ARCHIVIO ISTITUZIONALE
DELLA RICERCA

Alma Mater Studiorum Università di Bologna
Archivio istituzionale della ricerca

Quantum computing in the automotive industry: survey, challenges, and perspectives

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:
Arshad, M.W., Lodi, S. (2025). Quantum computing in the automotive industry: survey, challenges, and perspectives. THE JOURNAL OF SUPERCOMPUTING, 81(10), 1-34 [10.1007/s11227-025-07573-4].

Availability:
This version is available at: https://hdl.handle.net/11585/1045630 since: 2026-02-17

Published:
DOI: http://doi.org/10.1007/s11227-025-07573-4

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (https://cris.unibo.it/).
When citing, please refer to the published version.

(Article begins on next page)

09 September 2026

Quantum Computing in the automotive Industry: Survey, Challenges, and Perspectives

Muhammad Waqas Arshad[1*†] and Stefano Lodi[2*†]

[1,2*]Department of Computer Science and Engineering, University of Bologna, Street, Bologna, 40136, Bologna, Italy.

*Corresponding author(s). E-mail(s): muhammadwaqas.arsha2@unibo.it; stefano.lodi@unibo.it;
†These authors contributed equally to this work.

Abstract

Quantum computing is a rapidly advancing technology that has the potential to revolutionize the automotive industry. This survey examines the potential impact of quantum computing on the automotive industry, focusing on the challenges that the industry faces and how quantum computing can address these challenges. The article also discusses the potential risks and limitations associated with quantum computing in the context of the automotive industry. By a thorough analysis of the relevant research and industry advances, this review aims at offering understanding of the transforming role of quantum computing in the future of the automotive industry.

Keywords: Quantum computing, automotive industry, traffic congestion, vehicle safety, energy efficiency

1 Introduction

Quantum computing is a novel and fascinating area of science that unifies concepts from quantum physics, computer science, and mathematics to offer a new model of information processing [1]. It exploits the principles of quantum mechanics to manipulate a huge amount of data at once and is thus able to provide unmatched computational speed and efficiency, holding promise to become one of the most powerful computing technologies and create a kind of revolution in many industries. The

Table 1: Key differences between quantum and classical computers

Quantum Computing	Classical Computing
Qubits have the unusual capacity to represent both 0 and 1, in superposition.	Calculations are carried out using transistors, whose state stand for either 0 or 1 in digital representations.
Power rises exponentially with qubits.	Power increases in a 1:1 ratio as the number of transistors grows.
Error rates in quantum computers are high, and some quantum computers require extremely cold environments in which to function.	Traditional computers run at ambient temperature. They seldom make mistakes.
Quantum computers excel in solving optimization problems, analyzing data, and running simulations.	Classical computers are best suited for routine processing activities.

automotive industry is one sector that is set to gain substantially from this transformational power, in diverse areas such as supply chain management, autonomous drives, electric vehicles, and traffic optimization, through the development of advanced simulation, optimization, and data processing quantum algorithms. In fact, while technological advancements are nothing new in the automotive industry, which always moves forward to the ultimate of quality, safety, and eco-friendliness, classical computers are nonetheless reaching their potential in addressing difficult computational problems. With the instance size of such problems increasing, classically computable solutions will likely continue to be suboptimal for the foreseeable future.

Table 1 shows the key differences between quantum and classical computers. Unlike classical computers, which use binary bits to represent information as a 0 or a 1, quantum computers use quantum bits, or qubits, which may exist in a superposition of states, representing both 0 and 1 at the same time. This distinguishing feature enables quantum computers to do certain computations significantly quicker than classical computers, potentially leading to substantial advancements in a variety of sectors.

Figure 1 illustrates potential uses of quantum computing in the automotive sector. It provides a visualization of how quantum computing might alter crucial fields such as autonomous driving, traffic management, mechanical design optimization, cost effectiveness of materials, energy storage, and safety, by means of advanced simulations and optimization approaches [2][3][4]. The importance of this research stems from the possible benefits it might offer to the car industry, such as an increase in the safety and efficiency of self-driving cars, the optimization of energy storage solutions for electric vehicles, and the improvement of traffic control systems. These innovations have the potential to significantly reduce accidents, energy consumption, and congestion, therefore changing the future of transportation. Understanding the influence of quantum computing on the automotive industry helps to the greater academic and scientific conversation around quantum technologies and their real-world applications.

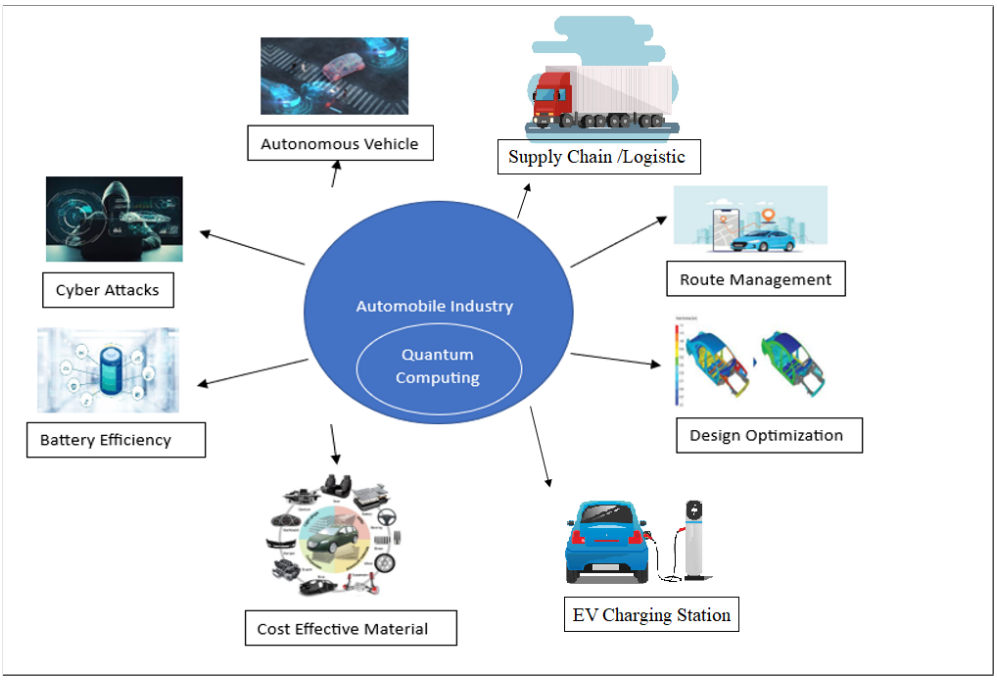


Fig. 1: Application of Quantum Computing in the Automotive Industry

The objective of this survey is to explore the computational challenges faced by the automotive industry, focusing on problems that are difficult to solve with classical algorithms and techniques, on the potential of quantum computing in addressing these challenges, and on the effectiveness of quantum computing in revolutionizing the automotive sector and the evolution of its applications over time. The article also discusses the limitations associated with quantum computing in the context of the automotive industry. We made sure our results were reliable by searching several times in the authoritative database of Scopus, and used the collected data from Scopus in the VosViewer tool [5] [6] for building and displaying bibliometric networks.

The following sections of the paper provide a discussion of different aspects of quantum computing in the automotive sector. In Section 2, literature review starts with the analysis of the existing literature on quantum computing with a focus on its use in vehicles. Then Section 3 focus on the principles of quantum computing with an emphasis on gate-based quantum computing and quantum annealing and their application in automotive optimization challenges. The discussion then turns to the computational problems in the automotive industry, pointing out the need for better methods in Section 4. The next Section 5 is the application of quantum techniques in the automotive industry, where real-life computational problems are discussed. Next in Section 6 focuses on the collaborations between automotive industry giants and quantum startups to show how these are shaping up its future. Lastly in Section 7, the conclusion highlights the possibilities of quantum computing and the difficulties

that need to be addressed to harness the advantages of quantum computing in the automotive sector.

2 Literature overview

A comprehensive search was performed by utilizing the Scopus and Google Scholar databases to acquire pertinent research publications. The Scopus search was narrowed down to the term "quantum computing," returning approximately 20,250 journal publications. The search provided insightful information about the involved fields, the distribution of articles within these fields, and the countries engaged in quantum computing research.Figure 2 displays the top 10 areas determined by the available data, sorted by number of publications in different areas. With the exception of Astronomy, Biochemistry and Genetics, these areas have a huge influence on the progress of the automotive industry. Figure 3 shows a plot of the countries which are among the top 10 countries by number of cars produced or by number of Quantum Computing documents published. It highlights a significant correlation between the variables, showing the potential for influence of Quantum Computing and the automotive industry and for internal partnership between car manufacturers and quantum startups.

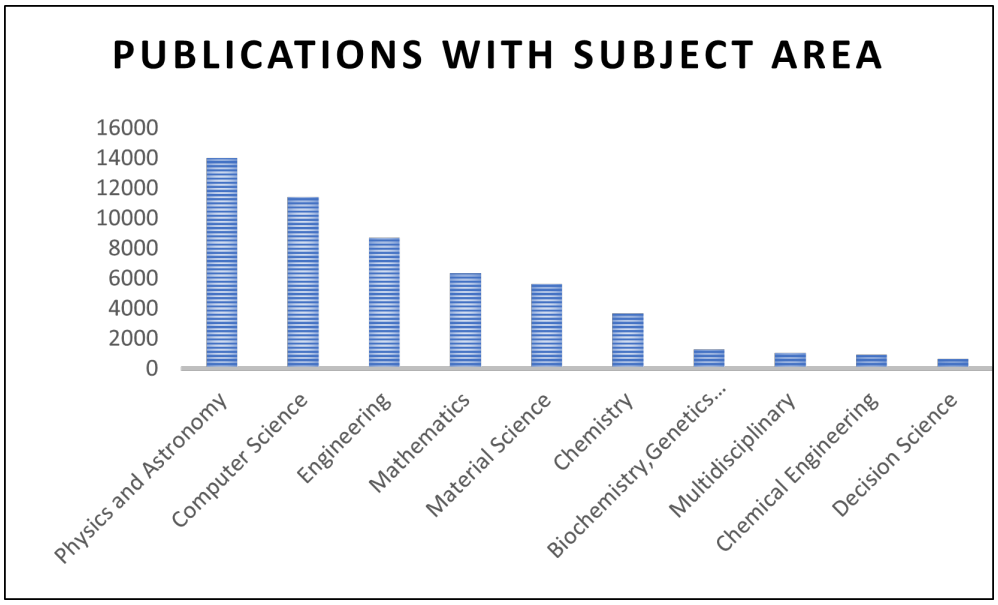


Fig. 2: Top ten areas based on the available publications by Scopus on the query of "Quantum Computing."

The results of a search on the topic 'Quantum Computing for Vehicles' yielded a total of 20254 publications. We are providing a quick overview of the most essential and current research in this field. A Scopus database query used with both subjects

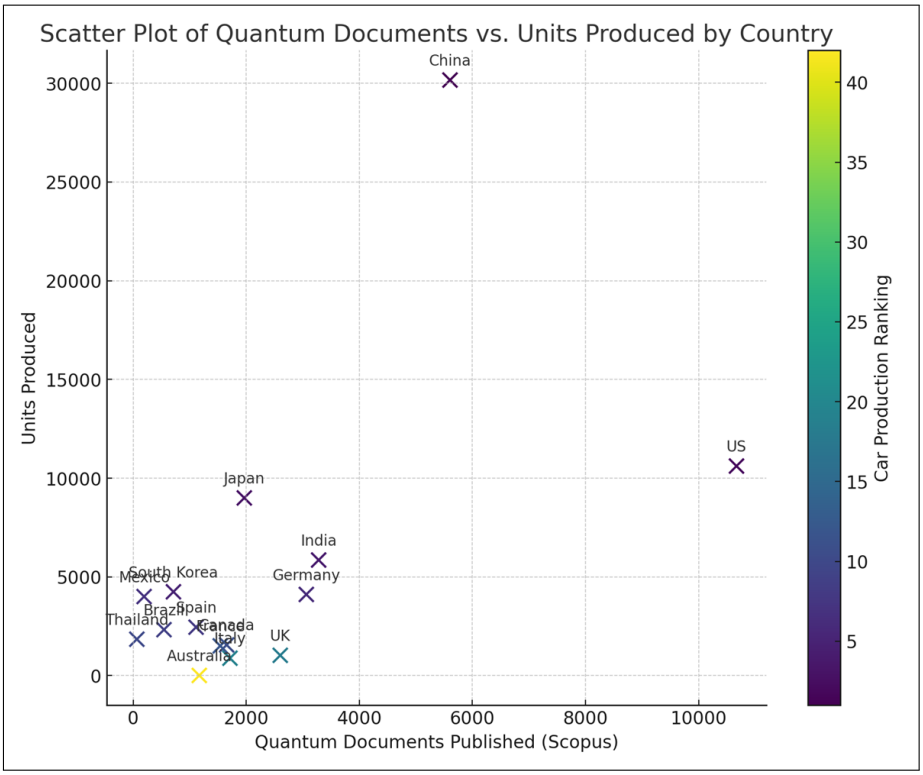


Fig. 3: Plot of countries by number of quantum documents published (1923-2025, Scopus) and thousands of car units produced (2023, International Organization of Motor Vehicle Manufacturers)

to find the authors who have worked on quantum computing optimization in the last ten years and to sort the results by document type in the areas of quantum computing and the automotive industry. Figure 4 shows the results.

Meta-analysis is a collection of statistical methods used to aggregate the results of the studies included in a systematic review. Statistical information in the research literature is provided by meta-analysis as an estimate of the sample-weighted average effect size across all studies [7]. We are not carrying out a meta-analysis of results, that is, a pooling of the results obtained in the studies, because the reviewed studies in our opinion are not homogeneous enough [8]. However, by adding a meta-analytic component to evaluate the comparative impact of different quantum algorithms in vehicular applications, we specifically extracted algorithm-specific records using title and abstract keyword matching, calculated a normalized citation-based proxy for effect size (log-transformed citations per year since publication), and performed inverse-variance weighted meta-analyses using weighted least squares (WLS) models. The most common quantum algorithms in vehicle applications, along with the number of occurrences, are: Quantum Annealing (24), QAOA (11), Grover (4), VQE (4).

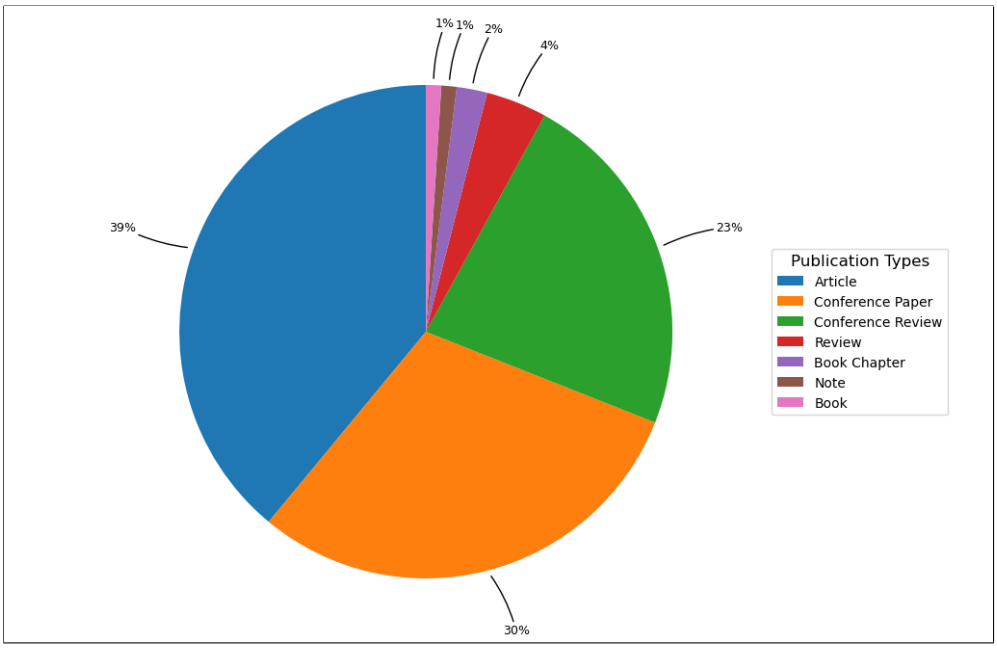


Fig. 4: The document types show published paper categories retrieved from the Scopus database. It illustrates the publishing source and its weight-age for Quantum Computing with respect to automotive industry.

