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BLOCKCHAIN TECHNOLOGY: A REVIEW OF FEASIBILITY AND ADOPTION LEVELS IN THE AUTOMOTIVE INDUSTRY

Abstract. Blockchain technology is undergoing a global transformation of industries, fundamentally reshaping how societies engage in trade and interactions. This paradigm shift is primarily attributed to its capability to facilitate the exchange of financial value and interactions among mutually distrusting entities, obviating the necessity for a trusted third party. The main objective of this review is to assess the feasibility of integrating blockchain technology into the automotive sector, with a particular emphasis on the current adoption levels among leading car manufacturers. Following a concise introduction, the paper tackles the challenge of evaluating the appropriateness of blockchain as a technical solution for specific application scenarios. The main portion of the study provides a comprehensive examination of blockchain applications that have been tested and implemented by leading automotive manufacturers. This enables the assessment of both the adoption level and the innovation capacity of these technologies within the automotive sector.

1. Introduction

Blockchain is a disruptive technology that is profoundly reshaping the entire industrial and economic landscape. Its security relies on cryptography, specifically asymmetric cryptography, digital signature protocols, and the utilization of hash functions. Blockchain has a wide range of application areas, and the automotive sector could be one of the most interesting and promising.

However, despite the growing interest in blockchain applications within the automotive industry, there is a lack of comprehensive frameworks for assessing their feasibility in different contexts. This study aims to fill this gap by providing a systematic approach to evaluate blockchain suitability based on specific problem requirements and real-world applications.

The main contribution of this work is the presentation of a new flowchart for the feasibility evaluation and a deep analysis of several blockchain-based projects developed by the most important automotive companies. In particular:

- By analyzing the positive and negative aspects identified from various feasibility studies, we introduce a decision flowchart for assessing the suitability of a blockchain based on specific problem requirements, along with considerations regarding the appropriate type of blockchain and data storage;
- We conduct a detailed analysis of the current level of adoption of the main car manufacturers, offering an evaluation of their applicability and impact. Our analysis of current adoption levels highlights areas for potential improvement and future research directions.

Organization of the paper. The paper is structured as follows. In Section 2, we present an exhaustive list of works related to the topic under discussion. Section 3 is dedicated to analyzing the current automotive market and the prospects for the coming years to assess the potential space available for the development of blockchain technology innovation. Section 4 outlines a methodology and a flow diagram to identify whether a blockchain is appropriate and, if so, what kind of blockchain would be suitable. In Section 5, we assess some of the most popular use cases and blockchain-based applications in the automotive industry. Section 6 delves into the adoption levels, examining the most relevant and concrete use cases of blockchain technology proposed by major car manufacturers. Finally, Section 7 concludes the paper with considerations and final evaluations regarding feasibility in the automotive sector.

2. Related works

In recent years, blockchain technology has garnered substantial interest, progressing beyond theoretical study and proof-of-concept to find extensive utilization in numerous commercial and operational applications across various industrial and economic sectors. This noteworthy shift has heightened the focus on blockchain within academic research, particularly in the automotive sector. Several works are dedicated to the feasibility evaluation of blockchain technology and its applications in the automotive industry. In [46], Wust and Gervais explore whether blockchain is the appropriate solution for specific applications. They conduct an in-depth analysis of three use cases (Supply Chain Management, Interbank and International Payments, and Decentralized Autonomous Organizations), providing a methodology to determine the suitability of blockchain as the technical solution for particular application problems. The authors assert that, depending on the specific application scenario, there are compelling use cases for both permissionless and permissioned blockchains, as well as centralized databases. These must be carefully evaluated to leverage their respective strengths. In developing our methodology, we drew inspiration from this study, specifically in terms of addressing the required trust assumptions, application requirements, involved parties, and technical characteristics such as throughput and latency. In fact, as stated by the authors,, when deciding whether to adopt a blockchain system, it is crucial to consider the trade-off between decentralization and throughput. Decentralization refers to the system's ability to scale with a large number of participants without requiring mutual trust, while throughput denotes the system's capacity to process a high volume of state updates within a given time frame. Balancing these factors is essential for determining the suitability of a blockchain solution for specific use cases. However, this study lacks a discussion on the distinctions between on-chain and off-chain data storage, as well as the implications of performing data operations either on-chain or off-chain. For this reason, we developed a decision flowchart based on the one proposed by Wüst and Gervais, but we also included a subsection to explore and analyze the issue of on-chain versus off-chain data storage. Additionally, [63] presents a scoping review examining frameworks and assessment models created to aid decision-makers in blockchain adoption. The study

explores how the appropriateness of blockchain for business applications has been addressed in existing literature. The authors provide a classification of blockchain evaluation approaches, which includes: (a) Suitability for Business Cases Evaluation, which encompasses decision flowcharts, conceptual frameworks, and decision models to assess the relevance of blockchain for specific business scenarios; (b) Usability and Adoption Evaluation, focusing on the ease of use and acceptance of blockchain technologies; (c) Platform Selection Evaluation, aimed at choosing the most appropriate blockchain platform for particular needs; (d) Performance Evaluation, which measures the effectiveness and efficiency of blockchain systems; and (e) Architectural Design Options Evaluation, which explores different design architectures for blockchain implementations. Moreover, the adoption path for implementing an innovative technology (such as blockchain) is analyzed. This path is divided into three main stages: the proof-of-concept stage, the multi-level value identification stage, and the pre-production and production stages. Each stage requires the evaluation of various aspects and dimensions to determine the final decision, which could be either to implement a blockchain solution or to seek an alternative suitable technology. In developing our work, we drew inspiration from this adoption path and the frequently used decision constructs found in the flowcharts reviewed by the authors. Regarding the automotive supply chain (ASC), a systematic review is provided in [57]. In this work, the authors address the challenges faced by the automotive industry in a VUCA world characterized by volatility, uncertainty, complexity, and ambiguity. They propose the adoption of blockchain technology (BCT) as a promising solution to enhance transparency and traceability in automotive supply chains. The paper presents a systematic literature review of BCT applications in the automotive sector, analyzing over seventy research papers to explore how blockchain can improve supply chain visibility and information transparency. Additionally, the authors propose a BCT implementation framework to provide a decision-making approach for practitioners in the VUCA world. In [68], the authors outline a blockchain-driven solution implemented to ensure transparency in automotive manufacturing processes. They explore how data captured by IoT devices are securely stored in the blockchain in an immutable manner, subsequently tracked. This innovative solution has the capacity to integrate data from various manufacturing units and IoT devices. These data become accessible to customers and buyers who join the blockchain, enabling them to gain insights into the complete history of the vehicle. In [45], Fraga-Lamas and Fernàndez-Caramés conduct an analysis of the applicability of blockchain technology to the automotive industry, delineating the most significant use cases, identifying the main stakeholders in the sector, and addressing the current specific challenges faced by the automotive industry. Building on the automotive blockchain-based services presented in this analysis, Section 5 focuses on the examination of specific use cases. Furthermore, the authors introduce a flow diagram for assessing the need for blockchain technologies in specific applications, taking into account considerations related to transaction speed. Building on this flow diagram, we have expanded the Wüst and Gervais flowchart by incorporating a question about data updating, to explore whether data should be modified after initial entry. A review of major opportunities for blockchain technology in car-sharing applications is also provided

in [4]. In this work, the authors emphasize the importance of ensuring integrity, trustworthy operations, and secure information storage between the car owner and the renter. They explore the implementation of Self-Sovereign Identity (SSI) into the blockchain to ensure user identity security and tamper-resistant data storage, highlighting the benefits of SSI and blockchain for car-sharing. In [71], the authors propose a decentralized platform tailored for car rental and leasing applications, facilitating the deployment of smart contract applications with minimal transaction fees. In the event of specific occurrences, such as accidents or unfavorable car behavior, the smart contract is designed to (i) relay information to relevant public entities and (ii) track all essential data to ensure the seamless success of the entire rental/leasing procedure. Moreover, [1] delves deep into the feasibility of a decentralized marketplace for used vehicles, optimizing automatic ownership transfers through the utilization of Non-Fungible Tokens (NFTs). The paper introduces a comprehensive framework and practical implementation of a Decentralized Application (Dapp), offering a detailed examination of the system's security, associated expenses, and future possibilities. In [67], the authors introduce the concept of connected, autonomous, and electric vehicles, facilitating extensive data exchange among stakeholders. The paper presents a groundbreaking blockchain-based architecture designed to address and resolve challenges associated with odometer fraud prevalent in the automotive industry. Additionally, blockchain can serve as a distributed solution for automotive security and privacy. For example, smart vehicles provide various advanced services beneficial for vehicle owners, transportation authorities, car manufacturers, and other service providers. These vehicles are often linked to roadside infrastructure, such as traffic management systems, as well as other nearby vehicles or more generally to IoT devices. However, the extensive connectivity of smart vehicles poses a significant challenge in terms of security and privacy (see [72]). Traditional security and privacy approaches employed in smart vehicles prove ineffective due to difficulties such as centralization (where every vehicle is recognized, authenticated, authorized, and linked through central cloud servers), lack of privacy (exchanging all vehicle data without the owner's consent), and safety threats (installation of malicious software). In addressing this concern, [56] proposes a blockchain-based architecture designed to safeguard user privacy and enhance the security of smart vehicles. The authors demonstrate the effectiveness of this architecture through examples like wireless remote software updates and dynamic vehicle insurance fees. Additionally, they provide a qualitative assessment of how resilient the proposed architecture is against common security attacks. In [3], the significance of blockchain technology is emphasized for its capabilities in ensuring the following: (i) preventing tampering or manipulation of data, (ii) maintaining data immutability, (iii) reducing points of failure through a distributed network architecture with multiple peers, and (iv) eliminating the need for intermediaries. Finally, comprehensive analyses on how blockchain can be tailored to meet the specific requirements of the Internet of Things (IoT) for the development of Blockchain-based IoT (BIoT) applications are available in [54, 55]. These works aim to underscore how blockchain can impact traditional cloud-centric IoT applications. They delve into existing challenges, explore potential enhancements, and address various factors influencing the design, development,

and implementation of a BIoT application.

