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Review

A Review of Blockchain-Based Systems in Transportation

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Received: 3 December 2019; Accepted: 24 December 2019; Published: 29 December 2019

Abstract: This paper presents a literature review about the application of blockchain-based systems in transportation. The main aim was to identify, through the implementation of a multi-step methodology: current research-trends, main gaps in the literature, and possible future challenges. First, a bibliometric analysis was carried out to obtain a broad overview of the topic of interest. Subsequently, the most influential contributions were analysed in depth, with reference to the following two areas: supply chain and logistics; road traffic management and smart cities. The most important result is that the blockchain technology is still in an early stage, but appears extremely promising, given its possible applications within multiple fields, such as food track and trace, regulatory compliance, smart vehicles' security, and supply-demand matching. Much effort is still necessary for reaching the maturation stage because several models have been theorized in recent years, but very few have been implemented within real contexts. Moreover, the link blockchain-sustainability was explored, showing that this technology could be the trigger for limiting food waste, reducing exhaust gas emissions, favouring correct urban development, and, in general, improving quality of life.

Keywords: blockchain; literature review; transportation; logistics; supply chain

1. Introduction

The blockchain is a universally acclaimed innovation based on a distributed ledger technology, which originated from the efforts of anonymous developers to create a secure digital currency. Digital currencies that are based on a blockchain are defined cryptocurrencies, since they rely on cryptographic mathematical tools. The first blockchain originated from a paper anonymously published in 2008 on the cryptography mailing list at metzdowd.com [1]. Since 2008, a great development, which has been carried out on initial concepts, has led to the creation of many distributed and active blockchains. The blockchain concept involves different kinds of knowledge and is technically complicated to the point that Bill Gates publicly said on TV about this technology: "I think it's a technical tour de force."

Many applications have been imagined for blockchain data systems, and many scientists and financial experts expect great innovations to be centred on this innovative concept, especially in the logistics sector [2–5]. Some authors have even defined this new technology as disruptive, with reference to the transportation field [6].

Recently, the number of academic papers published on blockchain-related subjects has dramatically increased. Many of the scientific contributions listed in [7] deal with technical topics, which are the main challenges of the blockchain technology (BT), such as security, usability, privacy, and wasted resources. It should be noted that several blockchain-based potential applications have been proposed and discussed in the literature. In [8], the following five main application domains are presented: finance, security and privacy, IoT, reputation systems, and public and social services. The main field of application of blockchain technologies is the financial one, as the technology originated precisely with the invention of the Bitcoin. There is a large base of Bitcoin users who believe the technology will disrupt the banking sector. Some ideas are presented in [9–12]. Big companies such as IBM and Microsoft have started to consider offering blockchain services. Insurances can take advantage of blockchain technologies in claims processing [13] and introducing smart contracts [14]; moreover, blockchain technology can also reduce custody risk and help in cross-border asset transfers. From 2004, some banks such as Santander have started to develop payments applications that allow customers to make international money transfers in 24 h [15]. Moreover, there are many potential blockchain Internet-of-Things (IoT) applications according to [16,17]. Special attention has been given to the potential of blockchain technology to strengthen the IoT by allowing secure sharing of data sets [18]. In general, blockchain security features are considered useful, if coupled with IoT, where security issues are a growing concern [19]. Privacy applications of blockchains have been proposed, especially to protect personal data [20] against cyber attacks [21] in public services such as health care [22–24] and voting systems [25–27], and in other government owned databases [28]. Blockchains can, in fact, store personal data (e.g., health care records or identity data [29,30]), allowing only the owner and the public entity to access with private keys. Every data access would then be stored on the blockchain forever, granting complete security and accountability. Blockchains are also able to store receipts of expenses that could be automatically sent to central entities as proof. Moreover, blockchains have been envisioned as having a great role in smart cities [31,32]. The blockchain ledger can be used to track ownership and movements of a certain merchandise along the supply chain [33] until it reaches the final consumer.

As previously said, there are many new technological features of blockchains. These innovations are the basis for many to signal the start of a "blockchain revolution" [34,35]. The main innovative technological features are:

- The possibility of safely completing trust-less exchanges between two parties without any control, supervision, or intermediation of a third party [36].
- Robustness, resilience, trustworthiness, and durability, since blockchains are distributed and do not have a central point that can be attacked. This feature is a guarantee against attacks, and a blockchain, which has nodes across the globe, can be expected to keep working as long as there is an internet connection between nodes. Data will be reliably kept, yet in many potential applications it remains to be solved how to ensure that they are also reliably entered [37].
- Open structure, which guarantees transparency [38] and the immutability of data [39]. Data stored on a blockchain cannot be altered.
- Pseudonymity: Owners of data or users in general can decide to stay anonymous or give proof of their identity as necessary. Blindly signed exchanges and contracts are possible on specific blockchains [40].
- Process reliability: In the sense that users can trust the system to execute transactions as requested, removing the need for a middle entity or supervisor and allowing the users to set up "smart contracts" [41].

Next to the above-listed technological features, there are also many problems, which must be solved in practical applications:

- Blockchains may be environmentally costly, in the case that they have a proof of work based on computer calculations, because they could use up an incredible amount of energy.
- Lack of regulation can create risks for the users. Smart contracts constitute a very new application which has still to be experimented on in practice to understand the application limits: one very important event in cryptocurrency history is the Ethereum fork, where a malicious use of an existing (badly laid-out) smart contract was able to extract the equivalent of 50 Million dollars from the Decentralized Autonomous Organization (DAO) network in 2016 [42].

- Blockchains represent a quite complex system, and many potential users may not understand the advantages and adopt the technology.
- Blockchains can also be slow in transactions when they become main-stream and are not the best place to store a huge amount of data. In other words, there is also a scalability problem which has been evidenced in the original Bitcoin system [43].