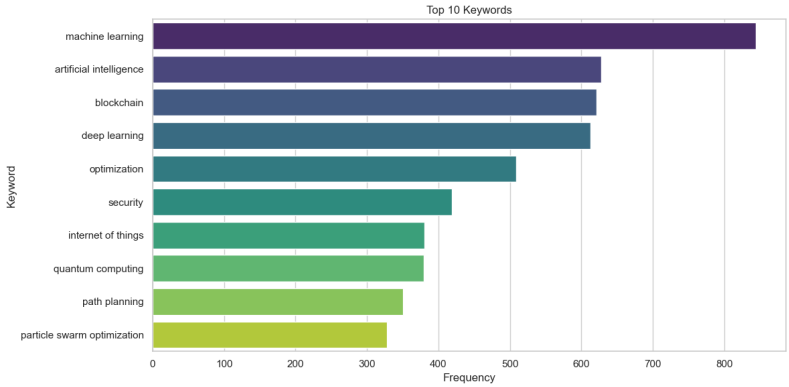
This approach allowed us to move beyond descriptive trends by estimating the relative scholarly impact of each algorithm. In Table 2, Quantum Annealing (Estimate = 0.35, $p < 0.001$) and QAOA (Estimate = 0.46, $p = 0.003$) showed significantly higher normalized citation impacts, while VQE and Grover-based studies exhibited smaller and statistically marginal effects. The analysis also included confidence intervals and p-values to support interpretability and rigor.This analytical enhancement aligns with recent trends in bibliometric meta-analysis, which aim to quantify knowledge maturity and impact across technologies more robustly [9][10].

Table 2: Meta-Analysis Results by Algorithm

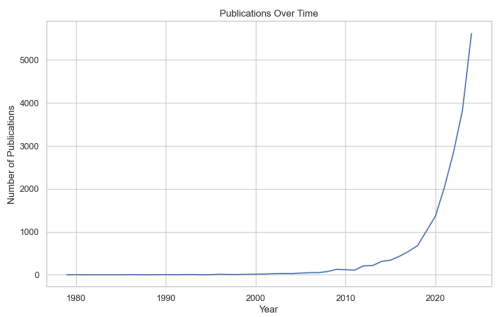
Rank	Algorithm	Estimate	Lower CI	Upper CI	p-value	Studies
2	Grover	0.626759	-0.166268	1.419786	0.086541	4
1	QAOA	0.463236	0.197659	0.728813	0.003027	11
0	Quantum Annealing	0.353426	0.225810	0.481043	0.000008	24
3	VQE	0.312142	-0.071115	0.695399	0.080939	4

According to Figure 5, the research output explosion focuses primarily on contemporary fields, which are represented by the most frequent keywords machine learning, artificial intelligence, blockchain, deep learning and Quantum computing in Figure 5a.

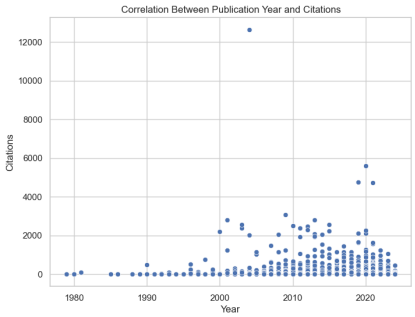
The number of publications increases dramatically in Figure 5b showing a slow growth from 1980 until 2010 before entering a steep exponential growth phase in recent years. The citation numbers in Figure 5c show that pre-2000 publications received fewer citations, but recent publications tend to receive more citations with significant variation and some highly cited exceptions, indicating that the recent publication surge in trending keywords has produced influential research which will need time to accumulate citations.



(a) Top 10 most frequent keywords



(b) Publications over time trend



(c) Correlation between the publication year and citations

Fig. 5: Research Trends: Publication Growth, Top Keywords, and Citation Patterns

In [11], the use of quantum computing to solve optimization problems is looked into. The potential to solve NP-hard problems is emphasized in [12]. A software approach for compiling quantum programs is discussed in [13], which contributes to the creation of effective implementation of quantum computing.

In [24, 34], the authors look into the Paintshop problem and the best way to route traffic and propose how it can be solved with quantum-based methods like quantum annealing, VQE, QAOA, and ADMM. In [27], discuss the application of

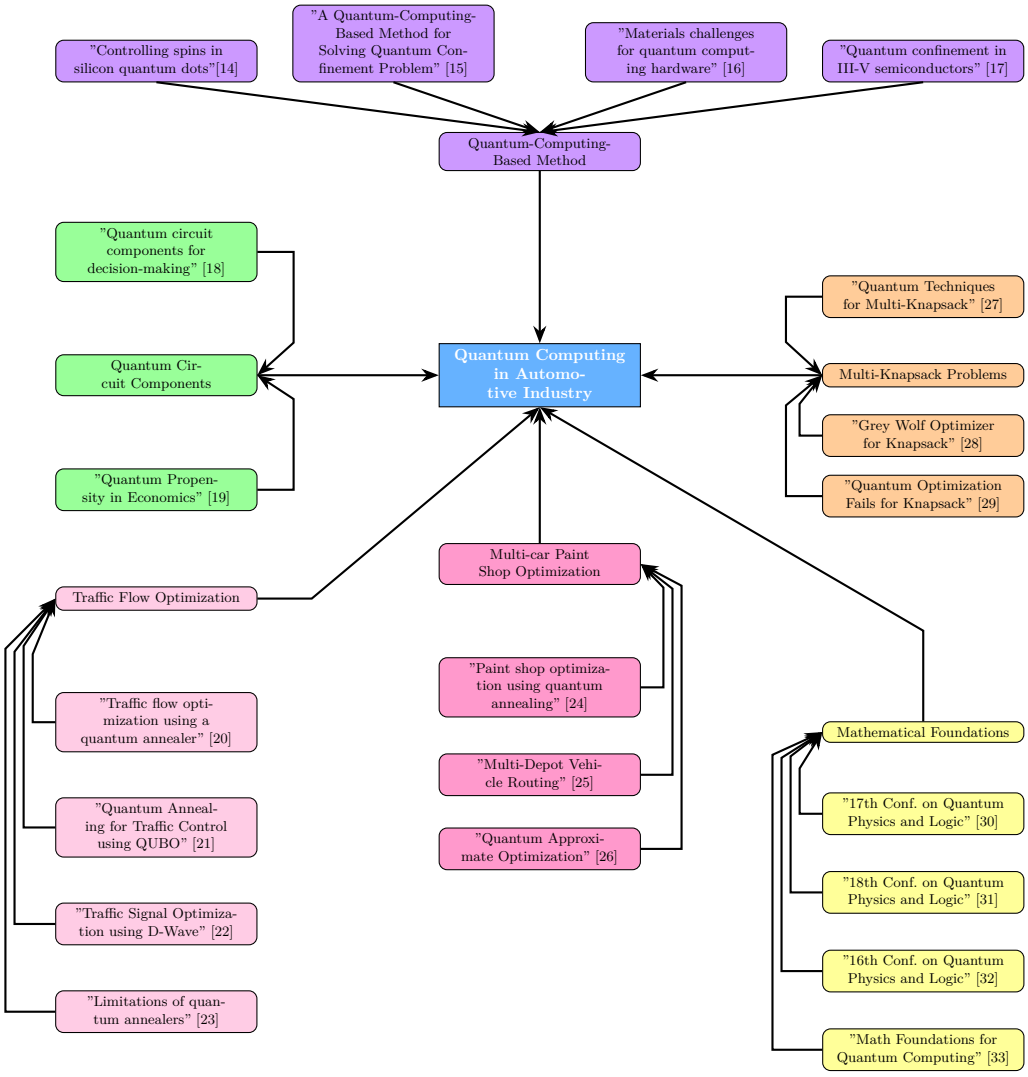


Fig. 6: Overview of the literature of quantum computing methods and its applications in the automotive industry.

multi-knapsack quantum computing is discussed. This study highlights the wide variety of automotive optimization difficulties that quantum computing technologies may handle as shown in Figure 6.

The collective research presented in the Proceedings of the 16th, 17th, and 18th International Conferences on Quantum Physics and Logic (2020-2021) shows significant progress in the mathematical underpinnings of quantum physics and computing [30–32]. The conferences place a strong emphasis on structural perspectives, logical

methodologies, and organized algebraic frameworks, underscoring the significance of using an interdisciplinary approach to enhance understanding of quantum systems. Moreover, the incorporation of computer science methods underscores the increasing convergence of computational approaches and quantum physics with the goal of discovering new quantum technologies and formulas.

When it comes to solving complex optimization problems, quantum annealing has been proposed as a novel approach to address the shortcomings of traditional algorithms. A novel method has been suggested, for instance, to resolve optimization problems on chimera graphs, which represent the intricacy of connections in urban transportation networks [23]. Also, research using quantum annealing has shown promising outcomes for managing real-time traffic patterns at urban intersections and traffic control systems [21], which makes it easier for cars and scooters to move around. Furthermore, by using a D-Wave quantum annealer to optimize square grid traffic signs, quantum computing has the potential to significantly reduce traffic inequalities and improve global traffic control [22]. This study demonstrated how, by outperforming classical methods in solving the binary paint shop problem, the Quantum Approximate Optimization Algorithm (QAOA) greatly improved industrial process optimization. to boost productivity [26]. Research on optimal QAOA programs and quantum annealing techniques has also yielded valuable insights into the relative effectiveness of different annealing schedules, opening up possibilities for strategy optimization in situations similar to multi-car paint shops [35]. Furthermore, dynamic multi-depot capacity can be addressed using the quantum annealing approach. The vehicle routing problem itself demonstrates the wide range of quantum optimization methods and illustrates its role in solving logistical issues akin to paint shop optimization [25]. Exploring quantum-inspired algorithms for solving the classical 0-1 knapsack problem that enhance optimization efficiency, particularly in scenarios with numerous dimensions. A novel hybridization strategy has been proposed, which blends quantum-inspired differential evolution with the grey wolf optimizer. This method emphasizes the ability to combine quantum computational principles with nature-inspired optimization strategies to solve complex computational problems [26]. However, testing adiabatic quantum optimization on the D-Wave 2000Q quantum computer shows that it cannot fully solve the integer-weight knapsack problem. This shows how different quantum algorithms perform compared to traditional ones and how hard it is to make quantum solutions fit specific optimization problems [35]. Furthermore, the development of a hybrid quantum genetic algorithm that merges quantum crossover processes and quantum gate approaches presents a novel strategy for addressing problems. This approach demonstrates enhanced efficiency in tackling knapsack problems by ensuring a wider range of solutions [25].

The automotive industry faces different complex problems in the production cycle. Applications of quantum computing may be effectively used throughout the automotive value chain to solve problems related to optimization, simulation, and machine learning. Of particular significance, quantum computing advances technological advancement by offering better solutions for important problems like the chemistry of batteries in electric vehicles [36].

3 Quantum Computing

Quantum computing can be understood as a broad field that encompasses two main approaches: gate-based quantum computing and quantum annealing. Gate-based quantum computing is a sequential processing of information that performs a sequence of operations, represented as *quantum gates*, on an initial quantum state, but with the ability to exploit quantum phenomena like superposition and entanglement to process a potentially exponential amount of information in parallel. Quantum annealing, on the other hand, is a process that attempts to look for the right solution to a given problem by looking for the quantum state of a system that is at its lowest energy level. As we have already stated, Gate-based quantum computing can be used to implement a broad range of quantum algorithms which require precise control of the quantum state, while quantum annealers are best suited for optimization problems, for instance, searching for the shortest path in a network or optimal resource allocation. These approaches make quantum computing a very versatile set of tools to address many computational tasks, and this makes the field of quantum computing rather robust and diverse [37].

3.1 Qubits

A classical bit represents either of the two mutually exclusive states, denoted by 0 and 1, of a usually electronic elementary device. The device's state can be retrieved at any moment, as a 0 or 1 bit value, without altering it. A register of n classical bits can be in any of 2^n mutually exclusive states, which can likewise be non-destructively read. The states are denoted as the n-bit strings $00\ldots0$, $00\ldots1$, $\ldots$, $11\ldots1$.

A qubit is an element of a 2-dimensional vector space on complex numbers, with basis vectors denoted by $|0\rangle$ and $|1\rangle$. A qubit can thus be expressed as a linear combination $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where α and β are complex. For any qubit, its coordinates α and β must satisfy the normalization condition $|\alpha|^2 + |\beta|^2 = 1$, therefore a qubit is always a unit vector. The basis vectors $|0\rangle$ and $|1\rangle$ are the quantum analogues of 0 and 1, and represent the base states of a quantum system, e. g., the spin states of a subatomic particle. Since a qubit is a linear combination of $|0\rangle$ and $|1\rangle$, it is said to be in a state of *superposition* of the basis vectors, in contrast with classical bits whose states are exclusive.

While a qubit in general exists in a superposition state, when the state of the underlying quantum system is measured, the result is randomly either $|0\rangle$ or $|1\rangle$, and the measurement operation irreversibly collapses the system to the base state that corresponds to the result. The probability amplitudes of measuring the superposition as $|0\rangle$ or $|1\rangle$ are $|\alpha|^2$ and $|\beta|^2$, respectively [33]. The normalization condition therefore simply imposes the unit probability of the sample space. Writing coordinates in polar form, a qubit is $|\alpha|\,\exists^{\phi_0}\,|0\rangle + |\beta|\,\exists^{\phi_1}\,|1\rangle$, where ϕ_0 and ϕ_1 are the arguments, or *phases*, of α and β. Since only the phase difference between ϕ_0 and ϕ_1 is physically meaningful, and recalling the normalization condition $|\alpha|^2 + |\beta|^2 = 1$, a qubit can be also written as the vector function $\cos(\theta/2)\,|0\rangle + \sin(\theta/2)\,\exists^{\phi}\,|1\rangle$ of only two real numbers θ and ϕ, with $0 \leq \theta \leq \pi$, $0 \leq \phi \leq 2\pi$. In this form, a qubit can be mapped to

point $(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$ on the three-dimensional sphere, and such geometric representation is known as the *Bloch sphere* (Fig. 7).

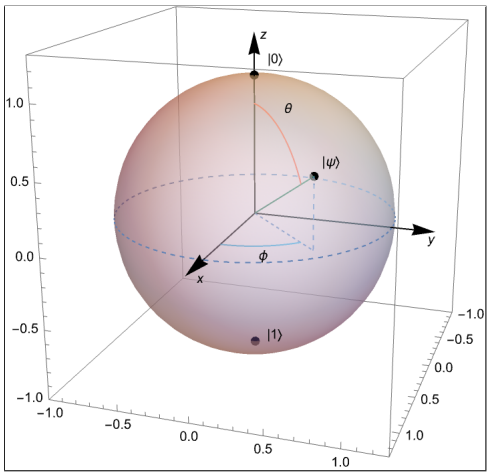


Fig. 7: The Bloch sphere representation of a qubit.