3. Market analysis and prospects

The automotive industry is undergoing significant transformation, primarily driven by the shift towards electric vehicles, the rise of car sharing services and the development of autonomous driving technology. Consequently, the global automotive market is experiencing a rapid expansion.

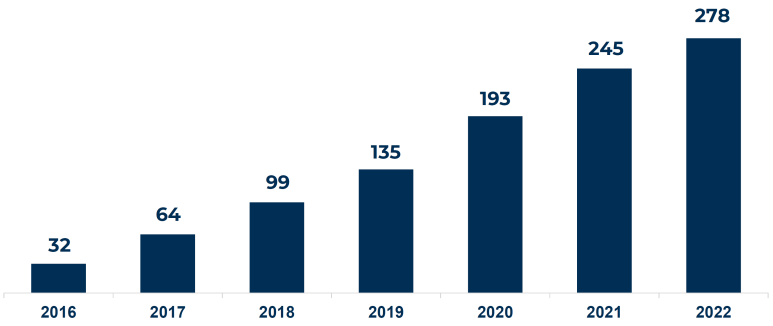

Figure 1: Analysis of 1046 international projects Blockchain-based developed by companies and public administrations from 2016 to 2022. This research was carried out on February 2023 by the Blockchain & Web3 Observatory of the Politecnico di Milano [7].

According to a report published by Allied Market Research [75], the global car sharing market was valued at $2,857.85 million in 2022 and is forecasted to reach $17,754.95 million by 2032, with a Compound Annual Growth Rate of 20.16% from 2023 to 2032. This forecast of significant market expansion in car sharing opens up very interesting opportunities for the development of blockchain applications as well. These applications could enhance the security, transparency, and ease of car rental management. Even if they only lead to a small percentage of cost optimization, it could result in substantial overall gains.

In April 2024 research by Zion Market Research [78] found that the global connected car market size had a valuation of approximately $95.31 billion in 2023 and is projected to reach around $275.11 billion by 2032. On the other hand the autonomous vehicle market size is projected to grow from $1,921.1 billion in 2023 to $13,632.4 billion by 2030, see [80]. In the realm of connected vehicles and autonomous vehicles, the possibility of blockchain utilization is anticipated, and indeed, some experiments have already reached the operational stage. The significant growth of the market will also entail equally substantial growth in opportunities for blockchain applications.

Another area that is rapidly evolving and poised to generate substantial value is the establishment of a digital battery passport [79]. The European Union, China, and collaborative efforts such as the Global Battery Alliance (GBA) or the Battery Pass

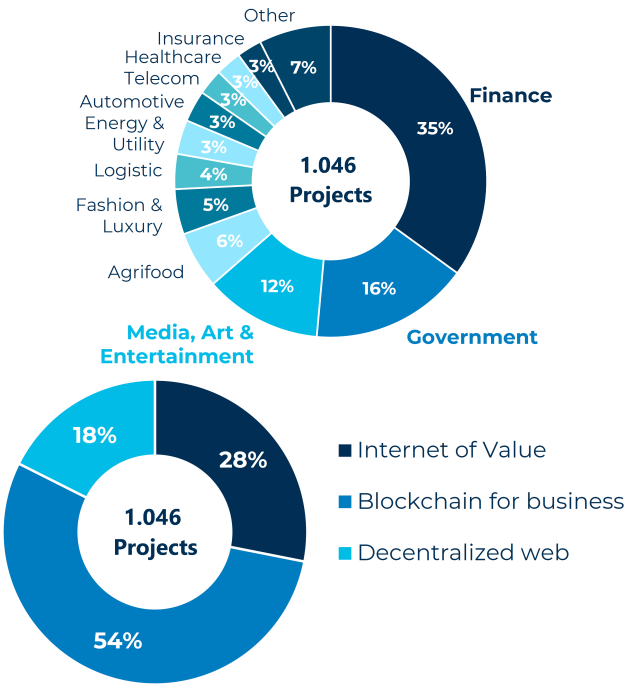

Figure 2: Main fields of application of Blockchain technology. This census was executed in February 2023 by the Blockchain & Web3 Observatory of the Politecnico di Milano [7].

consortium are spearheading the creation of a digital battery passport to enhance transparency and facilitate sustainable, circular value chains. This initiative will pave the way for a new range of technological applications with promising market opportunities.

At the regional level in Europe, there are studies outlining a comprehensive roadmap to sustain the competitiveness of the automotive sector globally [76]. Among the key steps highlighted are the digital transition, establishing a resilient, circular, and sustainable supply chain, and reclaiming leadership in battery production and distribution. These are all areas that intersect with the typical applications of blockchain technology.

We wrap up by citing a KPMG study that examines the disruptive impact of ESG (Environmental, Social, and Governance) policies on the automotive sector [77]. Specifically, it focuses on the transition to electric vehicles, sustainable supply chains, the necessity for a digital transformation to automate industrial processes, and the growing demand for transparency. In these cases, blockchain technology can play a pivotal role in enabling progress and generating value.

In Figure 3, we present a pie chart illustrating the nationalities of the automotive companies whose blockchain-based projects we analyzed, as detailed in Table 1. Germany leads with the highest percentage at 30.8% (BMW, Mercedes, Porsche, Volkswagen). China (Geely, SAIC-GM), Japan (Honda, Toyota), and the United States (Ford, Tesla) each account for 15.4%. France (Renault), South Korea (Hyundai), and the Netherlands (Stellantis) each represent 7.7%. Notably, Stellantis is a multinational holding company formed by the merger of Fiat Chrysler Automobiles (FCA) and PSA Group, with operations in France, Italy, and the United States.

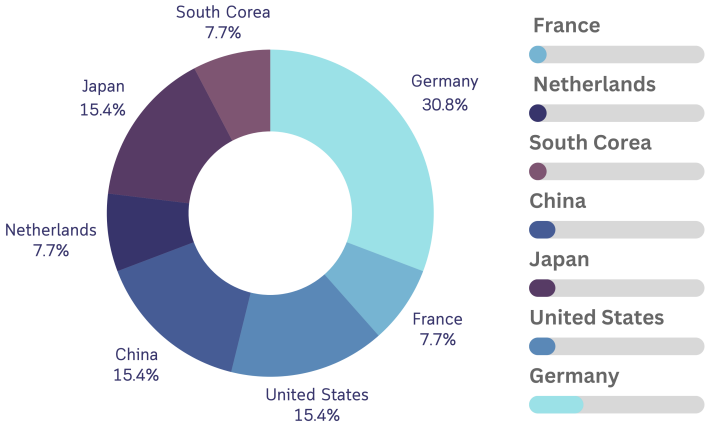

Figure 3: Geographic distribution of blockchain-based automotive projects by major car manufacturers. This pie chart shows the percentage of projects based on blockchain technology by country, as detailed in Table 1.1.

4. Feasibility evaluation

Blockchain technology has garnered significant attention in recent years for its potential to revolutionize various industries, spanning from finance and supply chain management to healthcare and beyond. However, it is easy to get carried away by the hype around blockchain technology. For this reason, before implementing blockchain solutions, it is crucial to conduct a feasibility evaluation, considering multiple key factors. This assessment involves a comprehensive analysis to determine whether blockchain technology is the most suitable solution for a specific use case. Moreover, a permissioned blockchain exhibits similarities with a central database, as discussed in [5]. This naturally raises the question of whether a blockchain surpasses a central database. In addition, it seems, sometimes. challenging to determine which blockchain to use, whether private or public, especially when there is a significant reliance on finding the right balance between decentralization and centralization, as well as the decision of on- and off-chain.

Decision flowcharts, also known as decision trees, were recognized as the primary method used in most of the studies examined to aid decision-makers to integrate

blockchains into business settings. Within this category, individuals can reach a decision by responding to various questions or following a sequence of nodes in a decision tree or flowchart. According to Wust and Gervais [46], permissionless and permissioned blockchains only make sense when multiple mutually mistrusting entities seek to interact, changing the system's state without relying on an online Trusted Third Party (TTP). Building on their assumptions, the authors proposed a flow chart to ascertain whether a blockchain is the appropriate technical solution for a given problem. The flowchart consisted of six questions aimed at directing decision-makers towards one out of four options: centrally managed database, public permissionless blockchain, public permissioned blockchain or a private permissioned blockchain. The researchers suggest that employing a blockchain is only practical when there is a need to record transactions among multiple parties in a collaborative system, and in case these parties are not willing to agree on an online TTP. However, according to [81], it is argued that an always online TTP doesn't exist in real-world scenarios. These researchers also made a significant adjustment of the flowchart to address the risk of potential data tampering by a single writer. On the other hand, the study conducted by [82] expands the decision framework developed by Wust and Gervais. It includes a question about the potential decentralization of the TTP, introduces a private permissionless decision option, and incorporates an extra stage to evaluate various constraints proposed by the authors. Likewise, the blockchain assessment model suggested in [83] distinguishes between private, public, and consortium blockchains. It provides various decision paths depending on access permissions and data security. In [84] and [85] authors devise their decision flowcharts by conducting a comparative examination between blockchain and classical database technologies. Their objective is to underscore the inherent characteristics of blockchains that render them a more fitting choice for specific business scenarios when compared to traditional alternatives. Koens and Poll [86] extensively review 30 existing decision frameworks designed to determine the necessity of adopting blockchain technology. They argue that previous decision aids are incomplete due to two main reasons: overlooking blockchain limitations and neglecting other feasible alternatives. However, they categorize key inquiries from previous decision frameworks into four groups: database, system design, process, and blockchain limitations. They then propose their own decision flowchart to address the shortcomings of existing frameworks. Additionally, Fraga-Lamas and Fernàndez-Caramés [45] create a flow diagram, offering general guidance on determining the appropriateness of using blockchain and selecting its specific type. Their first question is whether a traditional database can meet the application needs. If the answer is affirmative, then blockchain is not necessary, since a traditional database has a faster transaction speed. They then inquire whether multiple stakeholders require updating data, redundant copies in multiple distributed computers are necessary, all the stakeholders trust a third party, data need to be kept in private and finally whether it is necessary to control who can make changes to the blockchain software.