Potential Applications of Blockchain-Based Systems in Transportation

By transportation we intend the movement of people or goods from one place to another. In the following, we will distinguish specifically everything that pertains to movement of goods and we will consider it as part of a research cluster in supply chain and logistics. Regarding the means of transportation, we will show that the blockchain-based systems are being researched, especially in the road sector in connection with the concept of new autonomous and connected vehicles.

Transportation management can be positively affected by the adoption of blockchain technologies, in many ways. In the very well-made report of Catapult Transport Systems [6], blockchain technology is considered potentially disruptive for transport systems; at the same time, this report presents the fact that many experts involved in a survey on BT trends do not seem to be very informed about this emerging system. This work concludes by evidencing how the convergence of emerging services and technologies, such as Mobility as a Service (MaaS), IoT, artificial intelligence (AI) with deep learning, 5G (the new generation of wireless mobile data protocol), and distributed smart objects, may reshape the future of logistics and transportation.

The most widely discussed topic in terms of application of the BT in transportation is logistics; in fact, many papers have been presented in recent years, such as: [3,33,38,44–50]. BTs are presented by many as disruptive for the way supply chains are managed. In a globalised world, most industries have to develop efficient and long supply chains to succeed. This means that the complexity of delivering and tracing goods must be met with adequate informatics systems. Blockchains can serve many different functions by securing goods and data from any malicious attacks in multi-agent supply chains. Blockchains provide the possibility of controlling product storage quality during transportation and guaranteeing the origin of products, thereby creating trust among suppliers. Various important problems can be addressed in supply chain management by a blockchain, such as cost and quality control, avoiding counterfeiting, speed of transfer, reporting on stopped goods, risk reduction, and flexibility [44].

Important companies, such as IBM and Maersk, have created partnerships to investigate blockchain implementations. Multiple stakeholders can rely on the blockchain to gain trust and to manage the flux of information. Traceability along the supply chain can be facilitated, adding value to the final product: every transfer of goods could be recorded and validated through the consensus of all blockchain entities. The main problem in these supply chain BT applications is to overcome the difficulties of guaranteeing that the physical layer (i.e., the real goods) corresponds to the digital layer (i.e., data that are stored). The use of certified smart objects of IoT could brighten the future of these kinds of system. Many companies have invested in supply chain applications of BT, such as Provenance, Jiocoin (which is also launching its own crypto-coin), SKUchain, and Blockverify, which has created a service to avoid counterfeiting of goods. Special interest has been paid by many companies to BT, applied to the diamond supply chain for obvious reasons.

Many applications have been proposed also in the automotive sector [51] and for intelligent transportation systems (ITS) [52]. The automotive industry could use BT to shift its products toward MaaS, and the following services could be offered: remote software-based vehicle maintenance operations, insurance services, smart charging services, and car sharing services. Many companies have invested in car sharing and data sharing BT-based business, such as Arcade City and La'Zooz. Many potential applications of BT may emerge, especially in ITS systems where connected and autonomous vehicles may take advantage of this innovation and the convergence of IoT and MaaS.

Many companies and governments have started activities by setting up blockchain systems in different sectors [53] among them: Charity: Bitgive [54]. Cybersecurity: Guardtime [55]. Finance:

Barclays [56], Aeternity [57], and Augur [58]. Governments: Dubai, Estonia, the United Kingdom, and others [59]. Healthcare: SimplyVital Health [60]. Media: Ujo music [61] and Kodak, which in 2018 announced that it would start "KODAKcoin" [62], raising concerns that the blockchain technology was announced for mere promotion issues [63]. Peer to peer retail market: Openbazaar [64] (raising concerns that a new "Silk Road" [65] may start). Real estate: Ubitquity [66].

The remainder of this paper is structured as follows: Section 2 contains the most relevant information to explain to the reader the general functioning of blockchain technology; in Section 3, the methodology for conducting the literature review is explained and its first steps are implemented; Section 4 contains a bibliometric analysis and a study of the main scientific articles in the literature, in terms of topics covered, starting issues, and contributions; Section 5 provides a discussion about research trends, gaps that still need to be filled in the literature, possible future challenges, and perspectives. The conclusions are shown in Section 6.

2. Blockchain Technology: How Does It Work?

The first original paper on blockchain technology was the work: "Bitcoin: A Peer-to-Peer Electronic Cash System" [1], describing the conceptual basis for developing a digital currency called "Bitcoin". In January 2009 the first active blockchain was launched. Many websites, papers, and reports [67] explain in detail how a blockchain works. In the following, we just introduce the main concepts. A blockchain is based on a piece of distributed ledger technology, which is a distributed database with some specific characteristics. In the original version of financial blockchains, the ledger holds the currency transactions between different parties. In a blockchain, information is stored on many "distributed" computers which can be in different parts of the world and that store the same replicated ledger and database. Each computer that is holding the distributed database is called "node" of the blockchain network. The database in a blockchain is structured in blocks which are replicated and copied on all the nodes of the network. Every block is generated and univocally linked to the preceding block by a cryptographic signature system, creating a chronological chain of blocks and containing information regarding transactions (see Figure 1).