A multi-qubit system consists of multiple qubits in a *quantum register*, which is also an element of a Hilbert space. If the register consists of n qubits, one would expect the dimensionality of such a space to be $2n$; instead, it is dramatically higher. In fact, the combined system's state is represented by the tensor product $\psi_0 \otimes \psi_1 \otimes \cdots \otimes \psi_{n-1}$ of the individual qubits' states $\psi_0, \psi_1, \ldots, \psi_{n-1}$; therefore, its dimensionality is 2^n. Its basis vectors are all tensor products $\mathbf{b_0} \otimes \mathbf{b_1} \otimes \cdots \otimes \mathbf{b_{n-1}}$, with $\mathbf{b_k} \in \{|\mathbf{0}\rangle, |\mathbf{1}\rangle\}$.

For example, for a three-qubit system, the combined state $|\Psi\rangle = |\psi_0\rangle \otimes |\psi_1\rangle \otimes |\psi_2\rangle$ is given by:

$$|\Psi\rangle = \alpha_0\alpha_1\alpha_2\,|0\rangle \otimes |0\rangle \otimes |0\rangle + \alpha_0\alpha_1\beta_2\,|0\rangle \otimes |0\rangle \otimes |1\rangle \;+\quad \cdots + \beta_0\beta_1\beta_2\,|1\rangle \otimes |1\rangle \otimes |1\rangle$$

writing $|b_0b_1b_2\rangle$ for $|b_0\rangle \otimes |b_1\rangle \otimes |b_2\rangle$

$$= \alpha_0\alpha_1\alpha_2\,|000\rangle + \alpha_0\alpha_1\beta_2\,|001\rangle \;+ \cdots + \beta_0\beta_1\beta_2\,|111\rangle$$

Again, the system exists in a superposition of all possible states $|000\rangle, |001\rangle, \ldots, |111\rangle$ simultaneously. Generalizing, the state of an n-qubit system is

$$|\Psi\rangle = \sum_{b_i \in \{0,1\}} \alpha_{b_0 b_1 \ldots b_{n-1}} |b_0 b_1 \ldots b_{n-1}\rangle$$

or more compactly

$$= \sum_{i=0}^{2^n-1} \alpha_i |i\rangle,$$

where integers i are shorthand for their binary representations, and the α_i are complex amplitudes that satisfy the normalization condition $\sum_{i=0}^{2^n-1} |\alpha_i|^2 = 1$. When measuring a multi-qubit system, the state $|\Psi\rangle$ collapses to one of the base states $|i\rangle$ with a probability equal to $|\alpha_i|^2$. Therefore, instead of just existing in one of the states $|i\rangle$, the system can be in a superposition across an exponentially large number of possibilities, each associated with a complex number α_i, representing an amount of information that is exponential in the number of qubits. This feature indicates a potential exponential speed-up of quantum computers over classical ones, because state changes occur simultaneously for the system as a whole. Moreover, qubits can become *entangled*, meaning that the state of one qubit is directly linked to the state of another, no matter how far apart they are. This leads to correlations that we simply don't see in classical systems. An example is the two-qubit Bell state

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

On measurement, this system collapse to either $|00\rangle$ or $|11\rangle$ each with a 50% probability. This example demonstrates how multi-qubit systems can exhibit entanglement and probabilistic outcomes, which are fundamental characteristics in quantum computation and information processing.

3.2 Quantum gates

Quantum gates distinguish themselves from traditional logic gates due to their capacity to create superposition and entanglement. Quantum gates, such as Pauli-X, Y, Z, Hadamard (H), and CNOT, shown in Table 3, play a crucial role in controlling the states of qubits. Applying the Hadamard gate to a state represented by $|0\rangle$, yields

$$H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

demonstrating the formation of a superposition [38]. Quantum circuits consist of a series of quantum gates that are applied to qubits. The crux of quantum computation resides in the choice and configuration of these gates. Circuit diagrams utilize horizontal lines to represent qubits and employ distinct symbols for gates [39].

3.3 Computational complexity

Many computational problems arising in the automotive industry are optimization problems belonging to the class of non-deterministic polynomial hard (NP-hard) problems, for which no known deterministic polynomial algorithm exists [40]. Usually, they are search variants of well-known decision problems. For example, the INDEPENDENT SET decision problem requires determining the existence of a subset of the vertices of a graph of size greater than a given threshold, with the property that any two vertices in the subset are not connected by and edge. The optimization variant of the problem requires finding a subset of the vertices of maximum size with the same property, and it is called the MAXIMUM INDEPENDENT SET problem (MIS). The optimization of sensor placement on vehicles has been formalized as a MIS problem [41], in which each sensor represents a vertex, and an edge represents potential interference or overlap between sensors. The goal is to find the largest set of sensors (vertices) that can be placed without interference (edges).

Formalizations of numerous other problems in the automobile sector include optimization problems such as the TRAVELING SALESMAN OPTIMIZATION problem (TSO), the MAX CUT problem, and the PARTITION problem. TSO can be described as follows: INSTANCE: A set C of m cities, a distance $d(c, c')$ for each pair of cities $c, c' \in C$. SOLUTION: A tour of all the cities of minimum total length, that is,

$$\arg\min_{\gamma \in \Gamma} d(\gamma(1), \gamma(2)) + \cdots + d(\gamma(m-1), \gamma(m)) + d(\gamma(m), \gamma(1))$$

where Γ is the set of tours, that is, all bijections $\gamma\colon \{1, \ldots, m\} \to C$.

The Multiple Traveling Salesmen Optimization problem (MTSO) is a generalization of TSO in which more than one salesman is employed to visit the cities. In addition to multiple salesmen, a further variant introduces multiple depots, from which the salesmen must depart, and to which they must return.

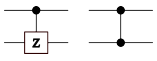
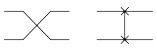
Quantum computing has proven to be effective in solving some NP-hard problems.

3.4 Quantum Algorithms

There are different approaches to writing general algorithms of quantum computing. The Quantum Approximate Optimization Algorithm (QAOA), which solves combinatorial optimization problems in approximately a polynomial time, works by formulating the problem as an input to a quantum circuit and then fine-tuning the parameter response to the cost function. It is a superb fit for problems like MAX CUT maximization, on which it has performed very well in simulations of near-term intermediate scale quantum computers [42]. Moreover, Quantum Neural Networks (QNN) may use QAOA to improve the learning process, and the performance has been proved to be convergent with lower times than classical learning [43].

There are other important quantum-inspired algorithms, which include the Quantum Particle Swarm Optimization (QPSO), that is the improved variant of the classical particle swarm optimization that has been developed through integration of some quantum behavior, hence possesses better search capability for global space and better convergence rates in most of the generic optimization problems [44]. Quantum

Table 3: The most widely used quantum logic gate symbol, represented by their operator, gates and matrix.

Operator	Gate	Matrix
Pauli-X (X)		$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$

Genetic Algorithm (QGA) and QNN are also important; QGA applies the Genetic Algorithm (QG) to improve GA capacity for global optima search in multisearch spaces and QNNs are other types of neural networks that have the potential to be implemented with quantum computation surpassing normal NN in data processing and analysis [43]. These algorithms as a whole form the current cutting edge of quantum computing in the field of optimization and machine learning, the technologies which aimed to disrupt industries requiring heavy data for the processing and optimization.

4 Computational Challenges in the Automotive Industry

In the following paragraphs, we highlight the computational aspects along with the inherent complexities of the different optimization problems dealt in the context of the automotive industry also visual in Figure 8 . These challenges entail the solution of NP-hard combinatorial problems such as the Multiple Traveling Salesman Optimization problem and the Vehicle Routing Problem, and other problems that require a computationally expensive search for an optimal solution.

Automated Path Optimization

The application scenario requires optimizing robot pathways in multiple areas of a manufacturing facility, such as bodyshop, paint shop, assembly, and logistics. The major focus is on factories with a large number of robots, particularly in the body and paint departments. The goal is to improve efficiency and production by optimizing the paths that these robots follow. Among the many applicable approaches and strategies, motion planning is a necessary component, for multi-robot systems which may require solving hard sub-problems, such as the multiple depot MTSO problem with collision constraints, to find optimal collision-free paths between task nodes of the graph of possible motions [45]. Their is another work in which authors improved A^* algorithm for autonomous vehicle path planning which combines turning penalty functions with obstacle coefficients to enhance adaptability and safety [46].The method reduces both computational complexity and path length while showing better performance in complex traffic environments.

Automotive Supply Chains

In an automotive supply chain, the management of inventory parts like engines, tires, and electronics is crucial, and its optimization presents a significant challenge, primarily due to the need to balance cost efficiency with maintaining high service levels. The core problem lies in the inherent complexity and variability of supply chains, where fluctuations in demand and supply can lead to either excess inventory or stock-outs [47]. Excess inventory results in higher holding costs and tying up valuable capital, while stock-outs can disrupt production lines, leading to delays and increased operational costs.

The complexity of this problem can expressed in a multi-objective optimization framework, where the goal is to minimize the total inventory cost while maximizing the service level:

$$\textbf{minimize} \sum_{i=1}^{n} (H_i \cdot I_i) - \lambda \cdot S$$

where H_i is the holding cost per unit for inventory item i, I_i is the inventory level of item i, S is the overall service level, and λ is a weighting factor that balances the trade-off between minimizing costs and maximizing service levels.

The general problem in manufacturing has been tackled by traditional and AI methods. For example, in [47], the authors focus on the multi-echelon, multi-period, single-product, and single-market inventory management problem (IMP) with

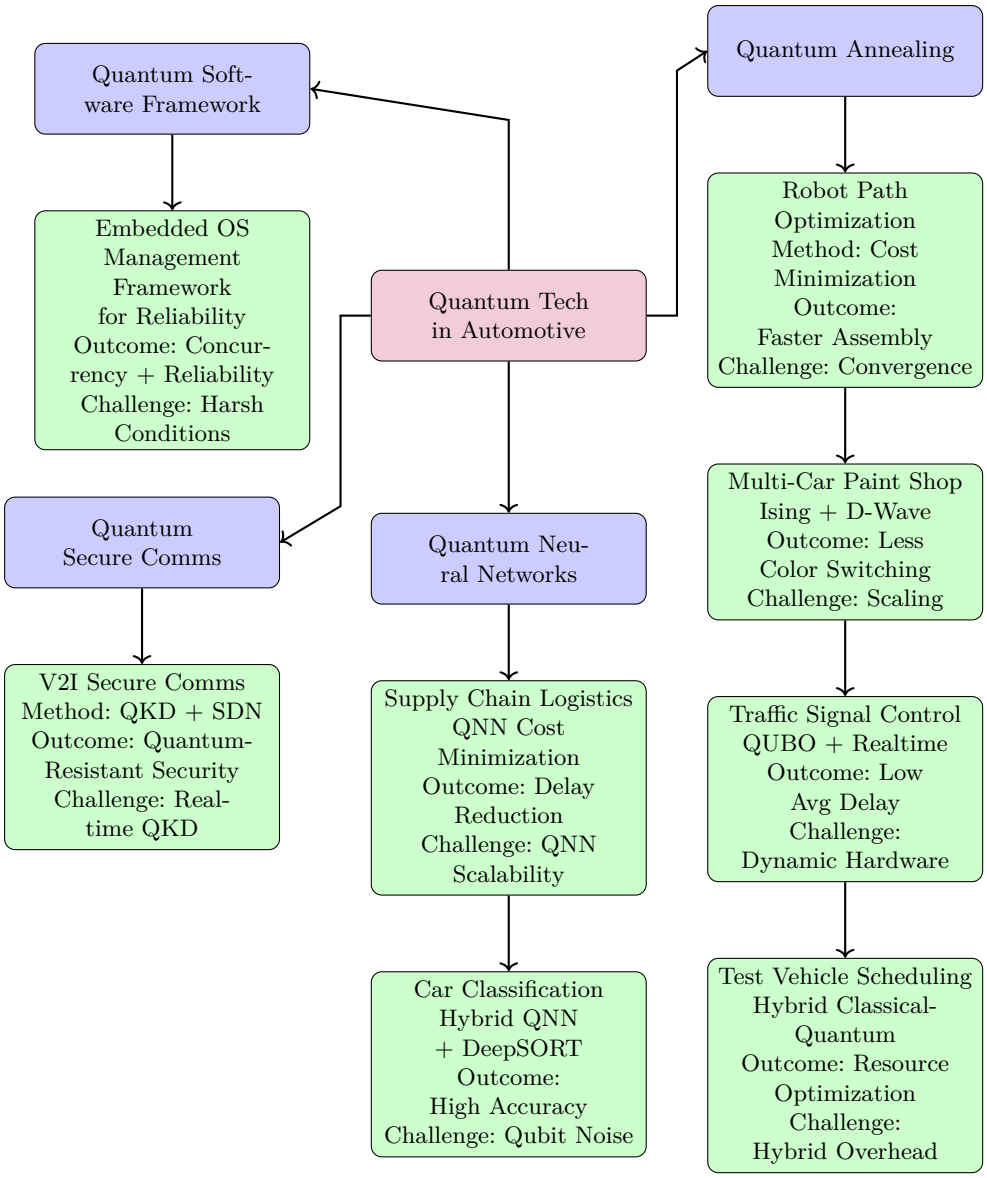


Fig. 8: Quantum Tech in Automotive. Mid-level blue nodes categorize key quantum application areas: Quantum Annealing, Quantum Neural Networks, Quantum Secure Communications, and Quantum Software Frameworks. Each green leaf node describes a specific use case, detailing methods, outcomes, and challenges associated with implementation in real-world vehicle systems.

uncertain stationary demand, using deterministic and multi-stage stochastic linear programming, and reinforcement learning. In the automotive sector, in [48] the authors use a genetic algorithm that enables the exploration of numerous potential inventory strategies in order to find the ideal balance that reduces costs and produces efficient and responsive supply chain operations. It is important to examines how advanced logistics technologies and digital transformation are changing automotive supply chains by highlighting the need for real-time visibility, predictive analytics, and integrated logistics networks to build supply chain resilience [49].

Classification of Vehicles

Vehicle classification, or vehicle segmentation, is a key component of traffic monitoring applications, which, in turn, are fundamental parts of any Intelligent Transportation System. A variety of sensor types and placements are employed and a hand-crafted or trained classifier processes the generated data to output one of a few broad vehicle classes [50]. Recently, vehicle classification has been extended to other tasks, such as traffic surveillance, access control, and security, for which a finer grained vehicle categorization from images is required [51], up to the differentiation between similar vehicle models, often under various and often extreme conditions. Orthogonally, the geographic coverage of vehicle classification has been extended by leveraging GPS data, to classify vehicles for traffic analysis [52].

EV Battery Swapping Station

In [53], authors propose a bi-level optimization framework to explain the coordination challenges between micro-grids (MG) and battery swapping stations (BSSs). The main objective is to minimize the total cost, which is expressed as:

$$J = \sum_{t \in T} C_{\mathrm{MG}}(t) + C_{\mathrm{BSS}}(t)$$

$C_{\mathrm{MG}}(t)$ represents the operational cost of the micro-grid at time t, and the $C_{\mathrm{BSS}}(t)$ denotes the cost of battery swapping station operations which includes battery degradation and service reliability costs. In more detail, the minimization problem can be expressed as:

$$\textbf{minimize} \sum_{t=1}^{24} C_t^{MG-DSO} + C_t^{MG-BSS} + C_t^{MT} + C_t^{PV} + C_t^{L}$$

where C_t^{MG-DSO} is the cost of power exchange between the microgrid operator and the distribution system operator, C_t^{MG-BSS} is the cost of power exchange between battery swapping stations and the microgrid operator, and the last three terms are the costs related to the micro turbines, photovoltaic, and loads.

By using a hybrid probabilistic approach which is used to model the uncertainties like load demand and market prices, combined with an Alternative Direction Method of Multipliers (ADMM)-based algorithm, which gives the significant cost savings, faster convergence, and improved reliability. The framework provides balancing for the

conflicting objectives between MG and BSS, which offers a scalable and efficient solution. Another optimization framework introducded which uses data to determine EV battery swapping station locations and sizes while using modular battery systems. The model enhances operational efficiency and user convenience by solving computational challenges that occur during urban deployment and fleet management [54].