Drawing inspiration from [46] and [45], we present a decision flow chart for evaluating the feasibility of blockchain as a technical solution for a specific use case

(Figure 4). The flowchart we present is a modified version of flowchart from [46]. Modifications include the addition of the second block about the need for a shared common database, the addition of the third block about the number of parties involved, renaming the fifth block, and finally, the addition of the sixth block about the necessity to update or delete data.

The initial block addresses the necessity to store data: if no data need storage, neither a database nor a blockchain is required. The second block considers the need for a common shared database, a fundamental aspect of this approach. Subsequently, we inquire about the involvement of multiple parties, emphasizing the significance of organizational heterogeneity. The fourth block focuses on trust among involved parties: if all parties trust each other, a traditional database with fast transaction speed and better performance may be more efficient. The fifth block addresses the presence of an online TTP, which can function as an authority in a centralized database. Conversely, an offline TTP can serve as a certificate authority in a permissioned blockchain. In the absence of any TTP, consideration can be given to utilizing a permissionless blockchain. The sixth block investigates the possibility of updating or deleting data, highlighting the immutability aspect of a blockchain compared to a centralized system. In the seventh block, we question the existence of multiple writers: if only one writer exists, a traditional database might be more suitable. The eighth block addresses whether all writers are known: if the set of the writers is not fixed and known, a permissionless blockchain can be a suitable solution. Otherwise, if the set of writers is fixed and known, a permissioned blockchain can make sense. Furthermore, if the writers mutually trust each other, a database with shared write access could be a viable solution. Finally, if the set of writers is known, a public permissioned or private permissioned blockchain can be adopted, depending on the requirement for public verifiability. If public verifiability is essential, a public permissioned blockchain is optimal. Conversely, if public verifiability is not necessary and the set of readers can be restricted, a private permissioned blockchain may be employed.

We are now presenting four main factors widely used in the feasibility evaluation process:

1. **Use case identification**: the initial step in evaluating the feasibility of blockchain technology is to clearly define the use case. Blockchain may not always be the sole suitable solution, and its advantages become evident when there is a need for transparency, security, and decentralization. For instance, Automotive Supply Chain (ASC), where traceability and accountability are critical, is a prime candidate for blockchain adoption.

2. **Technical requirements**: once the use case is identified, organizations must assess the technical requirements. Blockchain technology comes in various forms, including public and private, permissioned and permissionless, with different consensus mechanisms. This step involves considerations related to scalability, data storage, and the cost of maintaining the blockchain infrastructure.

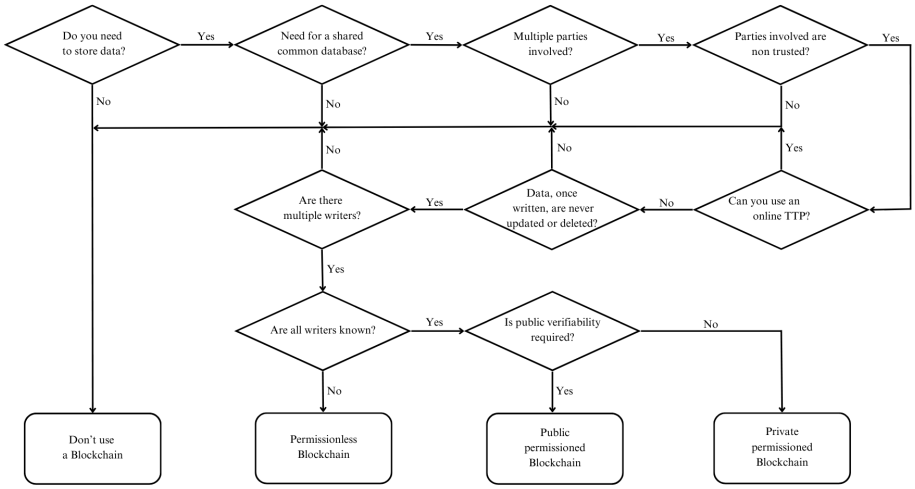

Figure 4: A flow diagram to determine whether a blockchain is the appropriate technical solution for a specific application.

3. **Regulatory and compliance considerations**: blockchain technology operates within a complex regulatory landscape. Organizations need to assess the legal and compliance aspects related to their use case. Depending on the industry and location, there may be specific regulations governing data privacy, smart contracts, and digital assets.

4. **Cost-benefit analysis**: evaluating the feasibility of blockchain technology also involves a comprehensive cost-benefit analysis. Organizations should consider the initial investment required to set up the blockchain infrastructure, ongoing maintenance costs, and the potential returns on investment.

After incorporating a decision flowchart to assess the feasibility of blockchain adoption across various sectors, including the automotive one, it becomes necessary to explore its specific applicability in the automotive industry. This entails gathering insights from a spectrum of stakeholders, such as manufacturers, suppliers, and customers, to gauge their perspectives on integrating blockchain technology. By doing so, we can gain a comprehensive understanding of the industry readiness, challenges,limitations and potential benefits associated with blockchain implementation. It is important, therefore, to establish a method to test various blockchains. When a blockchain is created, it should be tested with the agreed criteria to verify if the blockchain works as it should. In the testing phase, different criteria such as data store, data privacy, transaction history, access control, security, immutability, energy efficiency, throughput, latency and scalability must be evaluated, ensuring the efficiency and effectiveness of blockchain deployment in the automotive sector. In conclusion, the feasibility evaluation of blockchain technology is a multifaceted assessment that goes beyond the expectations surrounding this disruptive technology.

4.1. Data storage

The decision to store data on-chain or off-chain is critical in the design of blockchain-based applications, as it significantly impacts performance, security, and scalability. On-chain storage guarantees immutable and transparent transaction records, which are essential for applications requiring high levels of trust and verifiability, such as financial transactions and supply chain management. The inherent security of blockchain technology ensures the protection of on-chain data through cryptographic methods and distributed consensus, thereby maintaining decentralization and mitigating tampering risks. However, on-chain storage can present scalability challenges as data volumes increase, which can result in slower transaction processing and higher storage costs. The necessity to validate and store each transaction can exacerbate these issues, particularly during periods of high network congestion, leading to delays and increased transaction fees. In addition, while encrypting data before storing it on a blockchain can enhance confidentiality, it may also reduce performance, transparency, and independent auditability. Although storing only a hash of the data on-chain while keeping the raw data off-chain can improve both confidentiality and performance, this approach partially undermines the blockchain's core advantage of providing a distributed trust mechanism and immutable records. Conversely, off-chain storage improves scalability by offloading large data volumes from the blockchain, thereby reducing the system's load and enabling faster transaction processing at lower costs. This method is particularly advantageous for applications that require high transaction frequency or manage large datasets, and it is generally more cost-effective due to the avoidance of high on-chain storage fees. However, off-chain data may lack the transparency and immutability inherent in on-chain data, which can be a significant drawback for applications where trust and verifiability are critical. Additionally, off-chain storage solutions require careful design to ensure data security and necessitate additional infrastructure to link on-chain transactions with off-chain data, thereby increasing development and maintenance complexity. A review of the existing literature on blockchain decision flow diagrams reveals that there is a varied consideration of on-chain versus off-chain data storage. Some decision flow diagrams overlook this aspect by focusing primarily on the high-level feasibility of blockchain solutions without addressing the nuances of data storage decisions. This oversight can lead to incomplete assessments and suboptimal design choices. In contrast, more comprehensive diagrams [84], [89] explicitly incorporate the on-chain versus off-chain storage decision, providing a detailed framework that guides designers through the trade-offs between transaction speed, scalability, cost, and security. Therefore, after selecting the type of blockchain, it is advisable to include a question in the decision flow diagram addressing the importance of data durability.

5. Most relevant use cases

Over the past century, the automotive industry has undergone a remarkable transformation, profoundly impacting society. Within the automotive sector, blockchain technology can serve as a unified decentralized platform for securely recording, track-

ing, and managing information related to insurance, proof of ownership, patents, repairs, maintenance, and both physical and intangible assets. Blockchain has the potential to bring several benefits to the automotive sector, including enhanced data security, privacy, anonymity, traceability, and transparency.

In the following section, we outline some of the most relevant blockchain applications for the automotive sector. They have been selected as they represent the most developed use cases in the field. We discuss their value propositions and address challenges and limitations encountered during implementation.