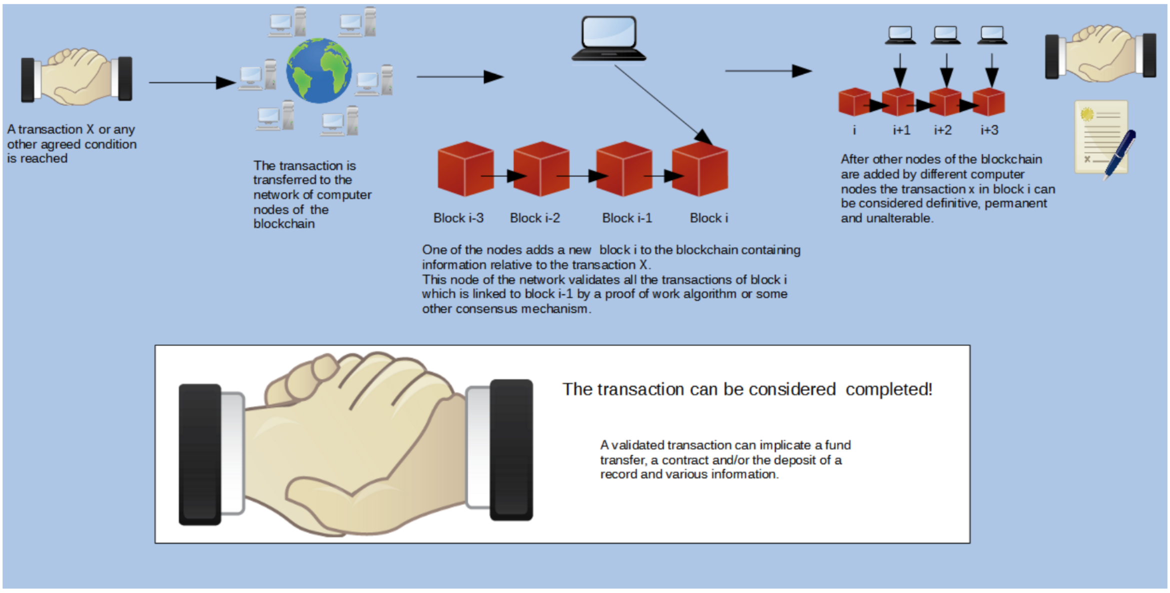

Figure 1. The blockchain made simple.

Consensus on the validity of data is reached in the blockchain with a mechanism that guarantees a certain effort before a network node is allowed to add a block in the chain. In other words, blocks in a blockchain can be added by every node of the network when certain conditions are met. To avoid the problem that different blocks (n + 1) could be added at the same time in different nodes of the network, this "consensus" algorithm is applied: in some instances of blockchain technology, the longest main blockchain prevails and the blocks added to other side chains are discarded. The mechanism is such that it is in the interest of every node to add new blocks to the main chain and to replicate the other blocks which are added to the main chain. One possible consensus mechanism is called proof of work (PoW). The PoW consists of performing computationally complex operations on each block that is added. The way PoW is performed guarantees that nobody can easily add an altered block at some point of the chain, since it would be necessary to also add all subsequent blocks, and that is computationally infeasible. PoW in cryptocurrencies has been criticised, since it requires enormous calculation power, which turns into a huge electricity drain [68].

In a general purpose blockchain, the information stored in a block is not only about currency transactions. Every datum could, in theory, be inserted in a block, including information about an event, value and object transactions of different kinds (e.g., logistic data of goods that are handled), and even automatic transactions which can be activated if a given condition is met (i.e., smart contracts). This is one of the main features that make blockchains useful for many different applications in the transport sector.

The Blockchain Is an Immutable Distributed Database with Specific Characteristics

As a consequence of their structure, blockchains offer some specific features in addition to the fact that they are decentralised, such as that they are immutable and irreversible, they can be transparent, and as described above, they are based on some form of consensus.

The transactions and the information which are stored in a blockchain become public and immutable. A block cannot be altered or faked once is added to the blockchain, since the crypto-graphical algorithm applied to connect univocally subsequent blocks makes any alteration infeasible. Each block also bears a time stamp. A blockchain can certify the sharing of information across a network of different entities, even in the case where two parties never met and do not trust each other, and without the need for a trusted middle or central entity. For this reason, blockchains are credited to being able to create trust and greater collaboration among potential partners that may be far away from each other.

It must be noted that the concept of the distributed database [69] has not been invented with the blockchain, yet other distributed databases were centrally managed. The innovation of blockchain systems is that they manage to be completely decentralised with competing and not friendly computer nodes that find the incentives to cooperate to keep the blockchain working. The incentive in cryptocurrency systems to persist in running a network node is that the computer nodes are candidates to receive award coins for the creation and the insertion of one block in the blockchain. In a normal database, the operations performed are: read, write, and verify data. In a blockchain, data are written only once by different parties, and signatures (verification) by different stakeholders are performed in every block. In this way the addition of every subsequent block guarantees the impossibility of data tampering. The trust in the information held in the blockchain can be complete, without requiring intermediation of a central server or entity. Blockchain databases can perform these services: history and proof of ownership of a physical (consignment) or documentary asset (data and intellectual property); immutability; consensus and agreement on the validity of data; a single version of truth, since the database is replicated in all nodes of the network; data transparency can be customised, allowing restricted data access according to who is reading the data (i.e., who is able to read what data); and decentralisation. As a consequence, a blockchain can allow users to operate transactions without a middle entity, perform a complete track of information, and establish smart contracts. Smart contracts [70] are contracts in the form of computer code that will execute, for example, a currency transfer when a certain condition is met. The typical example of a smart contract in logistics is a payment that is issued automatically when certain goods are received by a certain entity.

3. Review Methodology

The literature review about blockchain-based systems in transportation sector, proposed in this research work, has been carried out through the seven-step procedure shown in Figure 2. Similar methodologies are quite common in the literature [71,72].

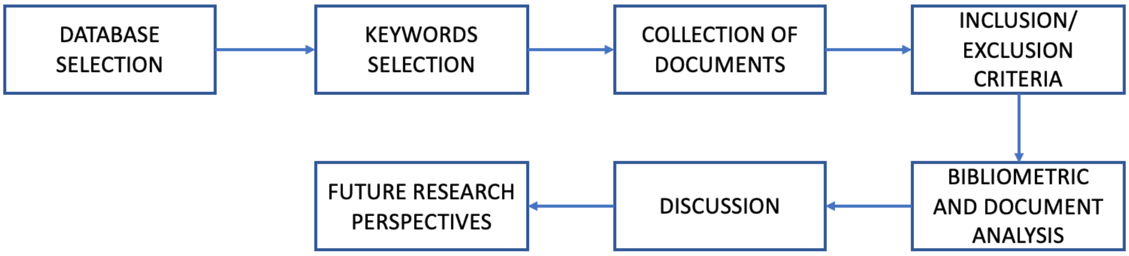

Figure 2. Seven-step procedure for literature review.

