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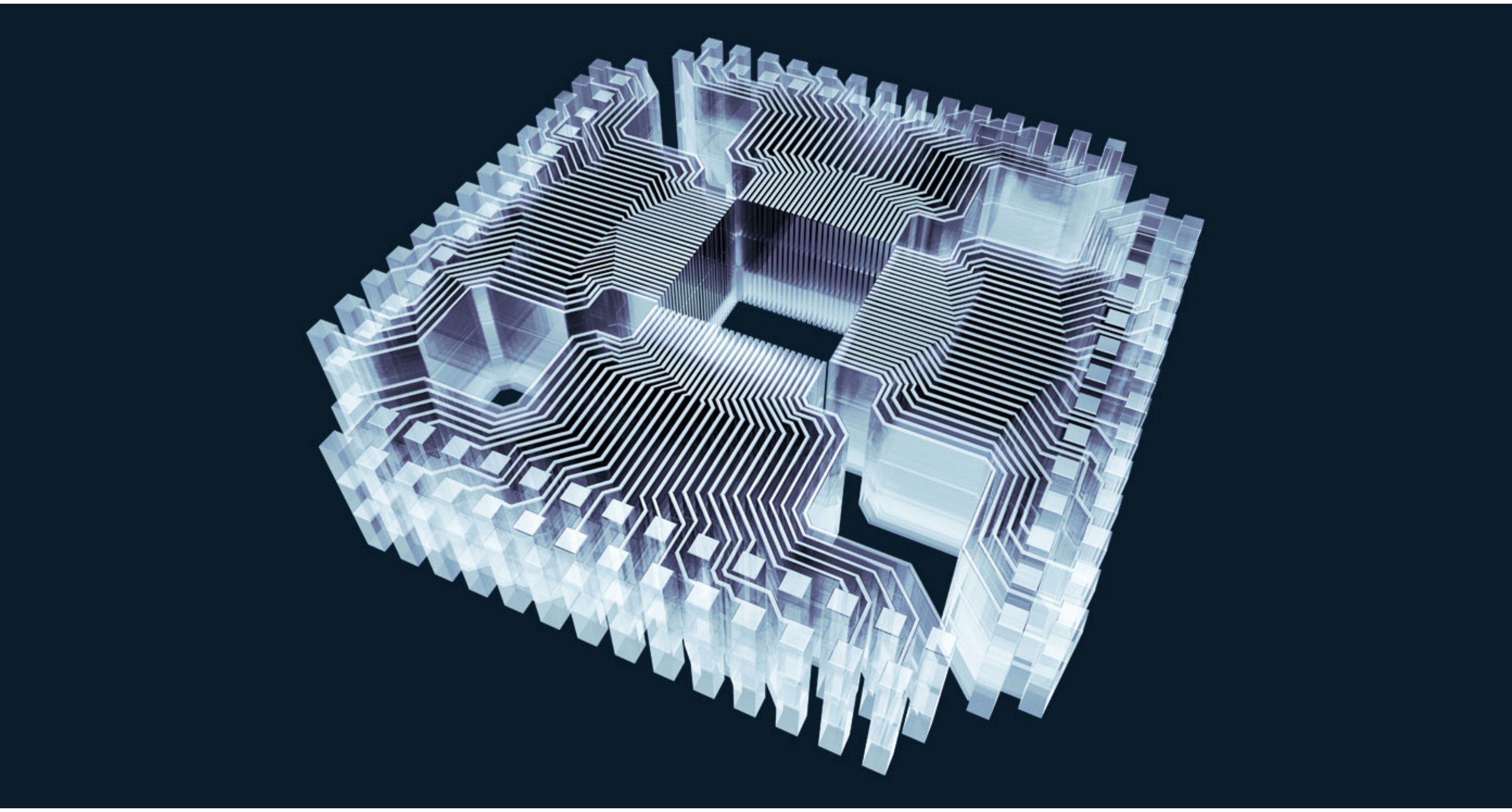
Will quantum computing drive the automotive future?