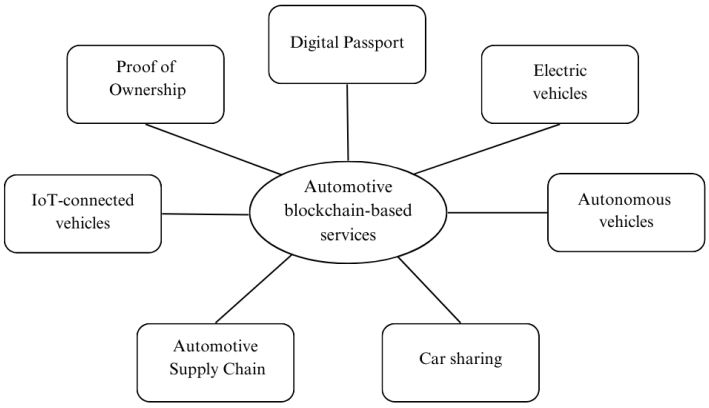

Figure 5: A visual overview of primary blockchain-based services in the automotive industry.

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1. **Automotive Supply Chain**

   Description

   The Automotive Supply Chain (ASC) poses unique complexities due to extensive geographical distances and the involvement of intermediaries across storage, production, and delivery phases [57]. Key stakeholders, such as suppliers, distributors, dealerships, regulatory authorities, and insurance companies, play crucial roles in this intricate supply chain. ASC is currently managed through established conventional methods, actively collecting significant amounts of data through IoT devices. By integrating IoT into these practices, there is an extraordinary potential to establish a unified data and real-time information source throughout the entire supply chain. This data includes timestamps, demand and inventory specifics, purchase and discount information, shipment particulars, consignee details, quality reports, part status, product descriptions, carrier codes, driver and vehicle specifics, as well as costs associated with inventory holding, manufacturing, outsourcing, transportation, and telematic and machine data [64]. In recent years, many automotive companies and network, such as RSBN [20], BMW [10], Hyundai [19, 17], Mercedes-Benz [24, 25],

Renault [29], SAIC-GM [33], Stellantis [34], Tesla [37], Toyota [38], Volkswagen [41], and Volvo Cars [14], have provided blockchain-based solutions to improve the ASC.

Benefits

For the automotive supply chain, blockchain infrastructure seamlessly integrates data, facilitating shared transactions and resulting in tamper-proof and immutable records [2]. Blockchain and smart contracts also have the potential to address supply chain challenges by eliminating the need for trusted third parties to verify the authenticity of raw materials, components, finished products, and financial transactions throughout the supply chain. Suppliers can benefit from incentives, on-time payments, increased transparency, and accountability in supply chain operations.

Challenges

Though the automotive industry is technologically advanced, the ASC is facing several challenges as: (i) inefficiency in sharing real-time data related to inventory, demand and transactions with supply chain members; (ii) scalability issues due to the high transaction volume; (iii) interoperability challenges due to the diversity of stakeholders and systems involved.

2. **Proof of Ownership and Digital Passport**

Description

Proof of Ownership for intellectual property is a frequently proposed and straightforward application of blockchain technology. When a creator aims to establish ownership of a digital object, leveraging a public blockchain as a timestamping service is a common approach. This process involves the commitment of the digital object along with the user identity, and recording the commitment on the blockchain. This method facilitates subsequent verification, confirming the object's existence at the specific timestamp and its association with the corresponding identity. Alternatively, a trusted third party, such as a patent office, could provide proof of ownership. One notable application is the development of digital passports for automotive assets, encompassing vehicles and their components. Digital passports mark a significant advancement in the automotive sector, providing a secure and decentralized solution for managing crucial vehicle information. This innovative application allows for the immutable recording of essential data, including maintenance records, driving history, and vehicle identity authentication. In this context, Porsche emerged as one of the pioneers in testing blockchain applications directly in vehicles [27]. The tested applications range from remotely locking and unlocking vehicles via a smartphone app to granting temporary access authorizations and pioneering innovative business models grounded in encrypted data logging. Moreover, in recent years, digital passports for components, such as batteries,

have gained prominence, especially in electric vehicles [12]. These passports provide a detailed record of battery manufacturing, usage, and maintenance history. Blockchain storage allows for effective monitoring and diagnostics of battery health, energy storage capacity, and efficiency data. If this trend continues, the future landscape of blockchain technology applications could see a significant role in notarizing battery systems.

Benefits

A public blockchain streamlines the process by offering decentralized proofs without revealing specific details of the digital object. Its decentralized structure ensures resistance to tampering, enabling easy verification by any authorized party. Additionally, blockchain technology increases transparency, allowing all stakeholders to access and verify data without compromising confidentiality. This visibility ensures that any changes to the digital passport are traceable, thereby reducing the risk of fraud. Blockchain also enhances verification processes by eliminating the need for multiple intermediaries, which in turn reduces time and costs. This efficiency significantly benefits the automotive industry, where the quick verification of vehicle ownership and component history is crucial.

Challenges

In the Proof of Ownership and Digital Passport sector, implementing blockchain technology in the automotive industry presents several challenges related to scalability, interoperability, and data security and privacy. Future trends may involve the development of more scalable blockchain solutions, such as sharding or Layer 2 protocols, which can help distribute the data load and improve transaction speeds. While blockchain inherently offers a higher level of security through its decentralized and immutable ledger, specific techniques must be employed to safeguard private data. Addressing privacy concerns may involve the implementation of advanced cryptographic methods, such as Zero-Knowledge Proofs (ZKPs) and anonymous credentials, which allow for the verification of information without revealing the actual data, thereby maintaining privacy while ensuring data integrity.

3. **IoT-connected vehicles**

Description

The Internet of Things (IoT) paradigm is steering us towards a future where myriad everyday objects will be interconnected, capable of interacting with their surroundings to collect data and perform automated tasks. The integration of the IoT paradigm within vehicles allows for the accumulation of a substantial volume of data. Sensors and devices connected via a designated mobile network facilitate the collection of data on various aspects, including driving events (e.g., mileage and speed), safety events (e.g., warnings for spare part replacement), and maintenance events (e.g., annual service). This data

can be transmitted to a shared ledger accessible to all stakeholders, including the vehicle owner. Currently, most IoT solutions rely on the centralized server-client model, where data is linked to cloud servers via the Internet. However, IoT infrastructure can also serve as an example of a blockchain oracle, providing critical inputs for a blockchain network. It is crucial to recognize that there is a potential issue at the intersection of the physical and digital realms. When computers feed data from sensors into the blockchain, the blockchain itself cannot guarantee the accuracy of this data. In other words, if smart contracts depend on sensor data, the sensors must be trusted to ensure the data's correctness. In many cases, a trusted third party might be employed to verify the digital identity of an IoT device and ensure data integrity, thereby enabling the functionality of the blockchain. Detailed explorations of blockchain technology and its application in the IoT domain are covered in [54, 55, 53].

Benefits

The integration of blockchain technology into IoT connected vehicles offers several key benefits that enhance the functionality and security of transportation systems. Blockchain provides a decentralized and immutable ledger for managing data across a network of connected devices, which improves data integrity and ensures secure, transparent transactions. This technology enables efficient vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication through cryptographically secure channels, facilitating real-time data exchange for applications such as collision avoidance, automated parking, and traffic management. Additionally, blockchain's smart contract capabilities automate complex processes, reducing the need for intermediaries and operational costs.

Challenges

In the future of IoT, significant challenges are to be dealt with. These include complex technical issues such as scalability, security, cryptographic development, and stability requirements for IoT applications. Additionally, blockchain technologies face design limitations in transaction capacity, validation protocols, and smart contract implementation, as well as the need to address tendencies towards centralized approaches. While blockchain can handle IoT data, its real-time effectiveness depends on factors like where data is stored (on-chain or off-chain), reliability, modularity, and the type of distributed application. Moreover, when compared to a well-configured centralized database, a blockchain solution typically performs less efficiently, leading to lower transaction throughput and increased latencies. Numerous small transactions could escalate energy consumption linked with communications, whereas a few large ones might entail significant payloads beyond the capacity of certain IoT devices. Typically, this decrease in performance reflects the cost of achieving trustless decentralization and resilience.

4. **Car sharing**

Description

The decentralized nature of a public blockchain is well-suited for various distributed services, such as providing users with car location, facilitating the connection between users and the car (e.g., unlocking and using the car), and protecting the vehicle from unauthorized accesses (only registered and authorized users can locate, unlock, and use a vehicle). The handling of payment and billing for car-sharing services is also seamlessly managed on the blockchain [65]. The power of blockchain technology and its associated cryptocurrencies in the context of car sharing is discussed in [4]. Contrary to traditional car-sharing rituals involving manual key swaps or signing sharing contracts, the new approach centers around smartphones and their connection to a black box linked to the car control unit. Users sign up via a smartphone app to access the digital key required to start the vehicle. This system, by monitoring the car's performance, distance covered, and staying alert for potential accidents or emergencies, adds an extra layer of safety and oversight to blockchain-based car-sharing apps. This functionality is intrinsically linked to the robust connection between the Self-Sovereign Identity (SSI) mechanism and blockchain technology. Many SSI systems operate on a decentralized architecture, involving the exchange of digital credentials through wallets with cryptocurrencies, tokens, and cryptographic schemes, using a public-key infrastructure for credential verification. In [66], Decentralized Identifiers (DIDs) are generated by the holder (e.g., car-sharing company) and exchanged with the issuer (e.g., customer), while verifiers (e.g., insurance company) verify signatures to ensure the security of the exchanged data. An example of a blockchain-driven car-sharing application that seamlessly integrates smart contracts, utilizing Solidity and the Ethereum blockchain, is introduced in [69]. The incorporation of blockchain in this field serves a dual purpose: reducing operational costs and enhancing data transparency. This implementation includes the use of non-fungible tokens (ERC-721) and a fungible token (ERC-20). In the case of zero-knowledge proof protocols and anonymous credentials within the context of car-sharing applications, [70] offers an analysis. The authors articulate a blockchain-based system involving end-users, government entities, and automotive industry suppliers, aiming primarily to safeguard user privacy. They opt for the Ethereum platform and provide insights into the application of the Hyperledger Indy project for effective implementation.