3.1. Database Selection

There are numerous scientific research databases which collect the contributions of various scholars. In this study, Scopus was selected. It contains more than 20,000 peer-reviewed journals, belonging to the most important publishing houses, such as Springer, Elsevier, Taylor and Francis, IEEE, and Emerald. Scopus is more comprehensive than Web of Science (WoS), another important and recognised database, which includes only ISI indexed journals; then, about 12,000 titles [73].

3.2. Keywords Selection

With the aim of constructing an exhaustive literature review in the transport sector, the authors identified a sufficiently large number of keywords to be combined with the term "blockchain": traffic, logistic, supply chain, airport, transport, transportation. A query was carried out through the "document search" of Scopus using simultaneously the AND and OR connectors, as follows: (blockchain AND traffic) OR (blockchain AND logistic) OR (blockchain AND supply AND chain) OR (blockchain AND airport) OR (blockchain AND transport) OR (blockchain AND transportation).

3.3. Collection of Documents and Filtering (Inclusion/Exclusion Criteria)

The first query returned a total of 874 publications. In order to have an idea about the contribution of each keyword to this result, Table 1 shows the number of documents retrieved by performing the queries separately. Obviously, a higher number (i.e., 1050) was obtained because some duplications were possible in this case.

Table 1. First search results.

Search Keywords	Results (No. of Documents)
Blockchain AND Supply Chain	522
Blockchain AND Traffic	190
Blockchain AND Transportation	138
Blockchain AND Logistic	122
Blockchain AND Transport	72
Blockchain AND Airport	6
Total	1050

It can be noted that the application of blockchain technology in the airport sector seems to be a research branch still quite unexplored; on the contrary, the number of contributions grows considerably if we refer to the supply chain topic.

Subsequently, all documents, belonging to one of the following types, were excluded: "Conference Review"; "Note"; "Editorial." Therefore, the number of publications was reduced to 745. Then, the authors read the abstract (and in some cases also the full paper) of the remaining documents, one by one, with the aim of excluding: duplicate publications (i.e., articles presented at conferences and then published in journals as an extension), documents not written in English, and especially, documents not relevant to the topic of this research work. The number of selected documents was further reduced to 371—those examined by the descriptive analysis below.

4. Bibliometric and Document Analysis

In this section, the application of the fifth step of the above presented review methodology is described.

4.1. Bibliometric Analysis

The bibliometric analysis was partly supported by the free software VOSviewer (1.6.13 version) [74].

4.1.1. Publication and Citation Frequency

In Figures 3 and 4, the number of publications and citations about the application of the blockchain technology in the transport sector over the years are reported, respectively.

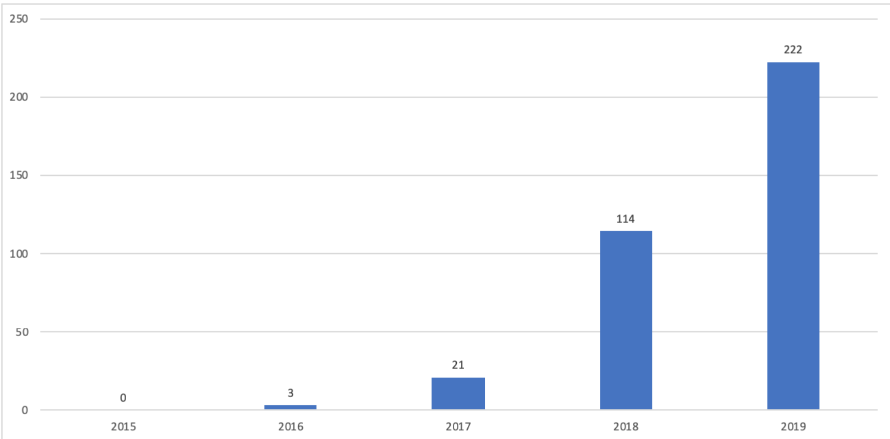

Figure 3. Number of publications on blockchain and the transport sector over the years.

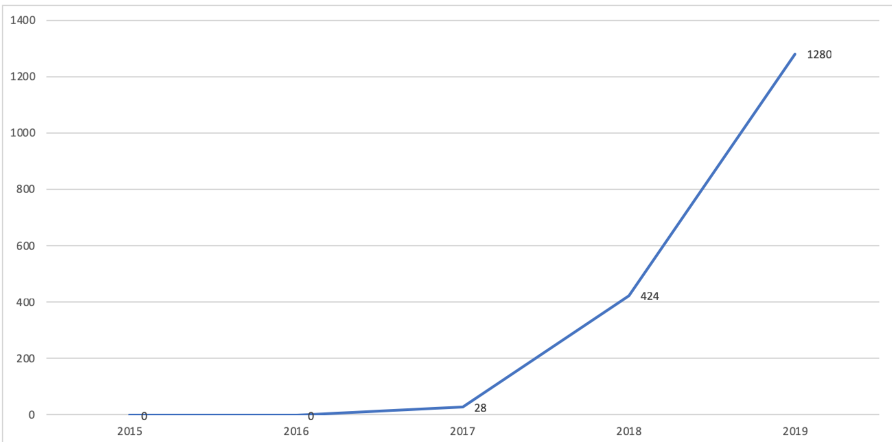

Figure 4. Number of citations on blockchain and the transport sector over the years.

As can be seen, in the last three years there has been a considerable growth in the application, theoretical or practical, of blockchains to the transport sector. Between 2018 and 2019, the number of published articles almost doubled, while the number of citations tripled. This trend is one of the main reasons behind the present study, which responds to the need for detecting the current state of the art and the main research gaps. In fact, the very high number of contributions published in recent years makes the issue of classifying and discussing the main methodologies proposed by the various authors very interesting.

