving safe, reliable, and efficient trucking operations without human drivers. Key technology levers include **X-by-wire**, whose new maturity will pave the way for highly autonomous applications in heavy commercial vehicles; and **centralized E/E architecture**, which makes the “software-defined vehicle” possible by enabling continuous upgrades throughout the vehicle lifecycle.

- **Autonomous driving (AD)**

The road freight industry in China has long faced challenges such as truck driver shortages, high fuel costs, and frequent accidents. This makes autonomous trucking a revolutionary technology that once widely applied, will not only deliver tangible cost savings but also improve the overall safety of road traffic.

**Fuel and labor costs currently account for more than half of the TCO of diesel trucks in China;** the remainder comprises insurance and taxes, vehicle purchase cost, toll and administration, depreciation, repair and maintenance, etc. Therefore, from the cost perspective, the biggest saving of autonomous trucking is undoubtedly **on driver labor costs**—this can only be achieved by **L4 driverless operation**, as L2+/L3 systems still require a driver. (See Exhibit 18.) The second greatest cost reduction

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**EXHIBIT 18 | The Levels of Autonomous Driving**

<table>
<thead>
<tr>
<th></th>
<th>Traditional driving</th>
<th>Autonomous driving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>Manual</td>
<td>Autonomous driving</td>
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<tr>
<td>Description</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Executing</td>
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<td>N/A</td>
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<tr>
<td>Driving</td>
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<tr>
<td>System</td>
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<td>N/A</td>
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<tr>
<td>Supervising</td>
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<td>N/A</td>
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<tr>
<td>Driving</td>
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<tr>
<td>Environment</td>
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<td>N/A</td>
</tr>
<tr>
<td>Usage conditions</td>
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<td>N/A</td>
</tr>
<tr>
<td>Example features</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Source: US National Highway Traffic Safety Administration (NHTSA); Society of Automotive Engineers (SAE); BCG analysis.
lever is fuel efficiency, delivered by the AD system which optimizes the speed, route, and driving behaviors. Furthermore, a mature AD system will in theory reduce the accident rate, improve safety, and save insurance costs.

Leading autonomous trucking players had already kicked off mass production and operation of L2+ heavy-duty trucks in 2021, while L4 trucks are still in the testing phase, and mass production of purpose-built L4 trucks (for AD) is expected to start around 2025.

- X-by-wire technology

X-by-wire technology is a prerequisite for high-level autonomous driving at the hardware level. X-by-wire refers to the use of electronic signals for the direct control of actuators (including drive, brake, and steering systems) which was traditionally achieved by mechanical, hydraulic or pneumatic linkages. (See Exhibit 19.)

**EXHIBIT 19 | The Fundamentals of X-by-wire Systems**

- Sensing
  - HMI
  - External environment
  - Vehicle status

- Decision
  - Planned motions + Instructions to controllers

- Actuation
  - DbW
  - BbW
  - SbW
  - ...

**The advantages of X-by-wire systems**
- Improved control accuracy and linearity
- Reduced delay between action and actuation
- Reliability ensured by redundancy design

**X-by-wire system is essential for autonomous trucking**

Source: Literature research; BCG analysis.
Autonomous driving relies on the efficient cooperation of the sensing, decision, and actuation layers for vehicle handling. It is essential for autonomous vehicles to have a high-precision, fast-response, safe, and stable actuation system, which requires X-by-wire technology. It is a challenge for traditional actuation systems to deliver precise control of AD (especially since HDTs are more difficult to control than passenger vehicles), and they are not well-suited to redundancy design, and are unable to decouple software from hardware. Therefore, the X-by-wire system is a necessary infrastructure for the implementation of autonomous trucking.

The key critical elements of X-by-wire chassis are drive-by-wire (DbW), brake-by-wire (BbW), and steer-by-wire (SbW). DbW is mature and widely applied, BbW is entering mass production, but SbW is not yet mature. In particular, X-by-wire products for commercial vehicles are not as mature as those for passenger vehicles, hence the current autonomous trucks are mostly adding by-wire control functions to traditional actuators—without ready-made mature and reliable X-by-wire solutions for trucks, it is necessary to adopt retrofitting or partially by-wire products. In this sense, truck OEMs, Tier 1 suppliers, and AD companies need to jointly develop and commercialize the X-by-wire chassis for HDTs.