Benefits

The implementation of a blockchain system integrated with a SSI framework offers substantial advantages for the car-sharing industry. By leveraging a decentralized ledger, this system ensures enhanced security for user identities and the secure storage of transaction data through smart contracts. The SSI framework empowers users with control over their digital identities, eliminating the need for central authorities and enhancing privacy through cryptographic methods.

Smart contracts automate and enforce the terms of car-sharing agreements, reducing administrative overhead and minimizing the potential for disputes. Additionally, the blockchain's transparent and immutable ledger provides a reliable audit trail for all transactions, boosting trust and accountability in the car-sharing process.

Challenges

Implementing blockchain-based car-sharing applications presents several challenges. Firstly, scalability issues arise due to the large volume of transactions, potentially leading to slower processing times and higher fees. Secondly, ensuring user privacy remains a concern, especially on public blockchain networks. Additionally, compliance with existing regulations and the integration of blockchain technology into current car-sharing systems pose significant hurdles. One of the main limitations in this field is interoperability which is essential for shared mobility where multiple companies and stakeholders access a platform through various services. In fact, there is a lack of research on the best blockchain or technology combination for car-sharing or shared mobility. On the other hand, Hyperledger Fabric would have the potential to provide the feasibility of implementing different business logic.

5. **Autonomous and electric vehicles**

Description

The automotive industry has evolved into one of the most intricate, advanced, and technologically sophisticated sectors, introducing innovations that encompass hybrid, electric, and self-driving smart cars, as well as the development of IoT-connected vehicles. Today, thanks to the Internet connection, vehicles have the capability to process vast amounts of real-time data, making instant decisions independently. This trend is expected to grow in the coming years, with every vehicle equipped with sensors that gather data on road conditions, traffic, vehicle status, and drivers' behavior and preferences. Autonomous Vehicles (AVs) have been a popular topic of discussion in recent years, drawing extensive attention from both academia and industry. Due to the majority of car crashes being attributed to human errors, an ideal solution is to employ a computer as a driver, utilizing sophisticated algorithms to determine appropriate driving actions. Autonomous vehicles, equipped with advanced IoT capabilities, navigation devices, and computer vision technology, can operate independently. Integrating blockchain as an underlying communication mechanism ensures trust and reliability in these systems. Moreover, AVs are anticipated to become a part of our daily lives in various forms, including autonomous drone delivery systems, driverless cars, automated guided vehicles in warehouses, self-sufficient home assistant devices, and Autonomous Electric Vehicles (AEVs) [28]. The type, purpose, and use of autonomous vehicles are determined by their level of automation [3]. The progress of automation in these vehicles has seen recent improvements due to advancements in tech-

nology integration. This includes technologies like blockchain, Industry 4.0, Artificial Intelligence (AI), Machine Learning (ML), neural networks, and cloud computing. Blockchain technology also plays a pivotal role in enhancing the functionality and security of electric vehicles [15], offering a range of applications that hold great promise. . In this sector, Hyundai Motor Group has introduced a groundbreaking innovation known as "smartphone-electric vehicle pairing-based performance adjustment technology," which empowers users to personalize essential vehicle functions directly via a smartphone app [16].

Benefits

One key application of blockchain technology in the electric vehicle (EV) industry is the authentication of EV components and parts. Blockchain enables an immutable ledger of component information, ensuring the authenticity and provenance of batteries, motors, and other critical EV parts. This not only builds trust in the quality and origin of components but also simplifies maintenance and replacement procedures. Moreover, blockchain facilitates secure charging and payment systems for EVs [44]. EV owners can seamlessly pay for charging services using cryptocurrencies or digital tokens. Furthermore, smart contracts automate payment processes and guarantee a secure and transparent transaction history. Blockchain's transparent and auditable ledger also provides regulators and consumers with real-time information on emission reductions and environmental impact, reinforcing the sustainability aspects of electric vehicles.

Challenges

In this last case, some of the challenges and limitations are: (i) insufficient implementation of smart contract-based, intelligent, and secure data handling in an autonomous vehicle (there is a need to design and analyze smart contracts for different types of AVs); (ii) the identification of internal vehicle parameters for blockchain integration within the autonomous vehicle network to enhance user experience and ensure error-free, attack-proof, and accident-free vehicle operation (these parameters, varying based on the type of autonomous vehicle, are crucial for designing smart maintenance contracts); (iii) massive storage requirements (with the rise in V2X connectivity and autonomous vehicle scalability comes increased challenges in storing large volumes of data, managing data, conducting V2V transactions, and ensuring data security).

Taking a step into the future, we can imagine a role for blockchain technology in making the decisions that self-driving cars make in a verifiable, transparent and immutable way, allowing audit systems in the event of accidents. Furthermore, by imagining vehicles connected not only to the internet but also to each other, blockchain could enable the secure micro-payments that may be necessary for the mutual exchange of information.

6. Adoption levels

In recent years, the entire business world has undergone transformation due to blockchain technology, increasingly establishing itself as a genuinely disruptive force. Naturally, the automotive sector has not remained untouched by these changes. Here, we present different applications of blockchain technology in the automotive world, starting with partnership initiatives and then exploring applications within individual corporate groups.

6.1. Partnerships

We highlight two joint ventures that play significant roles in driving Blockchain technological innovation.

MOBI (Mobility Open Blockchain Initiative)

The Mobility Open Blockchain Initiative (MOBI) [6] is a global consortium focusing on accelerating the adoption of blockchain and distributed ledger technology (DLT) in the automotive and mobility industry. MOBI was founded to explore the potential of blockchain to transform various aspects of transportation, including vehicle identity, supply chain transparency, data sharing, and more.

MOBI brings together a diverse group of stakeholders from the automotive, technology, and blockchain sectors, including automakers, suppliers, startups, technology companies, and other organizations. The consortium aims to collaborate on developing common standards, frameworks, and use cases for blockchain technology in the mobility space.

By fostering collaboration and standardization, MOBI seeks to address industry challenges, promote innovation, and create a more efficient, secure, and interconnected mobility ecosystem.

The MOBI consortium engages in various key activities, notably:

1. Circular Economy and the Global Battery Passport: Driving the adoption of a decentralized battery passport system, setting standards for global interoperability, and fostering a circular battery economy;
2. Vehicle Identity: Defining a vehicle's digital twin, enabling ownership verification, access control, and interaction within the mobility ecosystem;
3. Mobility and Insurance: Facilitating secure data sharing for usage-based mobility services pricing, including insurance;
4. Electric Vehicle Grid Integration: Establishing interoperable systems to manage grid load, carbon offsets, and P2P services in electric vehicles;
5. Connected Mobility Data Marketplace: Creating a privacy-preserving data marketplace, trip planning, and autonomy;

6. Finance, Securitization, and Smart Contracts: Enhancing vehicle finance transparency through blockchain;
7. Supply Chain: Improving transparency and efficiency in parts manufacturing and distribution;
8. Drives: Developing vehicle identity standards and exploring use cases like maintenance and repair.

Among the companies that are partners of MOBI, we can mention many companies in the automotive sector such as BMW Group, Ford Motor Company, General Motors, Honda, Marelli, Mazda, Nissan, Renault, Stellantis, and Toyota, along with other leading companies like Accenture, Reply, Amazon Web Services, Bosch, and IBM.

RSBN (The Responsible Sourcing Blockchain Network)

The cobalt mining industry, critical for lithium-ion battery production, often involves significant human suffering. The Democratic Republic of Congo (DRC) provides over 60 percent of the world's cobalt, with both large-scale and small-scale mining. Small-scale mining, conducted under dangerous conditions by children and adults, raises concerns about human rights abuses and environmental damage. This issue particularly affects industries reliant on lithium-ion batteries, such as electric vehicles and electronics.

Sustainable sourcing initiatives aim to eliminate hand-mined cobalt from supply chains due to ethical and environmental concerns. Various factors drive these initiatives, including demands from consumers, shareholders, governments, regulatory bodies, financial markets, and non-governmental organizations.

Blockchain technology, particularly the Responsible Sourcing Blockchain Network (RSBN) [20] built on the IBM Blockchain Platform and powered by the Linux Foundation's Hyperledger Fabric, offers transparency, trust, and security for demonstrating responsible sourcing. It provides an immutable audit trail, secure storage of provenance information, protection of confidential data, and decentralized control. This technology enables lower costs through digitization, scalability for new participants, and prevention of fraud.

RSBN, in collaboration with RCS Global Group, uses blockchain to track cobalt's journey from mine to end product. The network assesses compliance with industry standards and best practices, helping downstream companies verify their responsible sourcing practices. Blockchain's properties ensure the integrity of certifications and data.

RSBN benefits various participants in the supply chain. Automotive manufacturers using responsibly sourced cobalt can market their products as sustainable, contributing to corporate citizenship goals. Mines and smelters, where the sourcing process begins, can enhance their status as suppliers by demonstrating responsible practices.

Consumers increasingly prioritize sustainable brands, and products like electric vehicles, smartphones, and laptops can gain reputational value through responsible sourcing.

RSBN founding members include Ford Motor Company, Volkswagen Group, global battery manufacturer LG Chem, and cobalt supplier Huayou Cobalt. Volvo Cars, Stellantis, Norilsk Nickel, Glencore, and other companies that operate in "conflict-sourced" minerals supply chains are also members.

6.2. Automotive firms

Nearly every automotive company is actively embracing blockchain technology across various facets of their businesses. In this context, we provide a comprehensive overview of the extensive array of initiatives and the varying levels of implementation among the industry's key players.