4.1.2. Source Analysis

In Table 2, the top sources in terms of the number of published documents are reported.

Table 2. Main sources, in terms of published documents.

Source	No. of Documents
Advances in Intelligent Systems and Computing	13
Lecture Notes in Computer Science	13
IEEE Access	12
Proceedings—IEEE 2018 International Congress on Cybermatics	11
ACM International Conference Proceedings Series	9
International Journal of Information Management	8
International Journal of Production Research	8
Supply Chain Management	5
Sustainability (Switzerland)	5
Computers and Industrial Engineering	5
CEUR Workshop Proceedings	5
Communications in Computer and Information Science	5
Lecture Notes of the Institute for Comp. Sci., Soc. Inf. and Telecom. Eng.	5

It should be pointed out that a very large number of sources concern conference proceedings. That means that the blockchain topic has been commonly debated within the recent scientific conferences. The recent IEEE International Congress on Cybernatics (2018) has collected a significant number of contributions. Advances in Intelligent Systems and Computing, and Lecture Notes in Computer Science, are, however, the most prolific sources with 13 documents. IEEE Access, the International Journal of Information Management, and the International Journal of Production Research are, instead, the first three journals (i.e., sources not related to proceedings). It is worth mentioning also, that transportation-related journals have not yet published many works about blockchain technologies.

4.1.3. Keywords Statistics

In Table 3, the 10 most used keywords are shown.

Table 3. Top 10 keywords.

Keyword	No. of Occurrences
Blockchain	319
Supply chains (OR supply chain)	202
Internet of things	103
Supply chain management	87
Smart contract (OR smart contracts)	65
Information management	34
Intelligent systems	32
Blockchain technology	31
Food supply	28

Since the software used is not able to distinguish between singular and plural terms, nor between words having the same roots, the occurrences of the keywords having the same meanings (e.g., supply chain and supply chains) were merged. As expected, the term blockchain was the most used (86%), followed by supply chains (or supply chain) and internet of things, used, respectively, in 54% and 28% of cases. In order to highlight the links between the different keywords used in the 371 selected documents, a co-occurrence analysis was carried out. Only the keywords with a number of occurrences greater than 10 were taken into consideration, for a total of 52. Also, in this case, a cleaning phase was necessary for excluding duplicates. The output of this analysis is shown in Figure 5.

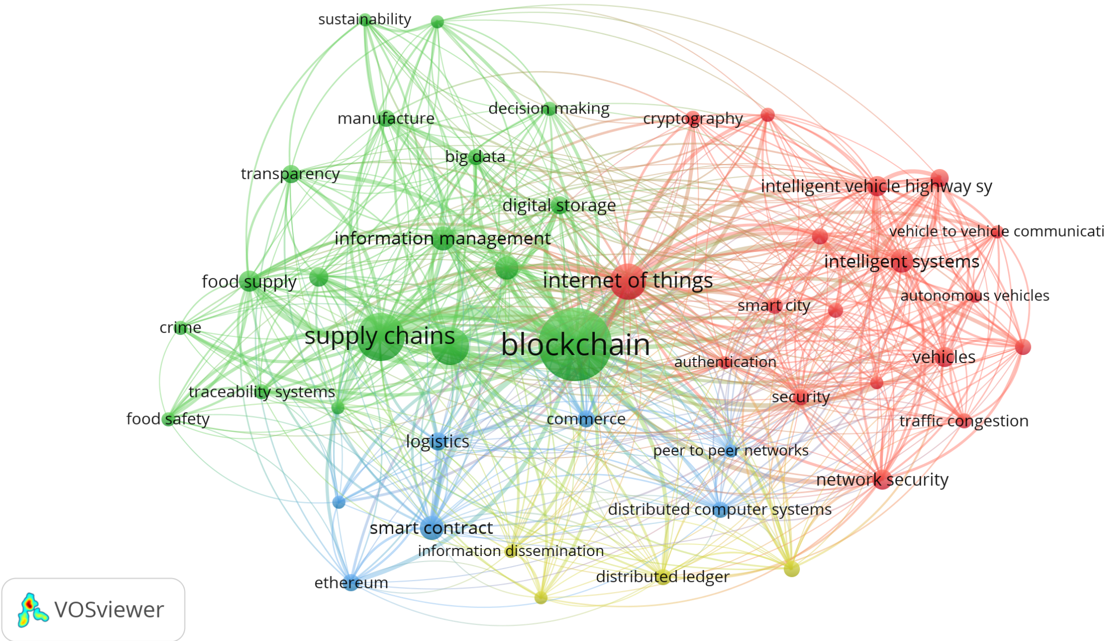

Figure 5. Output of the co-occurrence analysis on all the keywords of the 371 selected documents.

Note that the number of occurrences was the unit chosen for the size of each node of the created bibliometric network; therefore, a node was greater the higher the number of occurrences detected. Moreover, given two nodes in the network, the closer they are, the more likely the co-occurrence of the respective keywords they represent. Based on this aspect, four clusters, with different colours, were created. The green cluster is mainly concerned with the supply chain information management topic, and the most representative keywords, in this context, were: "information management," "big data," "digital storage," "traceability systems," "transparency," "supply chains," and "food safety." The red cluster, instead, mainly concerns logistics aspects, and some important recent research trends were detected: "smart cities," "autonomous vehicles," "intelligent vehicle highway systems," and "vehicle-to-vehicle communication". The blue and yellow clusters were the smallest and substantially concerned the basic aspects of the blockchain technology: "peer-to-peer networks", "distributed computer systems," "smart contract," and "distributed ledger."

The output of the co-occurrence analysis is extremely useful for defining the directions through which to explore the existing literature. In particular, from the observation of the network, it is possible to define two macro-clusters (i.e., C_1 and C_2): the first one concerns the application of blockchain-based systems to supply chains or logistics; the second one, instead, is related to road traffic management and smart cities.