Battery electric truck platforms are more compatible with higher-quality X-by-wire systems than diesel truck platforms, making the transition to autonomous driving seamless by saving a lot of retrofitting efforts. This is because the major actuators of battery electric platforms have already adopted electronic control to process instructions, which naturally reduces latency and improves linearity. Meanwhile, autonomous driving systems of L3 and above require redundancy on safety-critical functions. Developing battery electric truck platforms from scratch also provides an opportunity for truck makers to configure redundant designs on control systems with more stringent reliability, to better address the demand for autonomous trucks.

The Development of Brake-by-wire (BbW) Systems for Commercial Vehicles

Due to the heavy loads and harsh working conditions involved, HDTs typically use air-brake systems. The existing brake-by-wire solution, called electronic braking system (EBS), is based on the traditional pneumatic system, with an added electronic control function. EBS is not a completely brake-by-wire system, because although it is electronically controlled in the first half of the braking process (from the brake pedal to ECU), the second half (through the air pipes to the brake chambers) is still an air brake that relies on pneumatic links with latency in the boosting process.

The next generation of brake-by-wire for commercial vehicles is electro-mechanical brake (EMB), that is, where the system entirely eliminates the air pipes, the master cylinder, and vacuum boosters; and instead, the e-motor directly drives the brake caliper. Therefore, EMB is a completely brake-by-wire system. It overcomes the inherent shortcomings of commercial vehicles using compressed air as the control medium for braking, significantly improving the response speed and shortening the braking distance. (See Exhibit 20.)

EXHIBIT 20 | The Development of Brake-by-wire (BbW) Systems for Commercial Vehicles

Source: Gasgoo; Literature research; BCG analysis.

1 Electronic braking system.
2 Electro-mechanical brake.

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2 WANG Huaping, Introduction of EMB and brake-by-wire for Commercial Vehicles, Haldex VIE (Shanghai) EMB System Co.
The Development of Steer-by-wire (SbW) Systems for Commercial Vehicles

HDTs typically leverage hydraulic-powered steering systems due to their heavy loads; currently, penetration of electronic-powered steering in HDTs is low. Conventional **hydraulic power steering (HPS)** systems work by using a hydraulic pump driven by the vehicle’s engine to amplify the steering power. **Electro-hydraulic power steering (EHPS)** systems use an electric motor instead of the engine. **Electric power steering (EPS)** further eliminates the hydraulic system, with the electric motor directly powering the mechanical steering gears.

The mainstream steering solution for autonomous trucking at present is EHPS-based systems with redundant electronic control added. As high-output EPS products gradually become available, EPS is expected to be widely applied as the next-generation steer-by-wire solution for self-driving commercial vehicles. (See Exhibit 21.)

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**EXHIBIT 21 | The Development of Steer-by-wire (SbW) Systems for Commercial Vehicles**

<table>
<thead>
<tr>
<th>HPS</th>
<th>EHPS</th>
<th>EPS</th>
</tr>
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<tbody>
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<td><strong>1.0</strong></td>
<td><strong>2.0</strong></td>
<td><strong>3.0</strong></td>
</tr>
<tr>
<td>Hydraulic power steering</td>
<td>Electro-hydraulic power steering</td>
<td>Electric power steering</td>
</tr>
<tr>
<td>Engine</td>
<td>Motor</td>
<td>ECU</td>
</tr>
<tr>
<td>Pump</td>
<td>Sensor</td>
<td>Sensor</td>
</tr>
<tr>
<td>Reduction gear, etc.</td>
<td>Reduction gear, etc.</td>
<td>Reduction gear, etc.</td>
</tr>
<tr>
<td>Steering wheel</td>
<td>Steering wheel</td>
<td>Steering wheel</td>
</tr>
<tr>
<td>Steering column</td>
<td>Steering column</td>
<td>Steering column</td>
</tr>
</tbody>
</table>

**Source:** Literature research; BCG analysis.

1. Also include rotary control valve and integral power cylinder.
2. Vehicle speed sensor.
3. Torque sensor.
4. Steering angle sensor and torque sensor.