BMW

In 2019, BMW Group announced the adoption of Blockchain technology in its supply chain to optimize various processes, with a focus on tree key aspects:

- developing a digital vehicle passport through blockchain
- enhancing traceability of parts and critical raw materials within complex international supply chains
- charge e-cars more easily with blockchain automotive solutions.

To achieve these goals, the company introduced a Blockchain project known as PartChain, which aims to enable "tamper-proof and consistently verifiable collection and transaction of data in our supply chain," as stated by Andreas Wendt, a member of the Board of Management of BMW AG responsible for Purchasing and Supplier Network. The long-term vision of PartChain is to establish complete traceability of critical raw materials, spanning from the point of origin (mine) to the smelter. The implementation of this project represents a significant step towards advancing the digitalization of purchasing within BMW Group. The ultimate objective is to create an open platform that facilitates the safe and anonymized exchange of data within supply chains across the entire industry [10].

PartChain leverages not only Blockchain solutions but also Cloud technologies like Amazon Web Services and Microsoft Azure. This combination enables seamless tracking of component origins among all participating partners, ensuring there is no risk of manipulation in the data.

Additionally, it is important to highlight that the BMW Group played a significant role in co-founding the Mobility Open Blockchain Initiative (MOBI) in 2018 [9]. Moreover, the company not only continues to be actively engaged in all of its projects but

also participated in Series A and B funding rounds for Vendia, a prominent next-generation blockchain and web3 company, in both 2021 and 2022 [11].

Ford

In 2022, Everledger announced the launch of a pilot program for a battery passport in collaboration with Ford [12]. The primary objective of this initiative is to support the responsible recycling of electric vehicle (EV) batteries by leveraging technologies such as auto ID, blockchain, and artificial intelligence.

While EVs themselves do not produce direct greenhouse gas emissions, the energy used in manufacturing the vehicles, especially the batteries, still contributes to their overall environmental impact. Therefore, the climate benefits of EVs largely depend on the sustainable manufacturing and management of batteries.

In partnership with US lithium-ion battery recyclers Cirba Solutions and Li-Cycle, Everledger and Ford will employ the battery passport solution to track batteries in both new and older EV models. The pilot project may have received funding from a phase 1 funding round awarded by the US Department of Energy to Everledger in 2020 for providing battery identities. The pilot program is expected to run for six months, after which the battery passport will be released for commercial use.

Manufacturers will be required to report on their battery recycling practices in compliance with the European Battery Regulation adopted by the Council of the EU in july 2023.

The battery passport, secured by blockchain technology, will enable stakeholders along the supply chain to verify a battery's material provenance, chemistry, and identity. This functionality also allows for the measurement of its sustainability and environmental impact. By optimizing the recovery of raw materials and expediting the development of climate-friendly mobility solutions, the battery passport initiative aims to contribute to a more sustainable and environmentally responsible approach to EV battery recycling. Additionally, Ford has conducted a few other pilot projects using blockchain. One such study proved that blockchain, dynamic geofencing, and plug-in hybrid vans can help improve urban air quality [21].

Geely

Volvo Cars, a Geely group company, is one of the pioneer companies in using blockchain technology to trace the supply chain of the cobalt used in its batteries [14]. This commitment to transparency addresses the challenge of sourcing sustainable materials for lithium-ion batteries. Through partnerships with CATL and LG Chem, along with technology companies like Circulor, Oracle and IBM, Volvo aims to ensure ethical supply chains and risk reduction. The blockchain ledger records immutable transactions, securing data on cobalt's origin, attributes, and adherence to guidelines.

In 2022, Geely Holding and the Concordium Foundation collaborated to provide funding for the establishment of the Geely Holding Blockchain Innovation and Application Center located in Wuxi, China [13]. The primary goal of this joint endeavor is to propel the advancement of blockchain technologies and elevate the standards associated with blockchain in the automotive sector and other industries. Utilizing Concordium's Blockchain technology, this partnership aims to establish a prominent presence as a leading provider of Blockchain Technology and Services in China. Moreover, this collaboration will grant Concordium access to a diverse group of developers, innovative use cases, and an extensive array of tools and applications, all of which contribute to enhancing the Concordium ecosystem.

Additionally, in 2022, Volvo partnered with Mindshare India to conceive and implement a unique and innovative virtual world launch for its electric SUV, the Volvo XC40 Recharge, within its metaverse known as the Volvoverse.

Honda

In 2020, Honda Motor Company and General Motors announced a partnership to jointly research blockchain technology's potential for enhancing electric vehicles (EVs) and smart grid compatibility [15]. Their aim is to explore if EVs can contribute to stabilizing next-gen smart grids' power supply.

The project seeks to establish methods for efficiently retrieving data exchanged between power grids and EVs. As renewable energy sources in smart grids, like solar and wind power, can be unstable, EVs might offer a more dependable energy source. Successful implementation could allow EV owners to earn revenue by sharing power stored in their car batteries with the grid.

This collaborative research occurs within The Mobility Open Blockchain Initiative (MOBI)[6].

In 2022, Honda launched its own metaverse called "The Hondaverse," which was made available on both Fortnite and Twitch platforms.

Hyundai

In a 2019 press release, Hyundai Motor Group unveiled its innovative "smartphone-electric vehicle pairing based performance adjustment technology". This technology allows users to customize primary functions of their electric vehicles (EVs) through a smartphone application. Users can modify parameters such as maximum torque output of the motor, ignition, acceleration and deceleration abilities, regenerative braking capacity, maximum speed limit, responsiveness, and energy usage on climate control.

To ensure the security and integrity of user-customized settings when uploading and sharing them on the server, Hyundai integrated Blockchain technology into the project. During the process of uploading and sharing custom settings, the system

encrypts major performance parameters in a Blockchain network by creating new data blocks. These encrypted blocks are stored in a distributed data storage system, thereby preventing unauthorized manipulation and enhancing data security [16].

In the same year, Hyundai Commercial, the division responsible for leasing and financial services for commercial vehicles, explored an IBM solution for supply chain finance. This move aimed to enhance efficiency and transparency in their supply chain financing processes [19].

Moving forward to 2021, Hyundai launched a new parts software system named MAPS (Most Advanced Parts System) through its subsidiary, MOBIS. The MAPS platform utilizes Artificial Intelligence and Blockchain technology to streamline the distribution of after-sales parts for 300 models of Hyundai and Kia cars [17].

The scope of the system spans across the entire supply chain, including 16,000 dealers in more than 200 countries, with as many as 100,000 people accessing the platform. The IT system effectively manages three million different parts for 300 car models.

The implementation of Blockchain in this project aims to enhance the verification process of original parts, thereby addressing the issue of illegal counterfeit parts used in certain countries, which could pose safety risks. The system works by scanning the vehicle number at a repair shop, listing all the car's parts, and updating the maintenance history through a repair firm's log. This electronic logbook is accessible to various stakeholders, including the dealer, repair shop, insurer, manufacturer, and car owner, through the use of Blockchain technology, ensuring seamless data sharing and better control over the authenticity of the parts.

To conclude, in recent years Hyundai has also investigated with the collaboration of Meta Kongz the possibility of using one of the most innovative applications of the blockchain, the Non-Fungible-Token (NFT) [18].

Mercedes-Benz (Daimler)

Since 2017, Daimler Group has demonstrated active involvement in Blockchain technology. It became a part of the Hyperledger project of the Linux Foundation [22], and in the same year, it explored the financial advantages that Blockchain can offer. Daimler AG and Landesbank Baden-Württemberg (LBBW) jointly executed a financial transaction using Blockchain technology for a Schuldschein loan agreement, covering the entire process from origination to repayment and interest payments [23]. The successful test was carried out in compliance with regulatory requirements.

In 2019, Mercedes-Benz shifted its focus to the supply chain, partnering with Icertis for the joint development and implementation of Blockchain technology. They aimed to ensure consistent documentation of contracts in the supply chain, allowing transparent mapping and understanding of compliances across it. Sabine Angermann, Head of Purchasing and Supplier Quality for Raw Materials and Strategy at Mercedes-Benz Cars, highlighted the importance of transmitting contracts to each

member of the supply chain, particularly for sustainability and ethical conduct. The Blockchain prototype simplified and secured purchasing processes [24].

Continuing their exploration of Blockchain's potential in 2020, Mercedes-Benz worked on sustainable mobility under the project "Ambition2039", aiming for a carbon-neutral passenger car fleet in less than 20 years [25]. Collaborating with a battery cell manufacturer and Circulor, a start-up specializing in Blockchain technology and AI, Mercedes-Benz implemented a Blockchain-based system to map the production flow of materials and associated CO2 emissions. The long-term goal is to achieve a circular economy by closing material cycles and recording the amount of recycled material in the supply chain. The network also verifies whether sustainability requirements, including working conditions, human rights, environmental protection, safety, business ethics, and compliance, are communicated to all companies involved.

In 2021, Daimler Mobility AG granted the Mobility Blockchain Platform, developed in-house, to the mobility start-up bloXmove through a licensing agreement. The move aims to promote the platform's utilization for various applications and unlock its full potential. The successful pilot project is being continued and further developed at bloXmove, representing an expansion of the network and the addition of ecosystem partners [26].

Mercedes-Benz's ongoing commitment to exploring and implementing Blockchain technology demonstrates its belief in the future potential and benefits this technology can bring to various areas of operation and sustainability goals.

Porsche

Porsche was one of the first car manufacturers to explore and later implement the use of blockchain on their cars. In 2018, Porsche unveiled the outcome of its Porsche innovation contest from the previous year, which was won by the XAIN start-up. Following a successful test in December 2017, Porsche and XAIN deepened their collaboration to further develop and test XAIN's Blockchain-powered hybrid vehicle client [27].