In parallel, by reading the documents one by one, a manual categorization was carried out in the topics indicated in Table 4:

The results of the manual categorization confirmed the validity of the keyword analysis, which led to the aggregation of most papers in the two macro-clusters C_1 and C_2. Moreover, it can be said that very few papers have been published in the railway, maritime, and air transportation sectors: 10 out of 371; in other words, just around 2.5% of the total number of documents.

Table 4. Results of the manual categorization on the 371 documents selected.

Topic	No. of Occurrences
Supply Chain and Logistics	244
Road Transportation	78
General Interest	30
Smart Cities	9
Air Transportation	5
Maritime Transportation	4
Railway Transportation	1

4.2. Document Analysis

For each of the two macro clusters C_1 and C_2, the 10 most cited articles (excluding the documents in the form of a literature review) were selected, in order to highlight the main current research trends and the gaps that have yet to be filled. Tables 5–10 show the analyses of the papers, respectively, belonging to C_1 and C_2. The following features were taken into account: topics, starting issues, and contributions.

Table 5. Analysis of the most relevant documents belonging to C_1 (part 1/3).

Reference	Topic	Starting Issues	Contribution
[45]	Alimentary Supply Chain & Traceability	• Lack of information for consumer about the origin of food products • The recent increase in the amount of digitized data also means greater risk of attacks by malicious parties, which may wish to modify, eliminate or even steal private information	• A blockchain-based approach for storing all the transactions information regarding the alimentary supply chain of the case study • A multi-agent system (MAS), which exploits the functionality of smart contracts for efficiently managing the processes of the supply chain and enabling the circular economy principles • A ranking system for rewarding the actors, which mostly follow the rules of the new proposed supply chain model
[75]	Agri-Food Supply Chain & Traceability	• Traditional agri-food logistics systems are currently not able to match demand market • Food scandals, occurred in recent years, especially in China, such as: "Sudan red" and "trench oil" [76] • Very early stage of Chinese agri-food supply chain systems: lack of modern equipment, high difficulty in tracking and tracing the processes undergone by agri-food products, uncertain and undefined regulatory environment	• An RFID and blockchain based agri-food supply chain traceability system, in China, for ensuring: food product safety & quality, decreases in losses during the logistics processes
[77]	Food Supply Chain & Traceability	• Traceability systems are often centralized, monopolistic, and asymmetric; therefore, they are very vulnerable because a single point of failure can cause the dangerous collapse of the whole system • Trust in the information shared among the actors of the supply chain	• A food supply chain traceability system based on HACCP (Hazard Analysis and Critical Control Points), blockchain and IoT, for ensuring real-time food tracing • Guarantee of the following features: openness, transparency, neutrality, reliability, security

Table 6. Analysis of the most relevant documents belonging to C_1 (part 2/3).

Reference	Topic	Starting Issues	Contribution
[78]	Pharmaceutical Supply Chain & Regulatory Compliance	• In the healthcare context, regulations regarding the transport of medicines are stringent and complex • Need to automatically monitor compliance with the law regarding the shipment of medicines (e.g., temperature and humidity must be checked)	• Description of the main innovations by modum.io, a start-up, which uses the principles of IoT and blockchain to guarantee: data immutability, accessibility of temperature records, decrease in operational costs within pharmaceutical supply chains • Provision of a list of start-ups in non-financial areas, involved in the blockchain implementation, is shown. The main aspects and results are shown, in order to highlight the possibility of using blockchain not only in the financial area, where it was born some years ago
[79]	Supply Chain & Traceability	• Great difficulty of granular traceability of physical goods, considering the significant complexity of modern supply chains • Need to exploit new tools, such as IoT and blockchain, for evaluating knowledge provenance in an efficient way	• Development of a blockchain-based ontology for supply chain provenance • Proof-Of-Concept implementation
[80]	Supply Chain & Traceability	• Traceability systems usually store information in centralized databases, under the control of the service providers; the risk of data tampering is high	• OriginChain, which consists of the use of blockchain, instead of a centralized database, with the aim to: automate regulatory-compliance checking, guarantee tamper-proof traceability
[81]	Agricultural Supply Chain	• Supply-demand matching • Security and transparency of transactions; user privacy • Platform credibility: the dissemination of untruthful information about demand and supply of agricultural products is an event to be avoided	• A public blockchain based on a double chain architecture for agricultural supply chain • Introduction of the proposed public blockchain into a public service platform
[76]	Supply Chain & Traceability	• Inability of current information systems to track shipment in real-time • Many existing solutions for shipment tracking are extremely limited because they are populated from a single source (i.e., the carrier) and are not validated by an independent entity	• A framework, consisting of a set of private distributed ledgers and a single blockchain public ledger. It is independent, crowd-validated, and used for online shipment tracking. Information about the distribution phase is provided to all stakeholders, in order to increase supply chain visibility • Attempt to address the divide between completely private/permissioned and completely public/open blockchain architectures • Demonstration of the potential of combining public and private ledgers, for solving some issues in the supply chain

Table 7. Analysis of the most relevant documents belonging to C_1 (part 3/3).

Reference	Topic	Starting Issues	Contribution
[82]	Agri-Food Supply Chain & Traceability	• Many current IoT traceability systems are based on centralized infrastructures, which lead to some open issues, such as: data integrity and tampering, single points of failure • The majority of traditional logistic information systems in agri-food supply chains cannot provide important features, such as: transparency, traceability, and auditability	• AgriBlockIoT, a fully decentralized, blockchain-based traceability solution for agri-food supply chain management. It can ensure IoT devices integration • Evaluation and comparation of two different blockchain implementations (i.e., Ethereum and Hyperledger Sawtooth) on a classical use-case "from-farm-to-fork," in terms of: latency, CPU, and network usage
[83]	Supply Chain Management	• There are information asymmetries among the actors of the supply chain, which negatively influence the algorithms for planning activities • The data sharing between manufacturers, suppliers, and customers is an extremely important aspect, so that the entire supply chain can react effectively and efficiently in the face of high market variability • The coordination of information has become more difficult due to the great complexity of modern supply chains	• A blockchain-based solution for overcoming two main problems of supply chain management: double marginalization, information asymmetry

Table 8. Analysis of the most relevant documents belonging to C_2 (part 1/3).