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• **Centralized E/E architecture**

In the era of software-defined vehicles, **E/E architecture**, as the critical infrastructure of intelligent connectivity and autonomous driving, is becoming more centralized. (See Exhibit 22.)

A conventional distributed E/E architecture involves many **electronic control units (ECUs)** in the vehicle. They are connected by thousands of meters of wire harnesses, each of them supporting a single function. They are usually “black boxes” prefabricated by suppliers, and OEMs can only make function calls through an interface. To add new functions to the vehicle, additional ECUs are needed.

The development of vehicle intelligence inevitably means demand for more sensors, more complex algorithms, faster communication, and more frequent function updates. Merely increasing the number of ECUs is unsustainable, and neither delivers the computing power required by AD of L4 and above, nor achieves stable and reliable function upgrades through over-the-air (OTA) updates. This is because, under a distributed E/E architecture, each ECU’s computing power is independent and cannot be redeployed elsewhere. To build higher computing power, many ECUs need to match their computing power according to the peak demand, resulting in high costs. In addition, there are different versions of software in each ECU, the system architecture is scattered, and OEMs have varying levels of access to each of the ECUs,
which makes OTA upgrades nearly impossible. At the same time, the additional wire harness needed for excessive ECUs could overweight the vehicle.

**Domain control units (DCUs) can address the aforementioned pain points.** Domain centralization refers to the integration of the vehicle’s scattered functions into several functional domains, such as AD/ADAS, in-vehicle infotainment (IVI), chassis, powertrain, and body. The architecture deploys more powerful DCU SoCs to centrally process a category of functions originally separately handled by each ECU. Such a centralized architecture has several advantages:

- **Improved overall performance and reliability of the systems.** By leveraging the powerful SoCs of DCUs, intelligent functions such as autonomous driving and smart cockpit can be realized. Furthermore, OTA upgrades are more reliable after software and hardware are decoupled.

- **Reduced HW/SW complexity.** Integration facilitates a lightweight and optimized layout design for vehicles, by minimizing the number of ECUs, shortening the length of CAN bus cables, and reducing the weight of electronic systems.

**Case study:**

According to a study conducted by a Chinese heavy-duty truck OEM, commercial vehicles at present carry an average of 25 ECUs with bus cables of 6 km in length, totaling over 70 kg in weight, and taking up a lot of space. With a domain-centralized E/E architecture of DCUs, the average number of ECUs per vehicle can be reduced to 16 with bus cables 3.7 km long, and a total weight of less than 44 kg, nearly 40% more streamlined than traditional E/E architecture.

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The intelligent development of HDTs is currently evolving from distributed to domain-centralized E/E architecture. In the short term, the adoption of DCUs should deliver autonomous driving and intelligent functions for commercial vehicles. In the longer term, depending on the maturity of the value chain, the domain-centralized E/E architecture may gradually iterate towards vehicle centralization.
4. The Growing Battery Electric HDT Ecosystem

The mass commercialization of battery electric HDTs requires not only the involvement of OEMs but also the support of various ecosystem partners, including upstream suppliers (battery manufacturers in particular), charging/battery-swapping builders and operators, downstream HDT fleet customers, aftermarket service providers. With the introduction and implementation of a series of supporting policies, the ecosystem of the battery electric HDT industry is becoming established, and the future is bright.

Currently, the penetration rate of battery electric HDTs in China is still less than 1%. This may be due to factors across the industry chain, such as range anxiety, high purchase cost, and inadequate infrastructure. Similarly, the development of new energy passenger vehicles has also undergone a relatively long period of market education, policy subsidies and purchase cost decline, to achieve a nearly 500-fold increase in sales over the past decade, from less than 10,000 units in 2012 to over 5 million units sold in 2022\(^\text{16}\), thanks to the improving ecosystem. (See Exhibit 23.)