The development resulted in a vehicle client built upon XAIN's patented consensus algorithm called PPKW (Practical Proof of Kernel Work). By integrating different networks and systems both inside and outside the car with Blockchain technology, they introduced various features for customers:

1. Traffic Data Recording: The vehicle could record traffic data over the Blockchain through direct communication with other vehicles, enhancing data accuracy and facilitating improved traffic management;
2. Secure and Faster Car Lock/Unlock: Leveraging the Blockchain-powered direct offline connection, the car's lock/unlock process became much faster and highly secure, eliminating the need for a server connection;
3. Temporary Access Grant: The customer could grant temporary access to the vehicle to another party, even if the customer was not present physically;
4. Real-Time Notifications: Customers received real-time notifications regarding the time, location, and identity of those who accessed the car;
5. Secure Package Delivery: The system allowed for secure delivery of mail packages directly inside the trunk of a parked car, enhancing convenience and security.

The development efforts revolved around three main technology stacks, each featuring different types of clients. Additionally, XAIN's patented consensus mechanism, Practical Proof of Kernel Work, played a pivotal role in ensuring the integrity and security of the Blockchain-based system. Furthermore, the integration of an Ethereum Virtual Machine (EVM) module for executing smart contracts based on Solidity allowed for the implementation of sophisticated and automated processes within the vehicle ecosystem.

By harnessing Blockchain technology, Porsche and XAIN successfully introduced innovative features that transformed the customer experience, offering enhanced security, efficiency, and convenience in various aspects of vehicle ownership and usage.

Renault

The Blockchain solution being developed by Groupe Renault is named XCEED, which stands for eXtended Compliance End-to-End Distributed [29]. The group has been

actively working on Blockchain technology since 2015 and successfully tested a new Blockchain solution for certifying vehicle compliance at the Douai plant in 2019. Due to its success, the solution is set to be implemented in several Renault plants across Europe [28].

XCEED's primary purpose is to certify the conformity of vehicle components from design to production by establishing a trusted network for sharing compliance information between parts manufacturers, throughout the supply chain, and to vehicle manufacturers.

This innovative solution leverages Blockchain technology and integrates Big Data for data management and Artificial Intelligence for advanced analytics.

Renault has a long-term perspective for the XCEED project, with the ambition to create a comprehensive traceability and compliance platform for the entire European automotive industry ecosystem.

The medium-term objective of XCEED is to extend the application of Blockchain to cover various areas, including Software, Repair and Maintenance, Homologation, Battery, Recycling, and CO2 Footprint.

Furthermore, XCEED is open to other manufacturers and global suppliers, regardless of their size, across the entire automotive supply chain.

According to Groupe Renault, they view Blockchain as a catalyst for transforming the automotive industry. Several projects to deploy this technology have been identified, with a particular focus on enhancing the traceability of financial transactions and facilitating communication with equipment manufacturers and the sales network.

Renault has also implemented a portal for the sale of NFT-equipped gadgets [30].

SAIC-GM

In 2019, GM Financial partnered with the blockchain startup Spring Labs to address identity fraud [32]. The collaboration's objective was to create identity verification solutions, with the potential for GM to acquire a stake. Established by Avant's team in 2017, Spring Labs highlights the use of blockchain for secure information exchange among lenders and banks, with a focus on safeguarding sensitive data.

In 2020 SAIC and Goodyear team up in a blockchain pilot for secure supply chain transactions [33]. The pilot utilizes standard digital formats and secure smart contracts. Blockchain allows tracking and analysis of supply chain data, aiding informed buying choices.

Furthermore SAIC in collaboration with Guangxi Automobile Group, is set to integrate innovative blockchain technology to enhance cost efficiency, operational effectiveness, and minimize potential errors [31].

China's central government recently announced the selection of 15 pilot areas for the deployment of novel blockchain technology, encompassing diverse sectors such as

banking, utilities, healthcare, and local government entities. Notably, among these sectors, SAIC emerged as the sole representative from the automotive domain chosen for this trial initiative.

SAIC engages in daily procurement of nearly 1,000 distinct components from an extensive array of suppliers, potentially involving transactions in the millions. This context raises the likelihood of errors linked to traditional paper-based documentation. Here, blockchain technology emerges as a solution to mitigate such risks and to decrease costs.

Stellantis

In its 2017 corporate social responsibility report [34], the PSA Groupe (now Stellantis) declared its initiative in developing a decentralized, digital logbook to prevent mileage fraud and the sale of vehicles declared as wreckage. This innovative solution leverages the communication capabilities of the group's vehicles and Blockchain technology, which ensures that information is stored in an unalterable, decentralized registry, making it impossible to delete or modify recorded data. A proof of concept was developed in collaboration with La Poste and the Covéa insurance group, as part of the SystemX technological research institute's Blockchain program.

Continuing their efforts in 2018, Groupe PSA, along with IRT SystemX, several insurance companies (AXA, Covéa, Matmut), IMA assistance group, and Mobivia multibrand dealer shop, launched an initiative to develop a consortium Blockchain aimed at creating a digital vehicle passport. The primary objective of this joint work was to study the technical and economic feasibility of the solution, with the potential to provide greater transparency for second-hand vehicle buyers and prevent odometer fraud. Blockchain technology's key advantage in this context is enhancing data security and traceability, enabling seamless data sharing among various stakeholders in the value chain.

In 2019, the FCA group (now part of Stellantis) joined the Responsible Sourcing Blockchain Network (RSBN) for cobalt responsible sourcing traceability [35], a project that involves participants at every major stage of the supply chain, from mining to the end-user. Collaborating with Ford Motor Company, Huayou Cobalt, IBM, LG Chem, and responsible sourcing specialists RCS Global Group, the RSBN ensures compliance with responsible sourcing standards. Participants in the RSBN can contribute and access immutable data securely and in a permissioned manner, facilitating the near real-time tracing and recording of mineral flow across the supply chain.

The new Alfa Romeo Tonale from 2023 is sold equipped with an NFT certification on a blockchain, which sees Alfa Romeo become the first manufacturer to link a tamper-proof digital certificate to the car. The NFT allows future owners the opportunity to see the maintenance and driving history of a car, helping to support its residual value [36].

Tesla

In its 2020 annual impact report [37], Tesla expressed its keen interest in developing Blockchain technology through two collaboration projects:

1. Re|Source Blockchain Collaboration for Cobalt: The first project aims to enable users to fully track the journey of cobalt "From Mine To Battery". This initiative is a result of Tesla's collaboration with the Re|Source consortium, which consists of leading industrial cobalt producers. Ongoing pilot projects with Re|Source have resulted in the development of Battery Passports, containing technical specifications of batteries, traceability information about battery materials, and a summary of the battery supply chain's environmental, social, and governance (ESG) performance.

2. BHP Blockchain Collaboration for Nickel: The second project involves participation in a pilot program to enhance supply chain transparency and assess various sustainability criteria. Over a three-month period, Tesla traced nickel shipments from BHP's Nickel West operations in Western Australia through the different transformation phases, ultimately leading to vehicle production at Gigafactory Shanghai. The objective of this initiative is to accurately track the provenance of the products and confirm the absence of any "dilution" in the supply chain's raw materials. Utilizing Blockchain's digital nature, the technology enables scalability and CO2 tracking, which allows for the validation of Tesla's vehicles' environmental footprint. This, in turn, empowers the supply chain to adjust its long-term strategies in emission minimization and leverage these strategies in day-to-day operations.

Tesla's direction towards adopting Blockchain technology is grounded in its commitment to incentivize transparency, traceability, and sustainability throughout the battery supply chain. Through these initiatives, Tesla aims to facilitate clear external communication with relevant third parties, showcasing its dedication to responsible and environmentally-conscious practices in the industry.

Toyota

In April 2019, Toyota Motor Corporation and Toyota Financial Services Corporation jointly established the Toyota Blockchain Lab, a cross-Group virtual organization [38]. This initiative aimed to explore and harness the potential of blockchain technology. Through demonstration trials and collaboration with various Group companies worldwide, they have been verifying the practical applications of this technology.

The main emphasis of these initiatives has been on customers and vehicles, with a dedication to exploring various use cases, including:

1. Customers: Enhancing convenience through identity sharing and digitalization of contracts within and outside the Group, improving management of personal information, and utilizing points services;

2. Vehicles: Enhancing services and introducing new ones by accumulating and utilizing comprehensive information about the entire lifecycle of vehicles;

3. Supply Chain: Boosting efficiency and traceability in business processes by recording and sharing information about parts manufacturing, shipping, and related activities;
4. Value Digitalization: Using digitalization to diversify financing methods through the conversion of assets like vehicles and rights into digital forms. This also aids in establishing long-term relationships with customers and investors.

Volkswagen

In 2019, Volkswagen Group also joined the Responsible Sourcing Blockchain Network (RSBN), as Stellantis and Ford [40].

Similarly, Volkswagen collaborated with tech company Minespider to target transparency in the global supply chain for lead [41]. Their pilot project established a shared digital infrastructure allowing the transparent exchange of information through a multi-layer architecture, guaranteeing the security of sensitive supply chain data despite the open-source approach. The protocol consists of three layers: the first layer contains generally accessible information, the second layer contains private data blocks that cannot be altered afterward, and the third layer is the encryption layer. This approach enables suppliers, sub-suppliers, and entities responsible for mining or recycling raw materials to work with one system, even when multiple supply chains are involved. It promotes the creation and sharing of a digital infrastructure that enables transparent information exchange.