Reference	Topic	Starting Issues	Contribution
[51]	Interconnected Smart Vehicles	• There is a need to make smart vehicles safer because malicious attacks can compromise passengers' safety • There are cases of attacks on the car infotainment system to take control of the vehicle's core functions • Data exchanged between interconnected vehicles can be very sensitive (e.g., location), then user privacy must be ensured • Current smart vehicles systems rely on centralized infrastructures, which can collapse when the number of users is too large; moreover, a single point of failure can compromise the entire network	• A decentralized blockchain-based architecture to protect user privacy and to increase the security of the smart vehicle ecosystem
[52]	Intelligent Transportation Systems (ITSs)	• Lack of trust among the ITS actors. As a consequence, the information flow is usually complex and slow. For example, money cannot be transferred from an entity to another one, without the support of trusted intermediaries • The presence of centralized authorities or cloud computing can cause performance limitations or even temporary unavailability of the ITS, owing to malicious attacks	• A blockchain-based ITS framework for ensuring stability, efficiency and profitability of the ITS ecosystem • A case-study for blockchain-based real-time ride-sharing services
[84]	Smart City	• According to the 2014 report on the global outlook for urbanization in the United Nations, most of the world's population lives in urban areas, and a further 2.5 billion people are expected to arrive by 2050. For urban communities the challenge of satisfying residents' requests will be increasingly complex • Privacy and security of vehicular network	• A blockchain-based vehicle network architecture (Block-VN) in the smart city context • Analysis of the evolution of the vehicle network, when using paradigms focused on networking and vehicular information • Service scenarios and design principles are discussed for Block-VN

Table 9. Analysis of the most relevant documents belonging to C_2 (part 2/3).

Reference	Topic	Starting Issues	Contribution
[85]	Heterogeneous Intelligent Transportation Systems	• Despite the recent developments in the Vehicular Communication Systems (VCS), much effort is still needed to improve the key management schemes • Cryptographic materials need to be sent in timely manner to the Security Manager (SM), who is very useful in collecting and managing main vehicle information (e.g., vehicle departure information)	• A framework for secure key management within a heterogenous network. The first part is a blockchain-based decentralized network topology, which is very useful to simplify the distributed key management. The second part is a flexible transaction collection period selection method to reduce the key transfer time of the blockchain scheme • A set of simulations and analysis that shows the efficiency of the proposed framework with respect to a structure with a central manager. In particular, the use of a dynamic scheme allows the SM to fix the various traffic levels in a very flexible way
[86]	Vehicular Announcement Network	• Difficulties in forwarding reliable announcements, without knowing the users' identities • Lack of motivation and enthusiasm from users to forward announcements, especially for privacy and monetary reasons	• CreditCoin, a blockchain-based privacy-preserving incentive announcement network. Users are motivated to share traffic information, through some incentives • A set of experiments to show that CreditCoin is efficient and practical in smart transportation simulations
[87]	Vehicular Networks	• The non-trusted environments make it difficult for vehicles to evaluate the credibility of exchanged messages	• A blockchain-based decentralized trust management system for vehicular networks • A joint Proof-of-Work and Proof-of-Stake consensus mechanism • Performance evaluation of the system via simulation to demonstrate that it is effective and feasible in terms of collection, calculation and storing trust values in vehicular networks

Table 10. Analysis of the most relevant documents belonging to C_2 (part 3/3).

Reference	Topic	Starting Issues	Contribution
[88]	Electric Vehicles	• There is a need for an approach that allows customers to query charging stations for the lowest available price, but preserving their privacy: current position and energy need should not be revealed to the public	• A protocol for dynamic tariff decisions for electric vehicle charging • The presented protocol relies on a blockchain, where electric vehicles show their demand, while charging stations send bids. The overall mechanism is similar to an auction
[89]	Electric Vehicles	• Exploit the availability of some data (i.e., planned route, car battery status, real-time traffic information, drivers' preferences), to support a matching between the demand and supply of energy for electric vehicles, using the potential of smart contracts and blockchain	• Design of an architecture of a system for autonomous selection for electric vehicles charging station, including: negotiation for the most convenient option, automated payment • UML model to make clear the role of the various entities involved
[90]	Smart City	• There is a need to satisfy the design principles of modern service requirements for sustainable smart cities efficiently • The strong increase in smart devices, in terms of numbers and diversity, opens up important challenges about: scalability, efficiency, flexibility and availability in the context of smart cities	• DistArch-SCNet, an efficient, scalable, blockchain-based smart city network architecture, enabled by the light-fidelity (Li-Fi) communication technique • A hybrid communications modulation scheme, to utilize bidirectional multi-access Li-Fi communication • A controller-hoping algorithm, to optimize the performance of the distributed network
[91]	Connected vehicles & forensic applications	• Lack of some features, very useful for a comprehensive dispute resolution, in the case of accident investigation: data overwriting does not allow a complete reconstruction of the vehicle history due to the limited storage; moreover, the involved parties do not have direct control on the extracted data and third parties are necessary for guaranteeing data integrity. Finally, a system able to integrate all parties (i.e., other vehicles, road conditions, manufacturers, maintenance centres) does not existing	• Block4Forensic (B4F), a blockchain-based vehicular forensic system • Vehicular forensic investigation framework, to solve a dispute (e.g., car accident) in an efficient way

5. Discussion and Future Research Perspectives

Summarising, some of the articles of the first cluster (i.e., four out of 10) are strongly focused on the use of blockchain technology, with the aim of ensuring product traceability in food chains [45,75,77,82]. Although several frameworks have been introduced over the past few decades to protect food quality and safety, many limitations still remain and the blockchain can be a valuable means of overcoming them. Moreover, the attention towards the origin of the product by the final consumer has strongly increased in recent years. Three other contributions concern the concept of traceability, but in more general terms refer to the supply chain [76,79,80]. From the data in Tables 5–7, other important possible objectives, achievable through the adoption of the blockchain technology, can be highlighted: regulatory compliance in pharmaceutical supply chains [78], right supply-demand matching in agricultural supply chains [81], and alignment of information sharing among supply chain actors [83].