Electric Vehicle Charging Stations

The increasing trend of the number of electric vehicles (EVs) circulating in cities calls for a proportionate development of the charging infrastructure. However, increasing the number of charging stations alone cannot meet the increased demand for charging: the range of EVs is still limited, thus the placement of charging stations must be optimized so that EVs do not run out of charge. The charging station location problem (CSLP) is a family of related optimization problems, which differ by the type of demand (node-based or flow-based), the function to optimize, the customer coverage degree, among other variables [55]. For example, in [56] the objective to minimize is the total cost associated with the installation and operation of charging stations while ensuring adequate coverage for EV users:

$$\begin{aligned} &\textbf{minimize} && \sum_{i=1}^{n} f_i \cdot x_i + \sum_{j=1}^{m} g_j \cdot y_j \\ &\textbf{subject to} && \sum_{j=1}^{m} y_j \cdot d_{ij} \geq r_i \quad \forall i = 1, 2, \ldots, n \end{aligned}$$

where f_i represents the fixed cost of placing a charging station at location i, x_i is a binary variable indicating whether a charging station is placed at location i, g_j represents the operational cost associated with each station, y_j indicates the operational status of the station, d_{ij} is the distance between location i and demand point j, and r_i is the required coverage level at each demand point. The authors compare a general mixed-integer programming solution, an exact mixed-integer programming solution subject to a restriction, a greedy algorithm, and the Chemical reaction optimization (CRO) metaheuristic, showing that no approach is superior along all dimensions. Notably, both exact solutions failed to terminate due to out of memory errors for as few as 200 stations, with a projected time of several days for the general solution. In another study, the authors solved the multiobjective problem in which they integrated the optimization model for EV charging infrastructure that combines vehicle routing and charging station allocation with power grid constraints. The approach reduces operational costs and optimizes grid utilization while addressing the computational challenges of deploying the system at scale. The inherent complexity indicates that additional improvements in computational efficiency or solution quality are still required. [57].

Paint Shop Optimization for Vehicle Bodies

One current problem often faced by the automotive industry is how to coordinate the throughput of vehicles for painting in such a manner as to insist on a short color changeover time while at the same time achieving high quality in the paint job. This is because any car may need a different color, necessitating a different set of equipment, and the process of changing from one color to another is often involved because the surface of the equipment needs to be cleansed and prepared, a process that is time consuming and costly. From a computational viewpoint, optimising paint shop operations is a relatively new kind of scheduling problem, which was shown in [58] to be NP-complete in the general case. This problem can be modeled using a scheduling optimization framework where the objective is to minimize the total cost C, which includes both the processing time T_i for each vehicle i and the transition cost S_{ij} to switch between color i and color j. The goal is to find a permutation $p_1, \ldots, p_n$ of n cars $1, 2, \ldots, i, \ldots, n$ with assigned colors $c(i)$ that minimizes cost:

$$\underset{p_1,\ldots,p_n}{\textbf{minimize}}\ C = \sum_{i=1}^{n} T_i + \sum_{i=1}^{n-1} S_{c(p_i)c(p_{i+1})}$$

For instance, if a paint shop paints a series of vehicles where the first vehicle is red, the second vehicle is blue, and the third is red again, then the transition cost is very high. If one could arrange the entire sequence such that the number of such transitions is minimized (for instance, by painting all the red vehicles in a sequence), then the overall cost C could be reduced significantly. However, for a large number of vehicles and a large color space, determining the best sequence poses significant computational difficulties, making it a challenging optimization problem to solve efficiently. A similar study addressed the bi-objective optimization of automotive paint shops, focusing on minimizing pollutant emissions while meeting production deadlines. . The authors created a multi-objective particle swarm optimization algorithm to tackle this intricate scheduling problem by integrating environmental and operational objectives. The NP-hard nature of the problem highlights an opportunity for improvement using more efficient techniques. [59].

Sensor Placement Optimization

In [60], the authors tackle the problem of determining the optimal placement of road-side sensors for autonomous vehicle safety. The authors develop a model that simulates real-world road environments, using raycasting to estimate sensor coverage. By constructing a visibility matrix, the coverage of various sensor positions is calculated. The core solution involves solving a Binary Integer Programming (BIP) optimization problem, aiming to minimize the number of sensors while maintaining maximum coverage of the road network. The constraints ensure adequate sensor visibility while avoiding sensor overlap, optimizing for urban environments with obstructions like buildings.

This approach, for example, could be applied to an urban street with lamp posts, where sensors are positioned to ensure visibility despite buildings or parked cars obstructing the line of sight. The goal is to cover as much of the road network as possible while using the minimum number of sensors.

Traffic Signal Control

In the Intersection Traffic Signal Control Problem (ITSCP), the phase and duration of traffic signals at one or multiple intersections must be scheduled optimally to maximize traffic flow. ITSCP has been the subject of many research works over six decades, and a large number of solutions have been proposed, with different problem settings. Solution methods encompass simulation, mathematical programming, genetic algorithms, reinforcement and Q-learning, multi-agent systems, dynamic programming, neural networks and heuristics. The computational complexity of ITSCP is dependent on multiple factors: the road network type, the number of intersections and lanes considered, the real-time strategy used, the objective to minimize, and the constraints on the cycle length, the green phase duration and the phase sequence. Many solutions consider small networks with three-legged or four-legged intersections, and application to large, generalized networks is a direction for future research [61].

5 Integration of Quantum Techniques in Automotive Applications

Table 4 provides a summary of quantum computing in automotive sector, its application in the design of the cars, logistics, self-driving software, traffic regulation, and batteries. The following are some of the advancements that demonstrate how quantum computing has helped the automotive industry in aspects such as light weighting and strengthening of materials, manufacturing at a cheaper cost, safety and even environmentally friendly vehicles.

It provides a comprehensive assessment of the role of quantum computing in vehicle design, supply chain logistics optimization, and autonomous driving algorithms improvement and further evaluates these use cases based on their deployment feasibility and alignment with three criteria: Hybrid (compatibility with hybrid quantum-classical approaches), NISQ (suitability for current Noisy Intermediate-Scale Quantum systems), and Speed (potential performance gains over classical methods).The symbols used ✓, –, and letter codes like E, U, *and* P – defined in a table key: ✓ indicates applicability, – denotes not applicable , E stands for early-stage potential, U for under development or pilot tested, and P for proven in prototype or experimental settings. Quantum algorithms have played a huge role in automotive manufacturers material science for lighter and stronger vehicle parts, cost-effective production processes, and safety features. Furthermore, the table shows quantum-inspired traffic flow optimization and battery technology development leading to reduced carbon emission and cleaner transportation solutions. This integration amplifies quantum computing as the real disruptor of the automotive industry and demonstrates innovation in the utilization of quantum mechanics in practical and critical situation.

Combinatorial Optimization

The diagram in Figure 9 depicts the relationships between theoretical computational problems and their practical realization in quantum computing.

These problems can be formally expressed using approaches such as Quadratic Unconstrained Binary Optimization (QUBO), Polynomial Unconstrained Binary

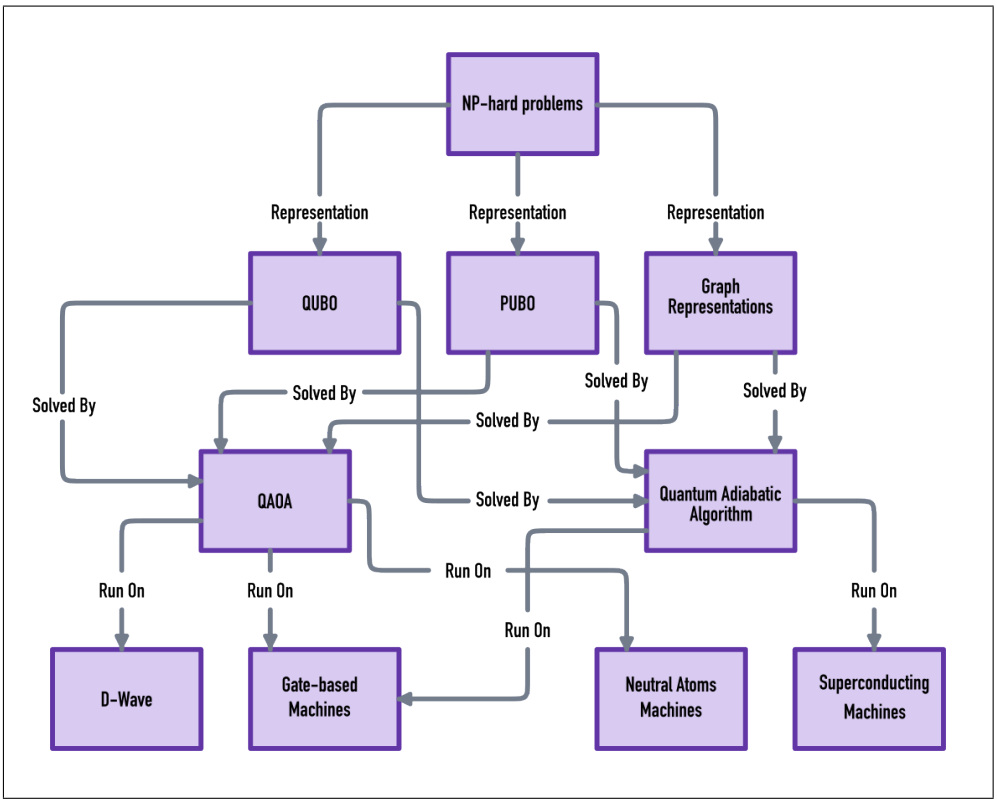


Fig. 9: Illustrating the progression from complexity to quantum solutions: The flowchart of NP-hard problems regarding SAT, TSP, Max-Cut problem, Graph partitioning, and the maximal independent set problem to their representations, mathematical and graphical too (QUBO, PUBO, graph representations).

Optimization (PUBO), and graph representations. Several quantum computing algorithms, such as the Quantum Approximate Optimization Algorithm (QAOA), the Quantum Adiabatic Algorithm (QAA), [62–64], are used to solve these kinds of optimization problems. In Figure 9, these algorithms take advantage of the unique features of quantum systems to effectively search and utilize the huge solution space. These algorithms seek to find optimum solutions for complicated optimization issues in the automotive sector by exploiting quantum computing's intrinsic parallelism and quantum superposition.

5.1 Quantum Optimization Algorithms

Electric Vehicle Charging Stations Placement

The problem discussed in [79] is to propose a solution for the efficient scheduling and location of electric vehicle (EV) charging stations in a power distribution grid. This is a complex, multi-objective optimization challenge, as it requires balancing various

Table 4: Summary of the applications of quantum computing to the automotive industry

Automotive application	Quantum solution	Practical implications	Challenges and limitations	Impact	Hybrid	NISQ	Speed
Vehicle Routing Optimization [65]	Quantum Approximate Optimization Algorithm (QAOA)	Improves efficiency and speed of routing decisions	Scalability and quantum hardware dependency	Enhanced route management and reduced operational costs	✓	✓	P
Sensor Placement Optimization [41]	Quantum-classical hybrid methods	Optimizes sensor deployment for functionality and coverage	Integration with classical systems; hardware limitations	Improved data accuracy and vehicle safety	✓	–	U
Enhancing V2I Security [66]	Lattice-based cryptography for post-quantum security	Secures communication against quantum attacks	Implementation complexity and overhead	Robust security protocols safeguarding V2I communications	-	✓	E
EV Charging Station Management [67]	Quantum SWARM algorithm	Enhances charging station efficiency	Quantum solution maturity and real-world application	Better resource management and service availability	–	✓	E
EV Battery Swapping Station [53]	Quantum Particle Swarm Optimization Algorithm	Efficient energy coordination system	Scalability and real-time constraints	Cost-effective scheduling improvements	–	✓	P
Secure Quantum Communications for V2I [68]	Free-space Optical Quantum Key Distribution (FSO-QKD)	Offers quantum-secure communications	Alignment and atmospheric conditions affect performance	Ensures unbreakable encryption for vehicle communications	–	✓	E
Quantum Computing in Autonomous Driving [69]	Quantum algorithms for computer vision	Potentially faster processing of visual data	Quantum hardware development is still nascent	Improved real-time decision making in autonomous vehicles	–	✓	E
Production Planning for Automotive Manufacturing [70]	Quantum-Inspired Hybrid Algorithm	Reduces costs and enhances production efficiency	Adaptation to specific manufacturing environments	Streamlined operations and reduced lead times	–	✓	E
6G-V2X Communication [71]	Quantum Key Distribution (QKD)	Enhances communication security	Technical challenges in deployment and scalability	Future-proof secure communication networks	–	✓	E
Quantum Software Development for Automotive [72]	Quantum programming frameworks	Simplifies the development of quantum applications	Steep learning curve and limited expert availability	Accelerates the integration of quantum solutions in automotive	–	✓	E
Multi-Car Paint Shop Optimization [24]	Quantum Annealing	Optimizes the painting process for efficiency	Scalability with large vehicle batches	Reduced operational costs and increased throughput	✓	–	U
Production of Test Vehicles [73]	Hybrid Constrained Quantum Annealing	Enhances efficiency in test vehicle production	Complexity in implementation and integration with existing systems	Streamlined production processes and reduced time to market	–	✓	E
Traffic Signal Control [74]	Quantum Annealing	Improves traffic signal control dynamically	Dependency on accurate real-time traffic data	Enhanced traffic flow and reduced congestion	–	✓	E
Powertrain Optimization for EVs [75]	Quantum Genetic Algorithm	Optimizes powertrain configurations for performance	Quantum algorithm stability and reliability	Improved energy efficiency and performance in EVs	–	✓	E
Supply Chain Logistics [76]	Quantum and Classical Annealing	Enhances logistics operations in the supply chain	Integration with current logistics systems; quantum resource requirements	More efficient logistics and reduced operational costs	✓	–	U
Robot-Trajectory Planning [77]	Hybrid Quantum Algorithms	Optimizes path planning for industrial robots	Computational overhead and hardware limitations	Increased efficiency and precision in robotic operations	✓	–	U
Car Classification with Hybrid Quantum Neural Networks [78]	Hybrid Quantum Neural Networks	Enhances the accuracy and speed of car classification systems	Stability and scalability of hybrid quantum systems	Improved automation and reliability in vehicle manufacturing processes	✓	–	U

conflicting goals: reducing installation costs, reducing power losses, and providing high quality service to the users of electric vehicles. The challenge is to find the optimal locations for these charging stations that would meet all these goals at once taking into account the limitations of the power system. The authors [79] introduce a new quantum inspired optimization algorithm to solve the problem of planning electric vehicle (EV) charging station. The solution involves developing a Multi-objective Quantum Atom Search Optimization (MQASO) to search for potentially ideal locations to install EV charging stations bearing in mind some objectives such as installation costs, power loss and quality of service. This approach improves the convergence property of the algorithm so as to arrive at a set of best solutions acceptable from the Pareto optimal solutions perspective.

EV Battery Swapping Station

Coordinating the operational efficiency between isolated micro-grids and a battery swapping station is one the problem currently facing in automotive sector. The researchers improve the effectiveness and dependability of energy systems, which are adopting renewable sources to an increasing extent [67]. They use the Quantum Behavior Particle Swarm Optimization (QPSO) algorithm to address the optimization of energy storage and distribution, which is important for stabilizing power supply and minimizing operating costs in isolated microgrids combined with battery swapping facilities [67].

This is especially useful in cases of complex non-linear optimization problems in energy systems where the algorithm has to deal with many operational and environmental constraints. The methodology includes simulation of different operational scenarios to get the optimal configurations in terms of minimizing energy waste and cost as well as maximizing system reliability and efficiency [67]. The output of implementing QPSO algorithm show its efficiency in achieving substantial improvements in system performance. The algorithm also operates on optimizing the allocation of capacity between the microgrid and the battery swapping station and on handling the fluctuations in renewable energy outputs [67]. As a result, a more stable and cost effective energy supply system is established, mostly in areas where traditional energy infrastructure is either lacking or inadequate. The research gives the detailed assessment of QPSO performance that it surpasses traditional methods, both in include characteristics of operational efficiency and cost-effectiveness, which makes it an attractive solution of future energy management system in isolated microgrids [67].