As quantum computing comes closer to reality, automotive players are exploring its potential.

by Ondrej Burkacky, Niko Mohr, and Lorenzo Pautasso



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Buzz and hype aside, something is going on in quantum computing (QC) that is hard to miss, and the technology will have real implications for the automotive industry. Much of the excitement relates to recent scientific leaps in the field as well as the development of the first industrial use cases, including those in the automotive and transportation sectors.

Recent headlines about QC reflect the excitement. IBM drew attention across the tech world when it announced the creation of Q System One, a quantum computer confined to a nine-foot cube, in 2018. In another big advance, D-Wave Technologies announced a QC chip with 5,000 "qubits," more than doubling its own previous 2,000-qubit record (see sidebar "What's different about quantum computing?").

The automotive industry has been following these developments, since QC provides computational improvements that could boost capabilities across the value chain. Several OEMs and tier-one suppliers have already begun investigating QC's ability to benefit the industry and resolve some existing issues, including those related to route optimization, fuel-cell optimization, and material durability. Several are now showcasing the first pilot use cases. Volkswagen, for example, has partnered with D-Wave to demonstrate a traffic-management system to optimize the individual travel routes of nine public-transit buses during the 2019 Web Summit in Lisbon, Portugal. Bosch, a German tier-one supplier, has acquired a stake in Zapata Computing, contributing to a $21 million Series A investment in the Cambridge, Massachusetts-based quantum start-up.

Although QC has great potential in the automotive sector and could translate into billions of dollars in value, OEMs and other stakeholders face some obstacles. The novelty of this technology combined with the relatively small market that has emerged thus far have prevented many automotive players from developing a clear QC strategy. To assist them, we reviewed QC's maturity and its potential in the automotive sector. We also examined opportunities for automotive stakeholders and potential next steps.

Gauging quantum-computing maturity

QC is undoubtedly on its way, but adoption at scale will not occur until five to ten years from now. Industry players now view QC in terms of four horizons with distinct milestones in each:

— Achievement of quantum supremacy. We likely reached this point in 2019.[1]

— Demonstration of the first quantum advantage. This step will involve developing practical use cases that will probably perform simulations of quantum phenomena. The first pilots on

What's different about quantum-computing applications?

Instead of using traditional bits as information-processing units, QC depends on quantum bits or "qubits." Players can physically generate qubits many ways, such as by trapping supercooled calcium ions in a magnetic field and creating interlinked superconducting capacitor circuits. Possible effects observed on a quantum level include superposition (how waves either add to each other or cancel out, as in noise-canceling headphones) and quantum entanglement (where particles remain connected such that an action on one will affect the other, even at great distances).

Shor's algorithm shows how much QC can improve processing time. Designed to run on quantum computers to find the prime factors of a given integer, it is almost exponentially faster than the best conventional factoring algorithm.

[1] A large tech company claimed that it achieved quantum supremacy in 2019. Some other companies have contested this claim.

quantum advantage, such as Volkswagen’s traffic optimization, are emerging today. Complex problem solving that requires many qubits working together will become feasible in 2035 or later.

— Attainment of broad quantum advantage. This is the point when it will become commercially viable to invest in programming quantum-computer software to tackle specific problems. Some predict this milestone will occur around 2030.

— Creating the quantum Turing machine. The final step involves building a full, universal quantum computer with quantum memory and random-access memory. The Turing machine will run on as many qubits as desired and can perform any algorithms. It should be viable in one to two decades.