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\(\text{Exhibit 23 | New Energy Passenger Vehicle Sales Volume and Penetration Rate in China}\)

![Exhibit 23](image)

Source: China Passenger Car Association (CPCA); China Association of Automobile Manufacturers (CAAM); BCG analysis.

Note: New energy vehicles (NEVs) refers to BEVs and PHEVs.

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\(\text{16 China Association of Automobile Manufacturers (CAAM).}\)
To realize the large-scale commercialization of battery electric HDTs, industries across the chain must work together to build the ecosystem. (See Exhibit 24.)

- Firstly, the upstream industry includes all kinds of mineral material providers and Tier 1 suppliers (such as suppliers of e-powertrains and other spare parts). Among these, battery manufacturers need to further cut battery prices while improving energy density, life span and safety, which are critical to improve downstream clients’ purchase willingness.

- Secondly, energy suppliers, charging stations, and battery swap stations also play a key role across the battery electric HDT ecosystem. Both charging and battery-swapping models are designed to minimize range anxiety in the daily operation of battery electric HDTs. With improvements to grid infrastructure, fiscal support, technical standards, etc., the construction of energy infrastructures will continue at pace, boosting the confidence of HDT OEMs and end customers.

- Meanwhile, compared to traditional diesel HDTs, the purchase cost of battery electric HDTs is still relatively high. Therefore, in addition to vehicle sales to fleet customers, diversified services such as battery leasing/recycling, financial services, second-hand truck trading, and aftermarket services are also key pillars of the business model of battery electric HDTs. The comprehensive offerings throughout the whole vehicle lifecycle could also accelerate the commercialization of the battery electric HDTs.
The Chinese government issued a number of policies covering a range of aspects to encourage the development of the battery electric HDT industry, such as purchase subsidies and flexible right-of-way management, such as applying flexible time frames and exemptions from road section restrictions for new energy HDTs, to promote them as a green alternative to diesel trucks. The US government has also introduced a raft of policies to support the development of battery electric HDTs. The federal, state, and local governments have provided multi-level purchase subsidies. Meanwhile, by introducing several supporting policies including electricity charge reduction and improved driver access to reduce the use cost of battery electric trucks, state governments have further promoted the development of a clean-energy economy.

In China, to encourage the construction of charging stations and battery swap stations, the government has introduced a number of guidelines. As of 2022, only around 100 battery swap stations were built nationwide, with limited coverage and density, indicating enormous potential for future growth. According to the latest regulations issued by the Ministry of Industry and Information Technology (MIIT) at the end of 2021, 11 cities were selected to be NEV battery-swapping pilots, with three of those cities carrying out HDT-specific pilots. It is estimated that these pilots will see over 100,000 battery-swapping vehicles hit the roads and over 1,000 battery swap stations established.

With the favorable environment, the relevant stakeholders have responded positively to the construction of battery swap stations, including green power companies, oil companies, battery swap station operators, OEMs, and battery manufacturers. Leading energy companies such as State Power Investment, GCL Energy, and Sinopec have published plans for the construction of battery swap stations through 2025. Sany Heavy Truck, an HDT OEM, established its own battery-swapping business and introduced battery swap stations that accommodated Sany HDT products at the end of 2021. In the future, all parties will work on standardizing the process of the battery-swapping model and accelerate its adoption nationwide.

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17 China Construction Machine Association (CCMA).
About the Authors

Brian Collie is a managing director and senior partner at Boston Consulting Group (BCG). He is the global lead for the automotive and mobility sector. He is also a core member of the Industrial Goods, Operations and Global Advantage practices.

Gang Xu is a managing director and senior partner at BCG and leader of BCG’s Industrial Goods practice in Greater China.

Chen Yu is a managing director and partner at BCG and leader of BCG’s Technology, Media and Telecommunications practice in Greater China.

Nicholas Ge is a managing director and partner at BCG. He leads the machinery and equipment sector in Greater China.

Haixu Wang is a managing director and partner at BCG. He is a core member of the leadership of Technology, Media and Telecommunications practice in Greater China.
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