Production Planning for Automotive Manufacturing

The scholars explored a new approach to the optimization of manufacturing processes, where planning and scheduling are united in a single activity in order to increase efficiency and decrease operational delays [70]. This is especially critical in dynamic manufacturing environments where on-the-fly responses to changes are of utmost importance. The research presents a quantum-inspired hybrid algorithm, which combines features of quantum computing with well-known optimization methods for solving integrated process planning and schedule (IPPS) problems efficiently [70]. The

methodology employs a hybrid-coding representation that amalgamates numerical and Q-bit representation that enables the quantum-inspired evolutionary algorithm to take advantage of the features of quantum computation such as superposition and entanglement to explore and optimize the solution space effectively. Customized conversion and repairing rules are used to create feasible solutions, whereas population evolution is made using Q-gate rotation strategies and group leader optimization techniques that improve the speed of convergence. The performance of this quantum-inspired hybrid approach in solving IPPS instances was assessed and it was found that it yielded better results than conventional methods. The study confirms the fact that the suggested algorithm leads to the substantial minimization of the makespan thereby reconciling the complexities of process planning with the requirements of the job shop scheduling [70]. This method not only demonstrates practical application of the principles of quantum computational in the traditional production processes but also opens new perspective for the increase of efficiency and quick response of the production systems.

5.1.1 Open problems in Quantum Optimization

There is one major open problem that is related to the field of quantum optimization algorithms and it is scalability and applicability of the quantum optimization algorithms to the real-world problems in large complex multi-objective domains such as automotive industry. Although successful solutions have been shown in ideal scenarios such as the QAOA for vehicle routing or QGA for powertrain optimization, these methods have many drawbacks when implemented in complex, actual-world problems. The enhancement of Battery Management Systems (BMS) in electric vehicles, energy management in microgrids and integrated process planning and scheduling (IPPS) in manufacturing industries all require quantum algorithms that can solve multiple objectives, dynamic environments, and large datasets. However, the incorporation of these quantum algorithms with the current classical approaches in a quantum-classical combined structure is still a topic for further research, especially to solve problems such as the speed of convergence, stability, and the computational complexity of quantum solutions. Mitigating these challenges would be important for the unlocking of quantum optimization algorithms in revolutionizing the automotive and related industries.

5.2 Quantum Annealing

Automated path optimization

Many of the conventional optimization techniques prove unsuitable for the path planning of robots especially when there are many robots involved and the environment is nonlinear and full of obstacles. In manufacturing on how to make robotic movements economical and efficient, especially as automotive manufacturers which enhance the speed and exactness of production lines. The authors [80] suggest a quantum annealing, a technique for quantum computing, to reduce costs associated with millions of movements of robots in the manufacturing industry. Many of the conventional optimization techniques prove unsuitable for the path planning of robots especially when

there are many robots involved and the environment is nonlinear and full of obstacles. This challenge can result in some movements being inefficient which subsequently increases time taken to produce a product and increases the cost of operations.

The core problem in optimizing robotic movement can be mathematically formulated as minimizing a cost function $C(x)$, where x represents the sequence of movements for the robot. The objective is to minimize the total distance traveled and the time taken while avoiding collisions and ensuring the robot follows a feasible path. The cost function can be expressed as [80]:

$$C(x) = \int (f(x(t), \dot{x}(t)) + g(x(t)))\, dt$$

Here, $x(t)$ denotes the position of the robot at time t, $\dot{x}(t)$ denotes the velocity of the robot at time t, f is a function that quantifies the efficiency of movement considering both distance and speed, and g accounts for additional costs such as energy consumption or deviation from a predefined path.

Minimize the following cost function:

$$\textbf{minimize } C(x) = \sum_{i=1}^{n} d_i + \lambda \sum_{j=1}^{m} t_j + \mu \sum_{k=1}^{o} c_k$$

where:

- d_i represents the distance components,
- t_j represents the time components,
- c_k represents the collision avoidance components,
- λ and μ are weighting factors that adjust the importance of time and collision components relative to the distance.

Lets consider a case in which several robots are used in a car assembling line and their purpose is to assemble car parts. The traditional approach to planning can generate suboptimal paths in which the robots might chose longer paths or wait for other robots to clear the area before moving and thus be inefficient. When using an FA based on quantum annealing, the work derives the best correspondences in movements that entail the smallest distance and time required from the start for the robots while avoiding the rebooting of other robots during their operation. The process of quantum annealing is actually a process of exploring a truly immense number of possibilities and finding the most efficient paths, which are not identifiable using other approaches.

Multi-Car Paint Shop Optimization

It is a complex problem of minimizing the number of color changes between consecutive cars in a production line , an NP-hard problem critical to the efficiency of automotive production. To solve this problem, the researchers utilize quantum annealing, employing the D-Wave 2000Q and Advantage quantum processors to represent and solve this problem as an Ising Hamiltonian. This quantum scheme is pitted against

either classical solvers or D-Wave Systems provided quantum-classical hybrid algorithm [24]. The problem can be expressed as minimizing an objective function $C(x)$, where x represents the sequence of vehicles, and the function includes terms for both the total painting time $T(x)$ and the number of color transitions $S(x)$:

$$\textbf{minimize } C(x) = T(x) + \alpha \sum_{i=1}^{n-1} S(x_i, x_{i+1})$$

In this equation, $T(x)$ represents the total time required to paint all vehicles in sequence x, $S(x_i, x_{i+1})$ represents the cost (in terms of time and resources) of changing from the paint color required by vehicle x_i to that required by vehicle x_{i+1}, and α is a weighting factor that balances the trade-off between minimizing total time and reducing the number of color transitions.

The methodology is based on the fact that the MCPS problem is encoded with the use of real data from a factory in Wolfsburg, Germany, and solved by the way of quantum annealing, which is a new way of solving the optimization challenges due to the properties of quantum bits (qubits) to look for their lowest energy states. The study highlighted that quantum annealing is most appropriate for small problems, however, its performance approaches a simple greedy algorithm as sizes increase, reflecting the limitations of current quantum technologies to scale to more complex problems [24]. However, the analysis does offer good information as to the quantum annealing as an appropriate tool for the industrial application revealing that it well reduces the expenses for a frequent color changing at the car production. This research does not only suggest the potential of quantum computing in revolutionizing the traditional manufacturing processes, but it also says that the quantum technology should be pushed further to realize its full potential for big-scale industrial applications [24].

Sensor Placement Optimization

It is a challenging problem of indicator-positioning optimization on vehicles which are critical to achieving desired performance and safety levels, which are especially important in autonomous driving system context. The operation of this work is through a qubit-based hybrid of quantum computing and classical computing which is formidable enough to greatly improve this optimization problem. The study combines a quantum algorithm of higher power with the classical counterpart in the context of strategic segmentation of the sensor placement and superiority of the technique in the solution to small problems that the classical algorithm can fail to solve [81]. The base quantum methodology considers the Quadratic Unconstrained Binary Optimization (QUBO) problem as this is fed to the quantum algorithm. It solves the optimal sensor configuration problem when classical methods are computationally expensive due to the exponential growth of the number of possible combinations when adding a new dimension and or a constraint. The process hybridization provides substantially supplement to speed and quality and also reports the accuracy improvement in both the vehicle sensors performance and the blind spot optimization [81]. Through this process, it achieves the employment costs reduction. This study s main point is that

the quantum computing can be a revolutionary factor in the optimization of automotives. It also proffers us a peek at what sort of a world there would be for the next generation cars with improved performance and safety.

Traffic Signal Control

Quantum annealing can be employed in an innovative way to optimize traffic light control and thus improve traffic flow in grid-structured road networks [74]. This study is focused on real-time traffic management, which is an important problem for urban centers everywhere. Quantum annealing is used through the representation of the traffic signal control problem as a Quadratic Unconstrained Binary Optimization (QUBO) problem, which is naturally adequate for processing on quantum annealers because of its equivalence with the Ising model in statistical mechanics [74]. The approach takes advantage of DWave Systems's quantum annealer, one of its strengths being that it has the ability to find ground states of intricate energy landscapes, which are the best suited traffic signal settings that reduce traffic jam. The present quantum hardware has a limited number of qubits and connectivity, therefore, a hybrid classical-quantum approach is used. This method of traffic signal optimization is based on periodically updating the QUBO model with live traffic data and solving it using the quantum annealer and, therefore, it offers a dynamic solution to the problem [74].

This problem is aggravated by the dynamic state of traffic flow, which includes different intensity levels of traffic and the presence of emergency automotives. The problem can be expressed as minimizing the total delay D. This delay D must be minimized across all intersections while considering factors that enhance the free flow of traffic and the safety of users. The objective function can be expressed as:

$$\textbf{minimize } D = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} w_{ij} T_{ij} \right)$$

Here, D represents the total delay across all intersections, T_{ij} is the delay at intersection i for traffic phase j, and w_{ij} is a weight factor that reflects the importance of minimizing delay at that specific phase or intersection.

Lets assume about a system of intersections where every intersection has several stages for example for straight vehicles, turning left or right, or crossing the pedestrian walkway. That is, the question is how long each phase should last at each intersection to minimize the total time loss. As pointed out by the authors, the timing sequences can be easily and efficiently sought by quantum annealing for this kind of combinatorial optimization problem because it can generate a tremendous number of sequences. Using concepts of quantum annealing, the right set of signal timings can be obtained and the flow of traffic through the network may be enhanced to a large extent, with concomitant improvement in travel times.

The outcomes of this research demonstrate a significant decrease in average traffic delay times, thus, providing a practical ability of quantum annealing to tackle dynamic and complex urban traffic management issues. The study identifies an opportunity of quantum computing technologies to bring a deep impact to real-life applications, introducing the new methods of preventing the overcrowding of cities and enhancing urban mobility [74].

Vehicle Arrangement

The application of quantum annealing to optimize the production scheduling of test vehicles is known as a difficult problem to solve due to the complexity of manufacturing processes [73]. This research also combines constrained quantum annealing with classical optimization methods to create a solid hybrid model, which improves effectiveness and flexibility of production planning. The methodology utilized is based on a hybrid quantum-classical approach where quantum annealing is implemented to solve the strongly non-linear and restrictive parts of the scheduling problem, whereas classical methods are used to improve and validate the solutions produced by the quantum process. This strategy enables the solution of certain production constraints, such as line balancing and resource allocation since these are hard to be optimized by classical techniques only because of their combinatorial complexity [73]. Solving combinatorial optimization problems aims to reduce the total amount of time it takes to produce the product, utilize resources optimally, and incorporate imposed constraints. Stating the problem mathematically, we have to work with an objective function $F(x)$, where x represents the set of decisions such as scheduling and the resources that must meet a set of constraints $C_i(x)$:

$$\textbf{minimize } F(x) = \sum_{i=1}^{n} T_i(x) + \lambda \sum_{j=1}^{m} P_j(x)$$

Here, $T_i(x)$ represents the production time for test vehicle i, $P_j(x)$ represents the penalty for violating constraint j, and λ is a penalty weight that balances between minimizing time and constraint violations.

For instance, if there is a need to design a production time table to assemble certain test vehicles where an organization has few opportunities to access some testing hardware and specific components then the hybrid quantum approach will assist to determine the best feasible time table that will decrease production downtimes and different resources clashes. The presented approach is an integration of quantum annealing into the problem solving, which allows to search through a wider solution space than classical algorithms in reasonable time, which could open way to improving the automotive production planning. The findings of this hybrid model show an enhancement in the optimization of production timelines and resource utilization as well as a decline in the overall production costs. [73].

5.2.1 Open problems in Quantum Annealing

Another major concern of the quantum annealing in the automotive industry is the scalability and real-time applicability of the same in complex and dynamic systems. Quantum annealing has been found to be effective in optimizing specific tasks like path planning for multiple robots, paint shop for multiple cars, and production scheduling but its performance reduces with increase in size and complexity of problem. The current quantum hardware architecture constraints in the number of qubits and the connectivity between them prevent the scaling of these solutions to more complex, practical problems. Furthermore, some of these problems have been solved using

quantum-classical combination, but they lead to the growth of additional computational time and do not reveal the full potential of quantum annealing. For quantum annealing to be a useful tool for large scale optimization in industries, there is need for improvement in both the physical implementation of the quantum annealer as well as the algorithms that can be implemented on the quantum annealer due to the exponential growth in the number of possibilities. This includes the enhancement of the approach of incorporating quantum annealing with classical optimization algorithms to address intricate systems such as traffic control, vehicle manufacturing scheduling, and robot motion planning in real-world manufacturing environments.

5.3 Quantum Secure Communications

Secure Quantum Communications for V2I

The scholars incorporate the Quantum Key Distribution (QKD) in vehicle-to-infrastructure (V2I) communications as a means of improving security against quantum computing threats [68]. which is critical because it is expected that the current cryptography would become obsolete in view of the innovations in quantum computing. The methodology integrates QKD, a quantum-secure communication protocol based on the laws of quantum mechanics for producing secure keys, with Software-Defined Networking (SDN) to dynamically and effectively manage network resources [68]. The integration ensures the development of an adaptable and effective propagation of secure communication channels in V2I networks making it a critical factor for security of future connected and autonomous vehicles (CAVs). The system introduced uses QKD to shield data transmissions from quantum and classical computational hazards, thus, guaranteeing multi-level security sustainability [68]. The study introduces an innovative design which accommodates the incorporation of QKD systems into an SDN framework thus ensuring simplified security management among other network performance improvements. According to the findings, this method is effective in developing a scalable and secure network architecture to meet the high-security requirements of the future transport systems. The implementation ensures that V2I communications are not only secure from likely quantum attacks, but it also optimizes for speed that such a combination of quantum security technologies and traditional network notions is achieved is a significant step forward [68].

Quantum Computing in Autonomous Driving

There is a problem of Traffic data occlusion in Computer vision algorithms. This problem influences the accuracy of traffic management and analysis algorithms, as the vehicles or other objects are only partially visible in video streams. This researchers proposes a novel approach that merges the DeepSORT algorithm (a leading method for object tracking in computer vision) with the quantum computing techniques that enable improving processing powers and eliminating limitations of classical computing [69]. The method is realized by the aid of quantum computing to accelerate some computationally intensive tasks in the DeepSORT framework particularly in solving the data association problem where the algorithm is required to associate detected objects across frames in a video sequence. Through the parallel processing functionality of quantum computers, the modified DeepSORT algorithm handles occlusions

better and can classify objects that are too close to each other or overlayed with a higher degree of accuracy [69]. The results of the performed research indicate high growth in the precision of tracking and uniformity of the system, even in heavy traffic situations where blockage is very common. In more detail, quantum-enhanced DeepSORT algorithm revealed the improved precision and recall measures in comparison to the corresponding classical version, which was the less number of false positives and general stability of the traffic monitoring system [69]. The application of quantum computing in the analysis of traffic data solves both the short-term problem of occlusion and represents the first step in a long journey of quantum technologies in very sophisticated real-world problems of computer vision and even beyond.

5.3.1 Open problems in Quantum Secure Communications

A current major issue in Quantum Secure Communications, especially concerning V2I systems, has been the issue of how to incorporate QKD into massive, real-time networks that are also complex and efficient. While QKD provides a theoretically impregnable way of protecting the communication against quantum attacks, it is not easy to implement it in real-world scenarios like CAVs. These are the high resource consumption in QKD, the requirement of a proper physical layer that can support the physical layer needs such as line of sight in free space optical system, and the compatibility of the proposed solution with other current network architectures such as SDN without the compromise of performance. Further, there is an urgent need to come up with solutions that can address the current QKD technology limitations such as the latency and bandwidth of the current technology, especially when it comes to networks that involve up to thousands of vehicles that are communicating at the same time. To unlock the potential of quantum-secure communications in the automotive industry and to safeguard the future transport systems from the new age of quantum threats, these challenges have to be addressed.