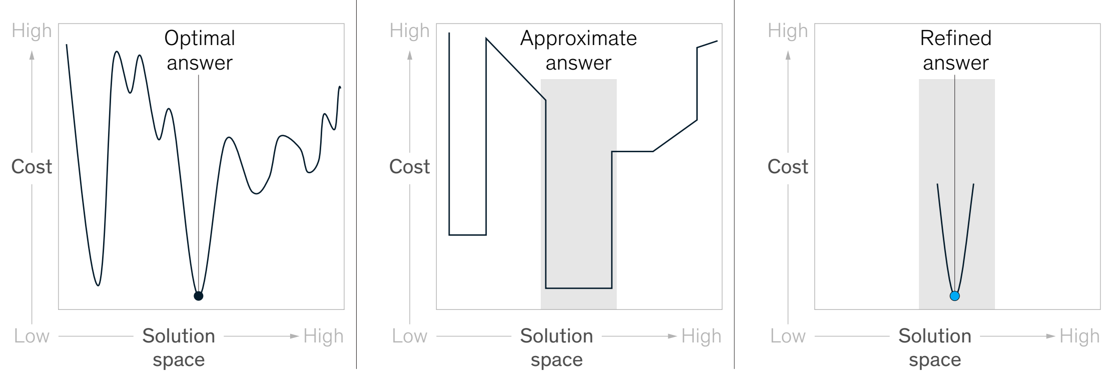
Even over the long term, QC will not likely replace existing high-performance computing (HPC), nor will the first attempts at value creation rely on at-scale QC devices that solve full problems. Instead, we believe that successful QC use cases will rely heavily on hybrid schemes over the next decade (Exhibit 1). First, a small QC-based subroutine will quickly generate a rough answer for an optimization problem. A conventional HPC will refine this answer with a narrower set of variables. In this way, programmers can employ early-stage QCs to run HPCs more efficiently.

Exhibit 1

In hybrid schemes, high-performance computing is used for the bulk of work, while quantum computing is used to analyze a subset of data.

How hybrid schemes work

1. **Transfer into a computational problem;** Example: find best (lowest cost) option among billions of possible combinations
2. **Do first iteration with quantum computer to get an approximate answer;** Example: quantum-computing (QC) step takes 1% of overall computing time and accounts for 3% of overall cost; remainder is for high-performance computing (HPC)
3. **Fast refinement with super-computer;** Example: QC step accounts for 99% of overall computing time and 97% of cost; remainder is for HPC



1. Practically unsolvable with conventional HPC; to find right answer with certainty would require calculating cost for all combinations
2. Fast but provides only rough assessment of complete solution space
3. Solvable sometime in next few years[1] using smart hybrid approach that assesses subset of solution space

[1]Depending on problem size; at earliest, 2022.
Source: McKinsey analysis

Automotive quantum-computing applications: Peeking under the hood

Currently, one-tenth of all potential QC use cases under exploration could benefit the automotive industry. In fact, automotive will be one of the primary value pools for QC, with a high impact noticeable by about 2025. We also expect a significant economic impact of related technologies for the automotive industry, estimated at $2 billion to $3 billion, by 2030. Most of the early value added will come from solving complex optimization problems, including processing vast amounts of data to accelerate learning in autonomous-vehicle-navigation algorithms. In later years, QC has the potential to have a positive effect on many areas in the automotive industry, such as vehicle routing and route optimization, material and process research, and the security of connected driving. Moreover, QC can also provide a boost to automotive players transitioning into the electric-vehicle (EV) era by notably accelerating research and development of novel technologies (see sidebar "How quantum-computing applications can accelerate the EV transition").

Near-term opportunities for QC—those from 2020 through 2025—will most likely surface in product development and R&D. Relevant use cases will primarily relate to solving simple optimization problems or involve parallel data processing for simple quantum artificial-intelligence/machine-learning (AI/ML) algorithms. These quantum-computing applications will be executed as part of a hybrid solution, where bits of a larger problem, processed by an HPC, are outsourced to a quantum computer and results are fed back into the HPC flow. Possible optimization use cases include the combinatorial optimization of multichannel logistics, highly local traffic-flow optimization, and improvements in vehicle routing. Quantum AI/ML might involve the time-efficient training of autonomous-driving algorithms due to an increase in the parallel processing of large amounts of data.