In 2021, VWFS Volkswagen Financial Services announced its use of the digital identity solution Onfido and Blockchain-validated e-signature solution Scrive for its recent digital funding solution in the UK [42] [43]. Customers can prove their real identity by taking a photo of their ID and a selfie, and Onfido verifies the authenticity of the ID and matches it to the user's face to ensure legitimacy. Scrive's service facilitates the formalization of documents on any device, whether in-person or remotely, resulting in legally binding agreements supported by a world-class evidence log and protected against tampering using Blockchain technology. Volkswagen aims to add this financing solution to other initiatives aimed at improving customer experiences and simplifying processes.

Due to the unprecedented growth in the adoption of electric vehicles, the e-mobility sector has the potential to generate substantial demand for renewable energy. Building on the successful launch of Energy Web's 24/7 matching Software Development Kit (SDK), Volkswagen, in collaboration with Energy Web and Elli, undertook a Proof of Concept (PoC) [44]. The purpose of this PoC was to evaluate the technical feasibility of employing blockchain technology to reduce the carbon footprint of electric vehicles charging.

In Table 1.1, we summarize the presented use cases of blockchain technology in the automotive sector. From the data collected, it is evident that the first automotive

companies to create blockchain application projects in their industrial activities were Stellantis, Mercedes, and especially Renault. Most companies began utilizing blockchain technology around 2019/2020. Renault, also due to its earlier adoption, stands out as the company with the most widespread experience and extensive use across various areas of its activities, followed closely by Mercedes and Hyundai. Some companies, such as Tesla and Porsche, are still lagging behind in experimenting with blockchain applications.

As illustrated in Figure 6, the most widely tested and implemented blockchain application by automotive companies is supply chain management, which constitutes 31% of the projects analyzed. This application is also one of the most prevalent industrial use cases in general. The second most common application is the development of digital passports for cars or spare parts, accounting for 20.7% of the projects. This approach is particularly valuable for ensuring the authenticity of components and for the effective management and maintenance of vehicles, ultimately aiming to preserve their value over time. Additionally, the remaining approximately 48% of the projects are focused on a diverse range of less common applications, including charging solutions, metaverse initiatives, NFTs, and smart contracts. This diversity highlights the various strategic choices and experimental focuses among automotive companies within the blockchain ecosystem.

For automotive companies that are only now looking to enter the world of blockchain applications, it is crucial to adopt a strategic approach to avoid the pitfalls of dispersing efforts across too many areas at once. Initially, it is advisable for these companies to concentrate on well-established and successful blockchain applications, such as supply chain management and the creation of digital passports. By focusing on these tested use cases, automotive companies can build a strong foundation and gain valuable experience in blockchain technology without spreading their resources too thin. At the same time, there is significant potential in exploring particularly innovative initiatives. For example, experimenting with the metaverse offers a unique opportunity for automotive companies to position themselves as pioneers in a field that is still in its infancy. We observe that, at the moment, the use of virtual reality, augmented reality, and the metaverse remains relatively limited across all sectors, including the automotive sector. However, we are convinced that this is a sector with great development potential and disruptive capabilities that could significantly transform traditional practices in the automotive industry, including areas such as vehicle design, maintenance, and marketing. Furthermore, to navigate the complexities of blockchain technology effectively, companies must address the broader challenges identified by the scientific community. These challenges encompass issues related to scalability, privacy, security, throughput, latency, and usability, which impact various aspects of blockchain systems, including transaction capacity, validation protocols, and the design and implementation of smart contracts and decentralized autonomous organizations (DAOs). Successfully addressing these technical challenges is essential for the effective integration of blockchain technology into existing business processes. In addition, achieving effective interoperability between blockchain systems and third-party or legacy systems is a key consideration

for successful blockchain adoption. To this end, companies should engage with key stakeholders from their business networks to facilitate smooth integration. This process involves implementing collaborative strategies and adhering to international standards for trust and information protection, including mechanisms for access control, authentication, and authorization. In scenarios where data access must be shared among multiple organizations (an aspect commonly encountered in the automotive industry) a consortium or federated blockchain approach can offer significant advantages. This model supports data sharing while ensuring that control and security are maintained among participating entities. Finally, given the current hype surrounding blockchain technology, there is a risk that developers might present inflated performance metrics to attract investors, as evidenced by practices such as Initial Coin Offerings (ICOs). Therefore, a thorough feasibility evaluation is essential to mitigate risks associated with exaggerated claims and to ensure that the selected blockchain solution aligns with the specific requirements and constraints of the application.

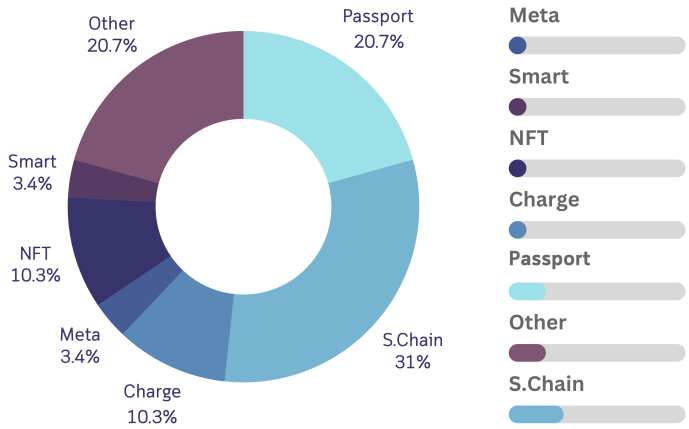

Figure 6: Distribution of different types of blockchain-based projects undertaken by major automotive companies in recent years. The pie chart illustrates the percentage distribution of projects across various applications such as automotive supply chain, digital passports, NFTs, and others, as summarized from the case studies presented in Table 1.1.

7. Conclusion

Blockchain technology is ushering in a paradigm shift across global industries by revolutionizing transactional and interactive processes. Its unique capacity to foster trust and facilitate value exchange among distrustful parties, while eliminating the need for intermediaries, is reshaping established norms. The automotive sector, as depicted in this article, makes no exception to this transformative wave.

This study delved into the fundamental attributes of blockchain, uncovering its

Name	Start	#	MOBI	RSBN	Passport	Supply Chain	Charge	Meta	Smart	NFT	Finance	CO_2	Hyperledger	Coop.	Other
BMW	2019	4	X		X	X	X								
FORD	2020	4	X	X	X										X
GEELY	2019	2				X		X							
HONDA	2020	2	X				X								
HYUNDAI	2019	5	X			X			X	X	X				
MERCEDES	2017	5				X					X	X	X	X	
PORSCHE	2018	1													X
RENAULT	2015	6	X		X	X				X		X			X
SAIC - GM	2019	4	X		X	X									X
STELLANTIS	2017	4	X	X	X					X					
TESLA	2020	1				X									
TOYOTA	2019	4	X		X	X					X				
VOLKSWAGEN	2019	4		X		X	X				X				
			7	3	6	9	3	1	1	3	4	2	1	1	4

Table 1.1: Blcockchain technology use cases

comparative advantages over centralized databases, particularly in use cases where the added value of blockchain-enabled features is most pronounced.

After the analysis of several flowcharts, we proposed a new one to conduct a feasibility evaluation along with detailed considerations about challenges and limitations in the automotive sector.

Moreover, this document comprehensively showed numerous relevant use cases within the automotive sector, illustrating how blockchain enhances transparency and traceability.

Analysis of adoption levels among major car manufacturers confirms that all have shown interest in blockchain technology for some years, progressively transitioning from initial exploration and pilot projects to full-scale implementation.

On the other hand, it is evident that not all car manufacturers are at the same stage of studying and utilizing this technology. Those that commenced earlier or invested more find themselves with a competitive advantage, which could prove pivotal in determining future market leadership.

However, we must take into account that blockchain technology has its limitations. For instance, encrypting data and the consensus mechanism can enhance confidentiality but may decrease transparency and performance. Storing only a hash of data on-chain, while keeping the raw data off-chain, can improve both confidentiality and performance. In terms of performance the research is continuing to improve the efficiency of the consensus mechanism. For example, consensus algorithm as Ethash [87] and X13 [88] can come to a consensus within 10 to 20 seconds, while Bitcoin takes 10 minutes on average. The linking of blocks through cryptographic hash establishes a form of immutability for all transactions recorded on the blockchain. While this typically ensures data integrity, it can also lead to complications. Real-world blockchain implementations face challenges such as disputed transactions, incorrect addresses, exposure or loss of private keys, data-entry errors or unexpected changes to assets tokenized on the blockchain. Moreover, using blockchain for data integrity may incur higher costs compared to classical methods. Existing mechanisms, such as hash functions and digital signatures, can establish data origin. Therefore, integrating blockchain into systems with established tracking mechanisms may not significantly enhance provenance information. Although blockchains currently face scalability issues, this limitation may not be fundamental and could be resolved in the near future. Consortium and private blockchains, when meticulously designed and optimized for performance, exhibit significantly better scalability compared to public blockchains. Finally, in terms of throughput, conventional public blockchains are currently limited to process an average of 3-20 transactions per second, whereas established payment services such as Visa and Mastercard can handle 50,000 transactions per second.

Consequently, blockchains alone may not fulfill the demands of all usage scenarios, particularly those requiring high volumes of real-time transactions. Some of the most important challenges in this sector rely on data storing, throughput, scalability, consensus mechanisms, key management, inter-blockchain communication,

compliance with the privacy regulations, oracles, smart contract security and interoperability with existing systems.

Looking ahead, the automotive industry stands on the cusp of a compelling technological transformation, with blockchain poising to play a central role in its evolution. Opportunities for further blockchain innovation and integration abound and this paper offers insights into leveraging the potential of blockchain technology to propel progress in the automotive industry.

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