5.4 Quantum Neural Networks

Supply Chain Logistics

The optimization of supply chain logistics in the automotive industry is a formidable challenge, particularly due to the complexity and scale of operations involved. The article by [82] explores the use of Quantum Neural Networks (QNNs) as a novel approach to address this challenge. Traditional methods often struggle with the massive data sets and intricate relationships between variables in supply chain logistics, leading to inefficiencies and increased costs. The dynamic nature of supply chains, where demand, supply, and transportation conditions can change quickly and necessitate real-time adjustments, exacerbates the problem.

In this context, QNNs offer a promising solution by leveraging quantum computing to handle the vast amounts of data and complex optimization problems more efficiently than classical methods [82]. The mathematical foundation of this approach can be expressed through the optimization of a cost function C, which represents the total logistics cost, including transportation, inventory holding, and penalty costs for delays. The objective function can be defined as:

$$\textbf{minimize } C = \sum_{i=1}^{n} (T_i \cdot d_i + H_i \cdot I_i + P_i \cdot L_i)$$

Here, T_i represents the transportation cost per unit distance for item i, d_i is the distance traveled, H_i is the holding cost per unit for item i, I_i is the inventory level, P_i is the penalty cost per unit delay for item i, and L_i is the delay in delivery. The challenge lies in optimizing this cost function while accounting for the complex inter-dependencies and real-time data within the supply chain.

Car Classification with Hybrid Quantum Neural Networks

Tuning hybrid quantum neural networks (HQNNs) for vehicle classification tasks is a difficult problem. This research is critical as it combines quantum computing capabilities with neural network approaches to solve problems of classification, which are usually computationally expensive and resource-consuming so the researchers uses a hybrid quantum-classical model where quantum circuits are combined with classical neural network layers to adjust the model's hyperparameters efficiently [78].

The optimization problem can be described as minimizing the loss function $L(\theta)$, where θ represents the vector of hyperparameters that influence the training process. The objective function is defined as:

$$\textbf{minimize } L(\theta) = \frac{1}{m} \sum_{i=1}^{m} \ell\left(f(x_i; \theta), y_i\right)$$

In this equation, $L(\theta)$ represents the average loss across the training dataset, ℓ is the loss function (such as cross-entropy), $f(x_i; \theta)$ is the output of the hybrid QNN given the input x_i and hyperparameters θ, and y_i is the true label for the i-th sample. The aim is to find the optimal set of hyperparameters θ^* that minimizes this loss function, thereby enhancing the classification accuracy of the model.

A quantum-enhanced optimization algorithm is the main technique used, aiming to reconcile the phases of exploration and exploitation throughout the training process thereby seeking to find an optimal set of hyperparameters that decreases error rates and improves classification accuracy [78]. The results show that this method is not only more accurate compared to purely classical or quantum methods but also provides computational efficiency enhancement. With the parameter space effectively reduced as well as the time for convergence being shortened, HQNNs outperform traditional deep learning models in speed and accuracy for vehicle classification tasks [78]. This move highlights the possibility of quantum technologies to change machine learning related tasks through the provision of more effective and powerful instruments of handling huge and sophisticated dataset [83].

5.4.1 Open problems in Quantum Neural Networks

Among the most important unsolved issues related to QNNs and their further enhancement and implementation, it is possible to mention the following: The questions of QNNs' scalability and their integration into real-time big data systems with the focus on the automotive industry, especially in the sphere of supply chain management

and classification. Despite the fact that QNNs have demonstrated the capability of efficiently processing large datasets and optimizing problems with many variables as compared to the traditional approaches, the application of QNNs is restricted by the number of qubits and error rates in the current quantum hardware. Also, the fine-tuning of QNNs to achieve the right trade-off between exploration and exploitation during the learning process, particularly when QNNs are used in conjunction with classical NNs in the form of the hybrid models, is still a problem. This is important for operations that involve real time decision making such as in supply chain management, especially in the routing and scheduling of deliveries. The open problem is focused on further enhancement of the QNN architectures and algorithms that can be easily incorporated into the existing systems, whose performance will be enhanced in various applications without limitations of the present quantum technologies. Solving these issues is crucial for achieving the intended purpose of QNNs in the industries that require massive data analysis and intricate decision-making.

5.5 Quantum Frameworks and Software Development

Quantum Software Development for Automotive

Design and application of quantum framework based on automotive embedded operating system, presented an innovative solution for increasing the automotive embedded application systems reliability and performance through a quantum framework approach [72]. One of the main difficulties in this study is presentation of various complex design tasks of embedded systems and their insurance against prospective damages that may occur under the harsh conditions of applications in the automotive industry. The approach choice uses a quantum framework that is able to cover the entire embedded operating system and make sure that it can keep track of all the aspects very well such as the active objects and hardware interrupt service routines [72]. This method is then followed for dealing with asynchronous events along with resources, which eventually results in optimal management of critical issues like deadlock among other hazards common to multitask automotive software. The obtained results prove the system showed a significant performance improvement and great reliability as the framework outperforms traditional systems in terms of handling more concurrency and resource management This quantum-based format not only offers a more resilient platform for the development and deployment of vehicle applications, but could be the springboard toward the application in other high demand areas such as aerospace industry and others [72]. The research strongly substantiates that the quantum technologies may play a key role in automotive developments of tomorrow enabling them to be more advanced, sophisticated and problem solving.

5.5.1 Open problems in Quantum Frameworks and Software Development

An important open question in the field of Quantum Frameworks and Software Development remains the development of sound quantum frameworks that can efficiently and robustly address the challenges and requirements of embedded systems in automotive and other critical domains. As mentioned above, there are several ongoing

advancements made in creating quantum-based frameworks for automotive embedded operating systems that improve the reliability, performance, and concurrency management of the system, there are still challenges that have to be addressed. These are, for example, the control of the quantum instability and errors, the real-time control in case of time-sensitive applications, and the integration with other existing classical systems. Moreover, the creation of quantum software that would be able to organize asynchronous events and resources and avoid problems like deadlock in the multitask operations is also an important topic for the further study. When moving forward in the development of quantum technologies, it will be important to design software frameworks that will not only take advantage of quantum computing features but will also solve such practical problems, so that quantum enhanced systems could be used in the automotive industry and other fields. This will require surmounting present hardware constraints, developing efficient quantum-classical architectures that are easy to integrate, and guaranteeing that these systems are robust to the hostile environment characteristic of automotive as well as aerospace settings.

5.6 Technology Readiness Levels

The development status of quantum technology in automotive sector is demonstrated the Technology Readiness Levels (TRLs) in Table 5 . The applications include traffic flow optimization and sensor placement and battery material simulation and autonomous vehicle perception with TRLs between 3 and 7. The development stages of quantum technologies are shown through these levels which start with early-stage research and simulation and progress to demonstrated use in pilot projects and industry trials. The readiness descriptions show the exact advancements achieved in each field through validation of industry datasets and prototype development and ongoing research. The TRL definitions use the standard NASA/EC scale from 1 to 9 which begins with basic research at TRL 1 and reaches full commercialization at TRL 9.

The unified evaluation framework is propose that provide a scoring matrix to rank and prioritize various quantum computing applications in the automotive industry which assesses them based on four criteria in Table 6:

- Feasibility: Whether the problem is tractable using current or emerging quantum methods.
- Readiness: Maturity of the associated quantum technique and its alignment with available hardware.
- Impact: Potential effect on performance, cost reduction, efficiency, or innovation within the automotive domain.

Each application area is rated on a scale from 1 to 5, where a higher score indicates better performance in the respective category. The table shows the relative priority of these applications based on their combined scores, which provides a strategic view of where quantum technologies could have the most significant impact in the automotive sector.

Table 5: Technology Readiness Levels (TRLs) of Quantum Applications in the Automotive Sector.

Application Area	Quantum Approach	TRL (1–9)	Readiness Description
Traffic Flow Optimization	Quantum Annealing (D-Wave)	5–6	Demonstrated in simulated and pilot settings (e.g., Lisbon quantum routing by Volkswagen)
Multi-Car Paint Shop Scheduling	QAOA / Quantum Annealing	5	Validated with industry datasets; early-stage trials, not yet production-ready
Sensor Placement Optimization	Hybrid Quantum-Classical QUBO	4–5	Prototypes and small-scale implementations in simulated vehicle environments
Battery Material Simulation (EVs)	Quantum Chemistry Simulations (VQE, QML)	3–4	Early-stage lab validation; significant hardware and algorithmic limitations remain
Autonomous Vehicle Perception	Quantum Neural Networks (QNNs)	3–4	Research and simulation phase; experimental integration with classical vision pipelines
Vehicle-to-Infrastructure (V2I) Secure Comms	QKD (Quantum Key Distribution)	4–5	Field-tested in other domains (e.g., telecom); limited but growing automotive integration
Production Planning / Scheduling	Quantum-Inspired Algorithms (Hybrid QGA)	6–7	Demonstrated in realistic manufacturing contexts with near-term benefits observed
Charging Station & Battery Swapping Optimization	Quantum Swarm Optimization, QPSO	4–5	Algorithm-level validation using real datasets; some deployment feasibility demonstrated
Supply Chain & Logistics	Hybrid Quantum Annealing, QNN	5–6	Validated in simulation; partnerships with OEMs show early traction

Note: TRLs are adapted from the standard 1–9 NASA/EC definitions [84], where TRL 1 indicates basic research, and TRL 9 indicates full commercial deployment in operational settings.

Table 6: Score Matrix of Quantum Computing Applications in the Automotive Industry

Application Area	Quantum Method	Feasibility (1-5)	Readiness (1-5)	Potential Impact (1-5)	Overall Priority
Traffic Signal Control	Quantum Annealing	5	4	4	1
Vehicle Routing Optimization	QAOA	4	3	5	2
Paint Shop Scheduling	QAOA	4	3	4	3
V2X Secure Communications	Lattice/QKD	3	3	4	4
Sensor Placement	Hybrid	3	2	4	5
Battery Design (Quantum Simulation)	Quantum Sim.	2	2	5	6

Note: Feasibility, Readiness, and Potential Impact are rated on a scale of 1 to 5, with 5 being the highest rating. The Overall Priority reflects the combined assessment based on these scores.

6 Collaborations in Quantum Computing: Addressing Optimization Issues in the Automotive Industry

Automobile manufacturers and quantum computing startups are working together to enhance aspects such as battery longevity and car setup. Quantum computing's transformative potential is receiving more attention, as already discussed in the quantum solution section.

Volkswagen

Volkswagen are leading in the research of the vast possibilities of quantum computing, With a focus on diverse applications that could immensely change the automotive industry. They have concentrated on creating smart and effective transport solutions, for example, the ability to find the nearest charging station for an electric car or available parking space [85]. Substantial resources have been devoted to quantum research to address challenging optimization issues; their Quantum Routing project in Lisbon enhanced the effectiveness of public transportation through dynamic traffic management [24]. Furthermore, Volkswagen is moving forward with battery production through the use of quantum computing with institutions such as Cambridge Quantum Computing and Google Quantum AI. Their long-term goal also includes protecting automotive systems from future quantum threats.

Toyota

In 2017 Toyota collaborated with D-Wave Systems to investigate the application of quantum computing in improving the future cars. This partnership was a major milestone in using quantum computing's huge computational capabilities for the automotive sector. In 2022, Toyota Tsusho, Toyota's trading company, entered into a partnership with Quantum Machines to develop quantum technologies in Japan with the goal of incorporating them in Toyota's cars [86]. Toyota has been involved in hybrid electric vehicles and battery technology through the Prius model and is now using quantum computing to model and find better materials for EV batteries that may enhance energy storage, charging, and battery life [87][88]. These initiatives demonstrate Toyota's commitment to innovation and its smart decision to use quantum computing in its upcoming automotive developments.

Ford

Ford Motor Company has adopted quantum computing by partnering with Quantinuum to work on the future of electric vehicle (EV) battery. Ford's research team has been able to gain a lot of insights into lithium-ion battery chemistry using Quantinuum's InQuanto quantum chemistry platform [89]. Their research is to predict and find new materials for the next generation of EV batteries with improved energy density and stability. Also, Ford is working on creating specific quantum algorithms for traffic management that can help minimize traffic issues in cities, consumption of fuel, and emissions, thus contributing to the achievement of sustainable development objectives worldwide [90]. Ford's investment in quantum computing places them in the right side of history when it comes to the development of batteries and smart cities [91].

BMW

BMW, a pioneer in automotive manufacturing, is already on the lookout for quantum computing to transform mobility services and production lines. In 2022, BMW collaborated with Amazon Web Services (AWS) to host the 'Quantum Computing for Automotive Challenges' where experts used quantum computing to solve intricate optimization issues, which is in line with BMW's focus on innovation. Also, BMW's

strategic collaboration with PASQAL, a quantum processor maker, is to employ quantum computing in modeling metal forming in manufacturing to advance materials science and manufacturing effectiveness [92]. These measures show that BMW is a pioneer in the progressive development of new technologies and the adaptation of the car industry, as well as the creation of new standards for environmental friendliness and performance.

Mercedes-Benz

A team at Mercedes-Benz Research and Development North America (MBRDNA) is using quantum computing to transform multiple automotive fields, such as batteries, aerodynamics, and production lines. Founded in 2018, this team based in Silicon Valley works with such giants as IBM and Google to create software and algorithms that can solve problems that were previously considered to be unsolvable [93]. Their work is dedicated to improving battery technology using quantum computing to help advance the creation of better and greener battery systems [94]. Lithium-sulfur (Li-S) batteries are also being developed by Daimler as they have higher energy density than lithium-ion batteries, which can enhance the range and efficiency of electric vehicles [95, 96]. Quantum computing helps to model the intricate chemical processes that occur and thus advances the battery materials and construction [94, 97, 98]. Furthermore, Mercedes-Benz is using quantum-powered modeling in manufacturing to increase accuracy, minimize losses, and optimize production, which will further establish them as leaders in the automotive industry and their dedication to a better and more efficient future [99–101].

Hyundai

Hyundai Motor Group, a South Korean car manufacturer, has joined forces with IonQ, a trapped-ion quantum processors company, to develop new electric vehicle (EV) technologies through quantum computing. This pioneering partnership is expected to transform battery science by creating novel quantum algorithms to simulate lithium materials and their chemical interactions. Quantum simulations allow for detailed study of battery performance during charge and discharge cycles, improving battery durability, capacity, and safety [102]. While quantum computing is still a relatively young field, its applicability in the automotive industry is gradually being realized, as evidenced by this collaboration. More partnerships are anticipated as OEMs keep on venturing into quantum computing. According to McKinsey, by 2030, quantum computing could generate a major economic effect on the automotive industry, ranging from 2 billion to 3 billion, and provide great opportunities for pioneers and leaders [103].

7 Conclusion

Quantum computing is on the cutting edge of game-changing technologies. It is set to tackle the toughest challenges that the automotive industry faces in terms of complexity and computational demands. By applying the principles of quantum mechanics,

this new area holds promise to offer exciting progress in many key application areas, with its capacity to handle intricate problems across diverse dimensions.

The automotive industry is experiencing a transformative change through quantum computing which solves complex problems that classical methods cannot handle. The report shows how quantum technologies are currently used in vehicle design and classification, transportation infrastructure, power distribution, self-driving technology, supply chain logistics, embedded systems and battery optimization and demonstrate improvements compared to classical computers in several dimensions: better accuracy, faster training times, better reliability in multitasking operations under limited resource conditions, and efficient simulation of physical systems, e. g., of chemical compounds, beyond what is possible classically.