Midterm plays, from 2025 through 2030, will probably center on the following:

— *Quantum simulations.* Focus areas will include the simulation of complex partial differential problems, such as those dictating heat and mass transfer, fluid dynamics, and compressible flows. Simulating material properties on the atomic level will also become relevant, for example to improve the selection and development of battery and fuel-cell materials.

How quantum-computing applications can accelerate the EV transition

The ascent of electric vehicles (EVs) entails new opportunities and challenges for all players across the automotive value chain. Suppliers whose core competencies are not central to EVs, such as transmission or fuel-tank and tubing manufacturers, can leverage QC to gain a competitive edge in producing goods outside of their traditional playing field. For example, companies that traditionally produced fuel tanks and tubing can apply their knowledge of liquid storage and transportation systems to the production of cooling circuits for EV batteries. The required innovation in tubing materials, as well as the potential development of novel cooling liquids and tube-routing strategies, could be achieved through a hybrid of HPC cluster and a quantum computer. This hybrid could help efficiently solve both quantum simulation and optimization problems.

Other key players across the EV value chain that can leverage QC to advance research and development include battery and fuel-cell manufacturers, which could leverage quantum simulations in material- and chemical-process research. Likewise, software manufacturers, could improve predictive maintenance and autonomous-driving algorithms through quantum AI/ML.

The novelty of quantum computing combined with the relatively small market that has emerged have prevented many automotive players from developing a clear QC strategy.

— *More complex optimization problems.* These will encompass high degrees of freedom. For instance, they may minimize the possibility of supply-chain defaults, optimize citywide traffic flow, or solve large-scale multimodal fleet-routing problems.

— *Complex quantum AI/ML.* These applications will be able to process even larger amounts of data. For example, they might lead to novel control processes by identifying new variable correlations, enhancing pattern recognition, and advancing classification beyond the capabilities of the current HPC cluster.

Over the long-term, from 2030 onward, quantum-computing applications will build on at-scale access to universal quantum computers. Prime factorization algorithms to break common encryption keys will therefore be universally available. The focus will likely move toward digital security and risk mitigation as players try to prevent the quantum hacking of communications in autonomous vehicles, on-board electronics, and the Industrial Internet of Things. The cloud-hosted navigation systems of shared-mobility fleets will improve their coverage algorithms through regular training enabled by QC.

Opportunities for quantum-computing applications across the automotive value chain

Stakeholders across the automotive value chain will be able to leverage QC, mostly as part of a hybrid solution with HPC clusters, to solve problems that are specific to their role and position in the industry's value chain (Exhibit 2). Below are a few examples.

'Tier n' suppliers

Companies can optimize their supply routes involving several modes of transport using algorithms developed through QC. Other applications include the development of new technologies, including those for improving energy storage and generative design. QC could also help suppliers improve or refine the kinetic properties of materials, such as lightweight structures and adhesives, or develop cooling systems. For instance, QC could help companies simulate chemical processes and fluid dynamics, allowing them to obtain important insights.

Warehousing, distribution, and supply-chain management

QC can improve logistics across the value chain. For instance, it can optimize the routing of warehouse robots or increase the accuracy of demand forecasting to tier-n suppliers by simulating complex economic scenarios.

OEMs

Automakers could use QC during vehicle design to produce various improvements, including those related to minimizing drag and improving fuel efficiency. They could also use QC to perform advanced simulations in areas such as vehicle crash behavior and cabin soundproofing, or to "train" the

Exhibit 2

Quantum computing may enhance key steps across the automotive value chain.

"Tier n" suppliers
With quantum-computing (QC) support, suppliers can develop new technologies, such as battery materials and cooling systems; supply routes can be optimized, including those that involve multiple forms of transport

Warehousing, distribution, and supply-chain management
QC can help improve the accuracy of demand forecasting and warehouse logistics across the value chain

OEMs
OEMs may use QC to optimize their vehicle designs, enhance autonomous-driving software, and improve safety (eg, through simulations of vehicle crash behavior)

Dealerships and repair shops
Together with OEMs, dealers can enhance predictive-maintenance software through QC-supported training of machine-learning algorithms

Service providers
Shared-mobility providers can use QC for optimal vehicle routing to improve fleet efficiency and availability, or to predict geographical demand by simulating complex economic scenarios

algorithms used in the development of autonomous-driving software. Given QC's potential to reduce computing times from several weeks to a few seconds, OEMs could potentially ensure car-to-car communications in almost real time.

Dealerships and repair shops
OEM dealers can employ QC to support the training of machine-learning algorithms that will enhance predictive-maintenance software.

Service providers
Shared-mobility players can use QC to optimize vehicle routing, thereby improving fleet efficiency and availability. Another critical use involves helping mobility providers simulate complex economic scenarios that allow them to predict how demand will vary by geography.

Assessing the QC market

We estimate the overall market value of QC services at $32 billion to $52 billion in 2035. Through that year, about 10 percent of this value will come from spending by advanced-industry players, including automotive companies, that want to capture benefits from QC.

The value chain for quantum technology is in flux, and it is still unclear which companies will emerge as the top players at each step of the QC value chain. There are now about 100 companies in the space. Some of these companies, including D-Wave, IBM, Microsoft, and Rigetti Computing, build QC hardware. Around 80 percent of companies are start-ups that aim to bridge the gap in the value chain between hardware manufacturers and end users by translating conventional problems into a quantum logic and by building hybrid architectures that combine HPC with QC steps.

Many stakeholders will shape the QC market, including hardware and software players and their enablers. QC-software users will also determine how the industry evolves.

Hardware. One-third of QC companies focus on hardware development. Players include global technology giants and start-ups, mainly based in the United States. It is unclear exactly how the industry will configure hardware for quantum computers over the next 15 years, because players are currently developing several competing approaches, and these will evolve over time. Many hardware companies currently strive to deliver QC as a service via the cloud, making it unlikely that users will have to set up their own hardware. Automotive companies will also have to decide how to access QC services in the short term, with on-demand cloud capacity being the least expensive and most flexible option.

Software. Roughly half of the participants in the QC value chain develop software. In contrast to hardware suppliers, start-ups make up the bulk of these players, with most in Europe and North America. Large hardware players, such as D-Wave and IBM, also develop QC software. Some programs are used for automotive use cases, such as process-design and hardware-design optimization. Such solutions are likely to be used at scale within the next five to ten years. Small players, such as the German start-up Avanetix, also focus on developing software solutions for process optimization. Some, for example, are designed to optimize the supply chain.