The readiness and feasibility assessment of Technology Readiness Levels across different applications in Table 5 shows a range from 3 to 7, which indicates research activities, pilot trials and early-stage implementations. The feasibility-readiness-impact matrices show that traffic optimization and battery swapping applications have the highest potential impact.

Since quantum computing technology is still under intense development, as the publication trend in Figure 5b and the correlation between citations and publication years in Figure 5c indicate, and not yet fully mature (see Table 5), the use of quantum computing in the automotive industry is still understandably at an early stage of development and its solutions are not widely implemented in practical applications yet. As a matter of fact, the current quantum devices used, mostly referred to as Noisy Intermediate Scale Quantum (NISQ) systems, face limitations such as noise interference, decoherence issues, and a restricted capacity of qubits, which hinder their ability to solve large-scale problems encountered in industrial settings. Furthermore, the expected improvements in processing speed through quantum algorithms rely heavily on the existence of fault-tolerant quantum systems, but it is anticipated that such systems may not be available for another ten years or more. Despite these shortcomings, progress in quantum technology is advancing quickly owing to companies like IBM and Google making strides in the field alongside D-Wave Systems, and the obstacles are diminishing for the automotive industry as they journey towards implementing quantum powered solutions on a practical level.

Directions in Quantum Computing for Automotive Applications

Technical obstacles remain substantial including the quantum hardware constraints above (noise, scalability, fabrication variability), despite the significant progress the field has made, and in order to fully harness the power of quantum computing, in the automotive sector several key technical and research areas need to be given top priority. The current open problems in QNNs and software frameworks demonstrate the immediate requirement for better hybrid quantum-classical architectures together with robust error correction and workload distribution middleware solutions. Combinatorial Optimization encompasses challenges in the automotive sector, like route optimization and traffic flow control in supply chain logistics operations, that are crucially significant. Cutting-edge algorithms such as the Quantum Approximate Optimization Algorithm (QAOA) and Variational Quantum Eigensolver (VQE)

hold potential for overcoming these hurdles, especially when employed in a blend of quantum and classical computing environments, as analyzed in Table 2. Dynamic programming techniques have the potential to elevate fleet management system efficiency and enhance real-time routing for vehicles through Quantum enhanced dynamic programming strategies.

In principle, material design for batteries and energy systems can leverage simulations to predict interactions and advance the creation of durable yet lightweight materials. One prominent example is the modeling of a Lithium-ion battery solid electrolyte interphase that forms at its anode, which is still unsatisfactory due to the limitations of current techniques. A quantum computer could simulate accurately the dynamics of the system. However, quantum algorithms for the simulation of key properties of Lithium-ion batteries are constrained to be fault-tolerant [104], or designed for NISQ devices [105].

Quantum computing plays a role in managing energy by optimizing the distribution of power within electric vehicle charging networks and designing effective power systems for streamlined vehicle-to-grid (V2G) operations. Autonomous systems involve the use of quantum-enhanced machine learning algorithms that can speed up the training of vehicle systems by enhancing decision-making abilities and improving object detection and predictive analytics tasks effectively and efficiently. Another perk is that optimization emulation, through QML techniques, can simulate optimization procedures to facilitate quicker development cycles for vehicle software creation.

Quantum error correction is an area of interest to minimize errors and enhance the reliability of computations in the quantum realm. Surface codes and robust quantum gates play a role in enabling quantum algorithms to be practical for use in industries. Adopting noise circuit designs and incorporating hybrid quantum classical approaches are crucial steps in overcoming the current obstacles presented by NISQ systems.

Specialized quantum algorithms designed for automotive purposes, like optimizing real-time operations in autonomous systems or predicting maintenance needs in manufacturing, play a crucial role in fully utilizing quantum systems potential benefits. Hardware-specific innovations, such as cryogenic interfaces for automotive environments, can enhance the integration of quantum systems into existing workflows.

Integration and Collaboration Strategies

For the foreseeable future, hybrid systems that partition tasks between classical and quantum computing will dominate. Research should focus on middleware solutions that facilitate this integration and optimize workload distribution between the two paradigms. Automotive manufacturers must partner with quantum computing experts and academic institutions to conduct pilot projects that explore quantum applications. For instance, projects could investigate traffic optimization at a city-wide scale or simulate complex scenarios in vehicle design. Establishing benchmarks for automotive-specific quantum computing problems is critical to measure progress and guide algorithm development. Metrics like quantum volume and circuit layer operations per second (CLOPS) should be contextualized for automotive applications to track advancements effectively [106]. The ethical and societal issues emerging

from quantum powered systems, such as data privacy risks, cybersecurity threats, and potential workforce displacements, need to be dealt with by policymakers. Open research efforts and national projects for quantum infrastructure are crucial to guaranteeing access to this revolutionary technology. Regulations should consider the effects as well when it comes to quantum systems impact on energy usage for big tasks; while quantum technology may save energy on a large scale job level, the power needs of quantum devices, like cooling necessities, must have eco-friendly solutions in place too for sustainability purposes. The quantum energy initiative programs aim to create power structures that support global sustainability objectives by integrating quantum computing capabilities effectively.

Regulatory, Ethical, and Societal Implications

From a perspective, it is important for the regulations concerning quantum-assisted automotive technology to progress and adapt accordingly. There are concerns surrounding liability issues, judgment, and privacy of data in the context of autonomous systems that utilize quantum computing. It is vital for policymakers and experts to work together in order to set guidelines that ensure safety, transparency, and equity in quantum-powered innovations.

Moreover, the environmental consequences of producing and using quantum hardware are worth considering. It will be crucial to create energy quantum chips and adopt sustainable manufacturing methods to reduce the environmental impact of this technology.

Vision for the Future

In the future, a world where quantum computing could reshape the way we think about transportation and mobility as a whole; envision vehicles that are not just intelligent but also seamlessly interconnected within ever-evolving transit networks. Imagine traffic systems fine-tuned by quantum technology to eradicate gridlock and cut down on emissions—ushering in a new era of city planning and design. Furthermore, progress in quantum simulation might bring about eco-friendly vehicles that prioritize safety and comfort alongside sustainability. Achieving this goal will involve making investments and working together across different fields while staying dedicated to research and innovation efforts over time. Creating quantum systems tailored to the automotive industry's requirements can open up new possibilities for progress and expansion like never before.

In conclusion, quantum computing represents an innovation with the potential to revolutionize the automotive sector significantly. Its capacity to address optimization, security, and simulation challenges presents possibilities for improving vehicle efficiency, environmental impact, and safety. Yet the path to putting this technology into practice is riddled with technical, social, and regulatory obstacles. By tackling these hurdles through targeted research and cross-disciplinary teamwork, the automotive field can fully leverage the power of quantum computing. The merging of quantum technologies with advancements in the industry is set to usher in a new era of smart and eco-friendly transportation systems that will reshape the way we perceive mobility moving forward.

Funding. Authors disclose support for the research of this work from Ferrari and the European Union under the PNRR (National Recovery and Resilience Plan) under Grant No. 2933.

Conflict of interest. The authors declare no conflicts of interest.

Data availability. Not applicable.

Code availability. Not applicable.

Author Contributions. Conceptualization, M.W.A. and S.L.; methodology, M.W.A. and S.L.; validation, M.W.A. and S.L.; formal analysis, M.W.A. and S.L.; data curation, M.W.A. and S.L.; writing—original draft preparation, M.W.A. and S.L.; writing—review and editing, M.W.A. and S.L.; visualization, M.W.A. and S.L.; supervision, S.L.; All authors have read and agreed to the published version of the manuscript.

References

[1] Steane, A.: Quantum computing. Reports on Progress in Physics **61**(2), 117–173 (1998) https://doi.org/10.1088/0034-4885/61/2/002

[2] Zhuang, Y., Azfar, T., Wang, Y., Sun, W., Wang, X., Guo, Q., Ke, R.: Quantum computing in intelligent transportation systems: A survey. CHAIN **1**(2), 138–149 (2024)

[3] Baek, H., Kim, D., Kim, J.: Fast quantum convolutional neural networks for low-complexity object detection in autonomous driving applications. arXiv preprint arXiv:2401.01370 (2023)

[4] Majumder, R., Khan, S.M., Ahmed, F., Khan, Z., Ngeni, F., Comert, G., Mwakalonge, J., Michalaka, D., Chowdhury, M.: Hybrid classical-quantum deep learning models for autonomous vehicle traffic image classification under adversarial attack. arXiv preprint arXiv:2108.01125 (2021)

[5] Perianes-Rodriguez, A., Waltman, L., Van Eck, N.J.: Constructing bibliometric networks: A comparison between full and fractional counting. Journal of informetrics **10**(4), 1178–1195 (2016)

[6] Van Eck, N.J., Waltman, L.: Visualizing bibliometric networks, 285–320 (2014)

[7] Cooke, R.: Meta-Analysis for Psychologists. Springer, ??? (2024)

[8] Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., Lim, W.M.: How to conduct a bibliometric analysis: An overview and guidelines. Journal of business research **133**, 285–296 (2021)

[9] PEREIRA, R.S., SANTOS, I.C., OLIVEIRA, K.D., LEÃO, N.C.: Metanálise como instrumento de pesquisa: Uma revisão sistemática dos estudos bibliométricos em administração. RAM. Revista de Administração Mackenzie **20**, 190186 (2019)

[10] Gusenbauer, M., Gauster, S.P.: How to search for literature in systematic reviews and meta-analyses: A comprehensive step-by-step guide. Technological Forecasting and Social Change **212**, 123833 (2025)

[11] Au-Yeung, R., Chancellor, N., Halffmann, P.: Np-hard but no longer hard to solve? using quantum computing to tackle optimization problems. Frontiers in Quantum Science and Technology **2**, 1128576 (2023)

[12] Symons, B.C., Galvin, D., Sahin, E., Alexandrov, V., Mensa, S.: A practitioner's guide to quantum algorithms for optimisation problems. arXiv preprint arXiv:2305.07323 (2023)

[13] Häner, T., Steiger, D.S., Svore, K., Troyer, M.: A software methodology for compiling quantum programs. Quantum Science and Technology **3**(2), 020501 (2018)

[14] Li, H., Zhang, X., Guo, G., *et al.*: Controlling spins in silicon quantum dots. Journal of Semiconductors **41**(7), 070402–070402 (2020)

[15] Yang, N., Guo, J.: A quantum-computing-based method for solving quantum confinement problem in semiconductor. IEEE Transactions on Electron Devices **70**(3), 1366–1373 (2023)

[16] De Leon, N.P., Itoh, K.M., Kim, D., Mehta, K.K., Northup, T.E., Paik, H., Palmer, B., Samarth, N., Sangtawesin, S., Steuerman, D.W.: Materials challenges and opportunities for quantum computing hardware. Science **372**(6539), 2823 (2021)

[17] Cipriano, L.A., Di Liberto, G., Tosoni, S., Pacchioni, G.: Quantum confinement in group iii–v semiconductor 2d nanostructures. Nanoscale **12**(33), 17494–17501 (2020)

[18] Widdows, D., Rani, J., Pothos, E.M.: Quantum circuit components for cognitive decision-making. Entropy **25**(4), 548 (2023)

[19] Orrell, D., Houshmand, M.: Quantum propensity in economics. Frontiers in Artificial Intelligence **4**, 772294 (2022)

[20] Neukart, F., Compostella, G., Seidel, C., Dollen, D., Yarkoni, S., Parney, B.: Traffic flow optimization using a quantum annealer. Front. ICT **4** (2017)

[21] Singh, A., Lin, C.-Y., Huang, C.-I., Lin, F.-P.: Quantum annealing approach for

the optimal real-time traffic control using qubo. In: 2021 IEEE/ACIS 22nd International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing (SNPD), pp. 74–81 (2021). IEEE

[22] Inoue, D., Okada, A., Matsumori, T., Aihara, K., Yoshida, H.: Traffic signal optimization on a square lattice using the d-wave quantum annealer. arXiv e-prints, 2003 (2020)

[23] Ohzeki, M.: Breaking limitation of quantum annealer in solving optimization problems under constraints. Scientific reports **10**(1), 3126 (2020)

[24] Yarkoni, S., Alekseyenko, A., Streif, M., Von Dollen, D., Neukart, F., Bäck, T.: Multi-car paint shop optimization with quantum annealing, 35–41 (2021). IEEE

[25] Harikrishnakumar, R., Nannapaneni, S., Nguyen, N.H., Steck, J.E., Behrman, E.C.: A quantum annealing approach for dynamic multi-depot capacitated vehicle routing problem. arXiv preprint arXiv:2005.12478 (2020)

[26] Streif, M., Yarkoni, S., Skolik, A., Neukart, F., Leib, M.: Beating classical heuristics for the binary paint shop problem with the quantum approximate optimization algorithm. Physical Review A **104**(1), 012403 (2021)

[27] Awasthi, A., Bär, F., Doetsch, J., Ehm, H., Erdmann, M., Hess, M., Klepsch, J., Limacher, P.A., Luckow, A., Niedermeier, C., et al.: Quantum computing techniques for multi-knapsack problems. arXiv preprint arXiv:2301.05750 (2023)

[28] Wang, Y., Wang, W.: Quantum-inspired differential evolution with grey wolf optimizer for 0-1 knapsack problem. Mathematics **9**(11) (2021) https://doi.org/10.3390/math9111233

[29] Pusey-Nazzaro, L., Date, P.: Adiabatic quantum optimization fails to solve the knapsack problem. arxiv 2020. arXiv preprint arXiv:2008.07456 (2008)

[30] Valiron, B., Mansfield, S., Arrighi, P., Panangaden, P.: Proceedings 17th international conference on quantum physics and logic. arXiv preprint arXiv:2109.01534 (2021)

[31] Heunen, C., Backens, M.: Proceedings 18th international conference on quantum physics and logic. arXiv e-prints, 2109 (2021)

[32] Coecke, B., Leifer, M.: Proceedings 16th international conference on quantum physics and logic. arXiv preprint arXiv:2004.14750 (2020)

[33] Fleury, G., Lacomme, P.: Mathematical foundations of quantum computing for computer science researchers. arXiv preprint arXiv:2303.01938 (2023)

[34] Harwood, S., Gambella, C., Trenev, D., Simonetto, A., Bernal, D., Greenberg,

D.: Formulating and solving routing problems on quantum computers. IEEE Transactions on Quantum Engineering **2**, 1–17 (2021)

[35] Brady, L.T., Baldwin, C.L., Bapat, A., Kharkov, Y., Gorshkov, A.V.: Optimal protocols in quantum annealing and quantum approximate optimization algorithm problems. Physical Review Letters **126**(7), 070505 (2021)

[36] Luckow, A., Klepsch, J., Pichlmeier, J.: Quantum computing: Towards industry reference problems. Digitale Welt **5**, 38–45 (2021)

[37] Nielsen, M.A., Chuang, I.L.: Quantum Computation and Quantum Information. Cambridge University Press, New York (2010)

[38] Mayero, C., Omolo, J.A., Okeyo, S.O.: Theoretical realization of a two qubit quantum controlled-not logic gate and a single qubit hadamard logic gate in the anti-jaynes-cummings model. arXiv preprint arXiv:2103.03297 (2021)

[39] Pronin, C., Ostroukh, A., Maksimychev, O., Kuftinova, N., Yadav, A.: Parametric synthesis of computational circuits for complex quantum algorithms in the transport and road sphere. In: 2022 Intelligent Technologies and Electronic Devices in Vehicle and Road Transport Complex (TIRVED), pp. 1–4 (2022). IEEE

[40] Garey, M.R., Johnson, D.S.: Computer and Intractability. W. H. Freeman and Company, New York (1979)

[41] Pramanik, S., Vaidya, V., Malviya, G., Sinha, S., Salsingikar, S., Chandra, M.G., Sridhar, C., Mathais, G., Navelkar, V.: Optimization of sensor-placement on vehicles using quantum-classical hybrid methods. In: 2022 IEEE International Conference on Quantum Computing and Engineering (QCE), pp. 820–823 (2022). IEEE