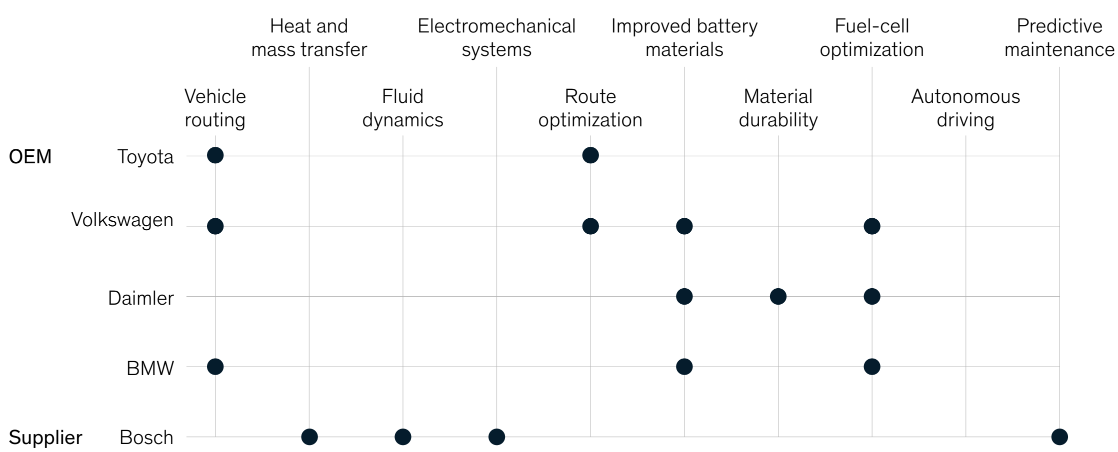
Enablers. One-fifth of companies in the QC value chain provide enabling solutions. Their offerings include existing components, such as cooling units, processing tools for making qubits, and the materials that compose qubits. This area could become a potential playing field for some upstream automotive suppliers, including tier-two and tier-three vendors, which produce control units and thermal solutions that are potentially transferrable to quantum computers. Automotive suppliers will not immediately profit from large-scale-production opportunities, since QC is still in its infancy, but they will over the long term. We expect enablers to become more relevant as the QC industry matures, gains scale, and one hardware approach begins to dominate.

QC software users. Many automotive players have publicly announced that they are actively pursuing QC research, sometimes partnering with companies in the upstream part of the QC value chain. Some announcements have come from BMW, Daimler, and Volkswagen. They all investigate quantum simulation for material sciences, aiming to improve the efficiency, safety, and durability of batteries and fuel cells. Bosch focuses its research on solving partial differential problems through QC. While quantum-computing applications based on this research may still be five to ten years down the road, OEMs have already demonstrated successful QC pilots in some areas, such as vehicle routing (Exhibit 3).

Exhibit 3

Quantum computing within the automotive sector is currently limited to select applications, such as traffic-flow optimization and routing.

Quantum-computing applications in the automotive sector (selected companies)



Source: Public announcements; McKinsey research

Moving forward with quantum-computing applications in automotive

As with every new technology, many uncertainties persist about QC, particularly when it comes to competing hardware technologies. QC teams may initially receive mixed responses regarding their advances, and some may find it difficult to move beyond negative reactions. With the QC-hardware industry making rapid progress, it seems unlikely that even the world's largest automakers will have their own physical QC systems, at least initially. Instead, they will probably develop their own algorithms and run them on the cloud-based QC systems of their partners.

One early challenge for automotive players involves building a solid cadre of talent. Since the initial need is probably small—say, three to five experts and "quantum translators" working full-time on QC research and applications—filling this gap seems doable. For example, training the sharpest IT people in QC language and translating classical problems into quantum-ready formulations may do the trick. As team members begin to immerse themselves in the technology, they should be allowed to experiment. Their work will primarily focus on using QC to enhance HCP, rather than automating manual work. Overall, the resources required to begin a QC initiative will be extremely small in the context of a large company's IT budget.

The need for an evolving strategy for quantum-computing applications

Given the uncertain pathway forward for QC, companies must understand their full range of options regarding the technology over different time horizons. While QC will not be commercially viable at most businesses for at least ten years, automotive players should still look for opportunities over the short term (the next one to two years). As a first step, they could begin to scout for a position in the value chain, build research partnerships and intellectual property, assemble a small team, and establish routines. Potential collaborators could include large tech companies, academic institutions, government laboratories, and start-ups manned by quantum-software developers and other specialists. In the short, medium, and long term, companies should also scout for potential opportunities for investment or joint ventures, keeping in mind that the market has many investors focused on only a few targets and that the stakes are high.

Over the medium term (five to ten years from now), players should prioritize application development and build focused capabilities. In the process, they should select front-runners, scale teams to midsize, and make the first pilots and prototypes operational. They should also strive to become innovators in a focus area.

In the longer term, over ten years from now, businesses should gain a technological edge through QC, build a competitive advantage in focus fields, and begin to expand their core capabilities.

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