[42] Wang, H., Zhao, J., Wang, B., Tong, L.: A quantum approximate optimization algorithm with metalearning for maxcut problem and its simulation via tensorflow quantum. Mathematical Problems in Engineering (2021) https://doi.org/10.1155/2021/6655455

[43] Das, M., Bolisetti, T.: Variational quantum neural networks (VQNNS) in image classification. ArXiv **abs/2303.05860** (2023) https://doi.org/10.48550/arXiv.2303.05860

[44] Sun, T., Xu, M.-h.: A swarm optimization genetic algorithm based on quantum-behaved particle swarm optimization. Computational Intelligence and Neuroscience **2017** (2017) https://doi.org/10.1155/2017/2782679

[45] Muradi, M., Wanka, R.: Sample-based motion planning for multi-robot systems, 130–138 (2020). IEEE

[46] Chu, L., Wang, Y., Li, S., Guo, Z., Du, W., Li, J., Jiang, Z.: Intelligent vehicle path planning based on optimized a* algorithm. Sensors **24**(10), 3149 (2024)

[47] Perez, H.D., Hubbs, C.D., Li, C., Grossmann, I.E.: Algorithmic Approaches to Inventory Management Optimization. Processes **9**(1), 102 (2021) https://doi.org/10.3390/pr9010102 . Number: 1 Publisher: Multidisciplinary Digital Publishing Institute. Accessed 2024-08-20

[48] Gonçalves, J.N.C., Carvalho, M.S., Costa, L.A.: Improving inventory management in an automotive supply chain: A multi-objective optimization approach using a genetic algorithm. Operational Research (2018)

[49] Tang, C.S., Veelenturf, L.P.: The strategic role of logistics in the industry 4.0 era. Transportation Research Part E: Logistics and Transportation Review **129**, 1–11 (2019)

[50] Won, M.: Intelligent Traffic Monitoring Systems for Vehicle Classification: A Survey. IEEE Access **8**, 73340–73358 (2020) https://doi.org/10.1109/ACCESS.2020.2987634 . Conference Name: IEEE Access. Accessed 2024-08-31

[51] Lu, L., Wang, P., Huang, H.: A Large-Scale Frontal Vehicle Image Dataset for Fine-Grained Vehicle Categorization. IEEE Transactions on Intelligent Transportation Systems **23**(3), 1818–1828 (2022) https://doi.org/10.1109/TITS.2020.3027451 . Accessed 2024-08-31

[52] Dabiri, S., Marković, N., Heaslip, K., Reddy, C.K.: A deep convolutional neural network based approach for vehicle classification using large-scale GPS trajectory data. Transportation Research Part C: Emerging Technologies **116**, 102644 (2020) https://doi.org/10.1016/j.trc.2020.102644 . Accessed 2024-08-31

[53] Esmaeili, S., Anvari-Moghaddam, A., Jadid, S.: Optimal operation scheduling of a microgrid incorporating battery swapping stations. IEEE Transactions on Power Systems **34**, 5063–5072 (2019) https://doi.org/10.1109/TPWRS.2019.2923027

[54] Liu, Z., Ma, X., Liu, X., Correia, G.H.d.A., Shi, R., Shang, W.: Optimizing electric taxi battery swapping stations featuring modular battery swapping: A data-driven approach. Applied Sciences **13**(3), 1984 (2023)

[55] Kchaou-Boujelben, M.: Charging station location problem: A comprehensive review on models and solution approaches (2021)

[56] Lam, A.Y.S., Leung, Y.-W., Chu, X.: Electric Vehicle Charging Station Placement: Formulation, Complexity, and Solutions. IEEE Transactions on Smart Grid **5**(6), 2846–2856 (2014) https://doi.org/10.1109/TSG.2014.2344684 . Conference Name: IEEE Transactions on Smart Grid. Accessed 2024-08-21

[57] Sayarshad, H.R.: Optimization of electric charging infrastructure: integrated model for routing and charging coordination with power-aware operations. npj Sustainable Mobility and Transport **1**(1), 4 (2024)

[58] Epping, T., Hochstättler, W., Oertel, P.: Complexity results on a paint shop problem. Discrete Applied Mathematics **136**(2-3), 217–226 (2004)

[59] Zhang, R.: Environment-aware production scheduling for paint shops in automobile manufacturing: A multi-objective optimization approach. International journal of environmental research and public health **15**(1), 32 (2018)

[60] Vijay, R., Cherian, J., Riah, R., De Boer, N., Choudhury, A.: Optimal placement of roadside infrastructure sensors towards safer autonomous vehicle deployments. In: 2021 IEEE International Intelligent Transportation Systems Conference (ITSC), pp. 2589–2595 (2021). IEEE

[61] Eom, M., Kim, B.-I.: The traffic signal control problem for intersections: a review. European Transport Research Review **12**(1), 50 (2020) https://doi.org/10.1186/s12544-020-00440-8 . Accessed 2024-08-17

[62] Farhi, E., Goldstone, J., Gutmann, S.: A quantum approximate optimization algorithm (2014) arXiv:1411.4028 [quant-ph]

[63] Aharonov, D., Dam, W., Kempe, J., Landau, Z., Lloyd, S., Regev, O.: Adiabatic quantum computation is equivalent to standard quantum computation (2005) arXiv:quant-ph/0405098 [quant-ph]

[64] Roland, J., Cerf, N.J.: Quantum search by local adiabatic evolution. Phys. Rev. A **65**, 042308 (2002) https://doi.org/10.1103/PhysRevA.65.042308

[65] Azad, U., Behera, B.K., Ahmed, E.A., Panigrahi, P.K., Farouk, A.: Solving vehicle routing problem using quantum approximate optimization algorithm. IEEE Trans. Intell. Transp. Syst., 1–10 (2022)

[66] Gupta, D.S., Ray, S., Singh, T., Kumari, M.: Post-quantum lightweight identity-based two-party authenticated key exchange protocol for internet of vehicles with probable security. Computer communications **181**, 69–79 (2022)

[67] Guo, Y., Lei, X., Wang, Q.: Capacity coordination planning of isolated microgrid and battery swapping station based on the quantum behavior particle swarm optimization algorithm. Int. Trans. Electr. Energy Syst. **31**(3) (2021)

[68] Stavdas, A., Kosmatos, E., Maple, C., Hugues-Salas, E., Epiphaniou, G., Fowler, D.S., Lord: Quantum key distribution for V2I communications with software-defined networking. IET Quantum Communication **5**(1), 38–45 (2024)

[69] Ngeni, F., Mwakalonge, J., Siuhi, S.: Solving traffic data occlusion problems in

computer vision algorithms using DeepSORT and quantum computing. Journal of traffic and transportation engineering **11**(1), 1–15 (2024)

[70] Liu, M., Yi, S., Wen, P.: Quantum-inspired hybrid algorithm for integrated process planning and scheduling. Proc. Inst. Mech. Eng. Pt. B: J. Eng. Manuf. **232**(6), 1105–1122 (2018)

[71] Yuan, H., Fowler, D.S., Maple, C., Epiphaniou, G.: Analysis of outage performance in a 6G-V2X communications system utilising free-space optical quantum key distribution. IET Quantum Communication **4**(4), 191–199 (2023)

[72] Fang, X., Gao, W., Han, Y., Chen, L.: Design and application of quantum framework based on automotive embedded operating system. In: Easa, S. (ed.) Seventh International Conference on Electromechanical Control Technology and Transportation (ICECTT 2022). SPIE, ??? (2022)

[73] Glos, A., Kundu, A., Salehi, Ö.: Optimizing the production of test vehicles using hybrid constrained quantum annealing. SN Comput. Sci. **4**(5) (2023)

[74] Hussain, H., Javaid, M.B., Khan, F.S., Dalal, A., Khalique, A.: Optimal control of traffic signals using quantum annealing. Quantum Information Processing **19**, 1–18 (2020)

[75] Wang, Y., Sun, D.: Powertrain matching and optimization of dual-motor hybrid driving system for electric vehicle based on quantum genetic intelligent algorithm. Discrete Dyn. Nat. Soc. **2014**, 1–11 (2014)

[76] Weinberg, S.J., Sanches, F., Ide, T., Kamiya, K., Correll, R.: Supply chain logistics with quantum and classical annealing algorithms. Sci. Rep. **13**(1), 4770 (2023)

[77] Schuetz, M.J.A., Brubaker, J.K., Montagu, H., Dijk, Y., Klepsch, J., Ross, P., Luckow, A., Resende, M.G.C., Katzgraber, H.G.: Optimization of robot-trajectory planning with nature-inspired and hybrid quantum algorithms. Phys. Rev. Appl. **18**(5) (2022)

[78] Sagingalieva, A., Kurkin, A., Melnikov, A., Kuhmistrov, D., Perelshtein, M., Melnikov, A., Skolik, A., Von Dollen, D.: Hyperparameter optimization of hybrid quantum neural networks for car classification. arXiv preprint arXiv:2205.04878 (2022)

[79] Asna, M., Shareef, H., Muhammad, M.A., Ismail, L., Prasanthi, A.: Multi-objective quantum atom search optimization algorithm for electric vehicle charging station planning. International Journal of Energy Research **46**(12), 17308–17331 (2022)

[80] Mehta, A., Muradi, M., Woldetsadick, S.: Quantum annealing based optimization of robotic movement in manufacturing. In: Quantum Technology and Optimization Problems: First International Workshop, QTOP 2019, Munich, Germany, March 18, 2019, Proceedings 1, pp. 136–144 (2019). Springer

[81] Pramanik, S., Vaidya, V., Malviya, G., Sinha, S., Salsingikar, S., Girish Chandra, M., Sridhar, C.V., Mathais, G., Navelkar, V.: Optimization of sensor-placement on vehicles using quantum-classical hybrid methods. In: 2022 IEEE International Conference on Quantum Computing and Engineering (QCE). IEEE, ??? (2022)

[82] Correll, R., Weinberg, S.J., Sanches, F., Ide, T., Suzuki, T.: Quantum neural networks for a supply chain logistics application. Advanced Quantum Technologies **6** (2022)

[83] Krause, J., Stark, M., Deng, J., Fei-Fei, L.: 3d object representations for fine-grained categorization. In: Proceedings of the IEEE International Conference on Computer Vision Workshops, pp. 554–561 (2013)

[84] Polzin, K.A., Martin, A.K., Curran, F.M., Myers, R.M., Rodriguez, M.A.: Strategy for developing technologies for megawatt-class nuclear electric propulsion systems. In: 2022 International Electric Propulsion Conference (2022)

[85] Volkswagen AG: Research project successful: Volkswagen IT experts use quantum computing for traffic flow optimization. [Online; accessed 7. Aug. 2023] (2023)

[86] Toyota Tsusho Corporation: Toyota Tsusho Signs MOU with D-Wave Systems Inc.- Using quantum computing-based optimization technology for value-enhancing business - | Toyota Tsusho. [Online; accessed 7. Aug. 2023] (2023). https://www.toyota-tsusho.com/english/press/detail/171114_004066.html

[87] Taniguchi, A., Fujioka, N., Ikoma, M., Ohta, A.: Development of nickel/metal-hydride batteries for evs and hevs. Journal of power sources **100**(1-2), 117–124 (2001)

[88] Scott, A.: Toyota hunts for novel battery materials. Chemical & Engineering News **95**(15), 12–12 (2017)

[89] Lovati, S., Lovati, S.: Ford Enlists Quantum Computing in EV Battery Materials Hunt. EE Times Europe (2023)

[90] Neukart, F., Compostella, G., Seidel, C., Von Dollen, D., Yarkoni, S., Parney, B.: Traffic flow optimization using a quantum annealer. Frontiers in ICT **4**, 29 (2017)

[91] Vella, H.: Quantum transforms travel. Engineering & Technology **14**(4), 50–53

(2019)

[92] Swayne, M.: BMW Group and Pasqal Apply Quantum Computing to Improve Car Design and Manufacturing. Quantum Insider (2022)

[93] Mercedes-Benz Group: Mercedes-Benz Group. [Online; accessed 7. Aug. 2023] (2023). https://group.mercedes-benz.com/company/magazine/technology-innovation/quantum-computing.html

[94] Kemmler, R., Müller, C., Deuschle, T., Liebing, M., Tyslik, S., Blum, V.: The challenges of wltp emission regulations from the vehicle manufacturer's point of view. In: 20. Internationales Stuttgarter Symposium: Automobil-und Motorentechnik, pp. 5–27 (2020). Springer

[95] Panik, F.: Fuel cells for vehicle applications in cars-bringing the future closer. Journal of Power Sources **71**(1-2), 36–38 (1998)

[96] Lamm, A., Warthmann, W., Soczka-Guth, T., Kaufmann, R., Spier, B., Friebe, P., Stuis, H., Mohrdieck, C.: Lithium-ion battery. ATZ worldwide **111**(7), 4–11 (2009)

[97] Hu, Y., Chen, W., Lei, T., Jiao, Y., Wang, H., Wang, X., Rao, G., Wang, X., Chen, B., Xiong, J.: Graphene quantum dots as the nucleation sites and interfacial regulator to suppress lithium dendrites for high-loading lithium-sulfur battery. Nano Energy **68**, 104373 (2020)

[98] Yu, B., Chen, D., Wang, Z., Qi, F., Zhang, X., Wang, X., Hu, Y., Wang, B., Zhang, W., Chen, Y., *et al.*: Mo2C quantum dots@graphene functionalized separator toward high-current-density lithium metal anodes for ultrastable Li-S batteries. Chemical Engineering Journal **399**, 125837 (2020)

[99] Ellingsen, L.A.-W., Hung, C.R., Majeau-Bettez, G., Singh, B., Chen, Z., Whittingham, M.S., Strømman, A.H.: Nanotechnology for environmentally sustainable electromobility. Nature Nanotechnology **11**(12), 1039–1051 (2016)

[100] Reinhardt, R., Christodoulou, I., Gassó-Domingo, S., García, B.A.: Towards sustainable business models for electric vehicle battery second use: A critical review. Journal of environmental management **245**, 432–446 (2019)

[101] Lipu, M.S.H., Mamun, A.A., Ansari, S., Miah, M.S., Hasan, K., Meraj, S.T., Abdolrasol, M.G., Rahman, T., Maruf, M.H., Sarker, M.R., *et al.*: Battery management, key technologies, methods, issues, and future trends of electric vehicles: A pathway toward achieving sustainable development goals. Batteries **8**(9), 119 (2022)

[102] Electronics, F.: Hyundai, IonQ use quantum computing to simulate EV battery chemical reactions. [Online; accessed 7. Aug.

2023] (2022). https://www.fierceelectronics.com/power-management/hyundai-ionq-use-quantum-computing-simulate-ev-battery-chemical-reactions

[103] Burkacky, O., Pautasso, L., Mohr, N.: Will quantum computing drive the automotive future? Accessed on 2025-05-04 (2023). https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/will-quantum-computing-drive-the-automotive-future

[104] Delgado, A., Casares, P.A., Dos Reis, R., Zini, M.S., Campos, R., Cruz-Hernández, N., Voigt, A.-C., Lowe, A., Jahangiri, S., Martin-Delgado, M.A., *et al.*: Simulating key properties of lithium-ion batteries with a fault-tolerant quantum computer. Physical Review A **106**(3), 032428 (2022)

[105] Rice, J.E., Gujarati, T.P., Motta, M., Takeshita, T.Y., Lee, E., Latone, J.A., Garcia, J.M.: Quantum computation of dominant products in lithium–sulfur batteries. The Journal of Chemical Physics **154**(13) (2021)

[106] Wack, A., Paik, H., Javadi-Abhari, A., Jurcevic, P., Faro, I., Gambetta, J.M., Johnson, B.R.: Quality, Speed, and Scale: three key attributes to measure the performance of near-term quantum computers (2021). https://arxiv.org/abs/2110.14108