The second cluster refers first of all to intelligent transportation systems and interconnected smart vehicles; in this context, the blockchain is considered a valid means to: increase trust among actors and secure the exchange of money and information [52], minimise malicious attacks to cars by increasing security standards [51], improve key management schemes [85], and provide legal support in the event of a road accident [91]. Moreover, two research works aimed to increase the credibility of messages exchanged between vehicles, introducing incentives for drivers who are motivated to share information about traffic or unexpected events, such as car accidents [86,87]. An important branch of research concerns electric vehicles and, in particular, the matching between the demand and supply of energy for recharging: the use of smart contracts and a blockchain can indeed promote safe auction mechanisms [88,89]. Smart cities are another important topic treated: in a world where mobile devices are increasingly widespread, a blockchain can face challenges such as scalability, efficiency, and flexibility [84,90].

Practically, the vast majority of the documents that belong to the macro-clusters C_1 and C_2 and that are listed in Tables 5–10 present ideas and concepts that are applied without developing and implementing a real blockchain. Some of them propose new platforms just at a concept level [45,51,52,75,77,83,84,88,89,91], some of them present proofs of their concepts [76,79,81], and only three of them present a real implementation based on real blockchains: [78,80,82].

It must be noted that developing, implementing, and maintaining a working blockchain is a complex task that requires great computational resources. By definition, a blockchain is a distributed ledger so it requires a network of nodes that act as servers for the system, while classic databases are hosted on a single server. To keep active the different nodes of a blockchain, it is necessary to introduce some form of incentive for the different node owners, and it would be a contradiction of the blockchain premise if a single interested entity should rule all the nodes.

In detail, for the macro-cluster C_1, related mostly to traceability problems in supply and logistics, the only listed paper that introduces a real implementation based on a new blockchain is [80], which introduces the private developed blockchain OriginChain. Papers [78,82] also propose real implementations, but based on existing blockchains: Ethereum [78] and Ethereum and Hyperledger [82]. Other works in macro-cluster C_1 propose a proof of concept based on Ethereum [79], Matlab [81], and an experimental blockchain based on three nodes [76]. The remaining papers of cluster C_1 present platforms that are proposed only at a concept level [45,75,77,83]. In the macro-cluster C_2, there are no real implementations or computationally derived proofs of concept. Papers [85–87,90] conducted analyses of the proposed systems in simulations. This proves how the implementation of blockchain technology for the solution of road traffic problems is still in its early stages. Table 11 summarises the implementation level of the proposed solutions in papers belonging to the two macro-clusters C_1 and C_2. Checkmarks and hyphens mean, respectively, adoption and non-adoption of a certain level of implementation.

Table 11. Level of implementation of papers belonging to C_1 and C_2.

Reference	Platform Proposed at a Concept Level	Real Implementation Based on	Proof of Concept Based on
[45]	✓	-	-
[75]	✓	-	-
[77]	✓	-	-
[78]	-	Ethereum	-
[79]	-	-	Ethereum
[80]	-	OriginChain (private blockchain)	-
[81]	-	-	Matlab
[76]	-	-	A testing environment consisting of three nodes
[82]	-	Ethereum and Hyperledger	-
[83]	✓	-	-
[51]	✓	-	-
[52]	✓	-	-
[84]	✓	-	-
[85]	Simulation of performances	-	-
[86]	Simulation of performances	-	-
[87]	Simulation of performances	-	-
[88]	✓	-	-
[89]	✓	-	-
[90]	Simulation of performances	-	-
[91]	✓	-	-

Figure 6 depicts the main issues emerging from our literature review. First of all, some general issues can be detected: trust, regulatory compliance, decentralisation, information sharing, and supply-demand matching (i.e., use of smart contracts). However, there are also four main transportation-based issues: food track and trace, electric vehicle recharging, smart city enabling, and smart vehicle security. These latter four are explored below, including in the discussion the five detected general issues as well, and highlighting the current state of the art and the possible future research perspectives.

- *Food Track and Trace*: Food traceability has been one of the main research challenges of the past few decades. Several approaches have been proposed by scholars to increase food quality and safety: RFID, QR Code, NFC, ontology, etc. The main purpose is to provide the final consumer with all the information about the processes that a product on the shelf has undergone. In particular, tracking means being able to collect all the information about the various steps of the food supply chain from upstream to downstream, while tracing is the ability to reconstruct the product history backwards [92]. The benefits of food traceability are twofold: (1) increasing the perceived value of goods; (2) guaranteeing regulatory compliance [93]. However, even today there are several shortcomings because many traceability systems are ineffective: frauds are still quite widespread [94], while the recall costs are often very high in the case of food scandals because the granular traceability is onerous, especially in the case of batch mixing [95]. In this context, blockchain technology constitutes an immense opportunity to improve food traceability: the decentralisation of the overall system avoids the existence of third parties, and this makes the information exchange between the actors faster and more efficient; the information recorded remains over time and it is quite easy to trace the actor who inserted it into the system. Furthermore, there is no problem of incompatibility among the information systems of the various entities involved, because a single platform can be used. The main future research perspectives are the following: the need to have real case studies because the simulations present in the literature are not enough to demonstrate the feasibility of the blockchain; some companies are practically applying this technology in the food supply chains, but still few real data are present on the academic side. Moreover, considering that, especially in agriculture, many supply chains are not very technology-based, we should investigate more about the impacts that the introduction of mobile devices could have on the entities involved: the costs to train the actors and to redefine the chain processes should be most investigated in the next few years.

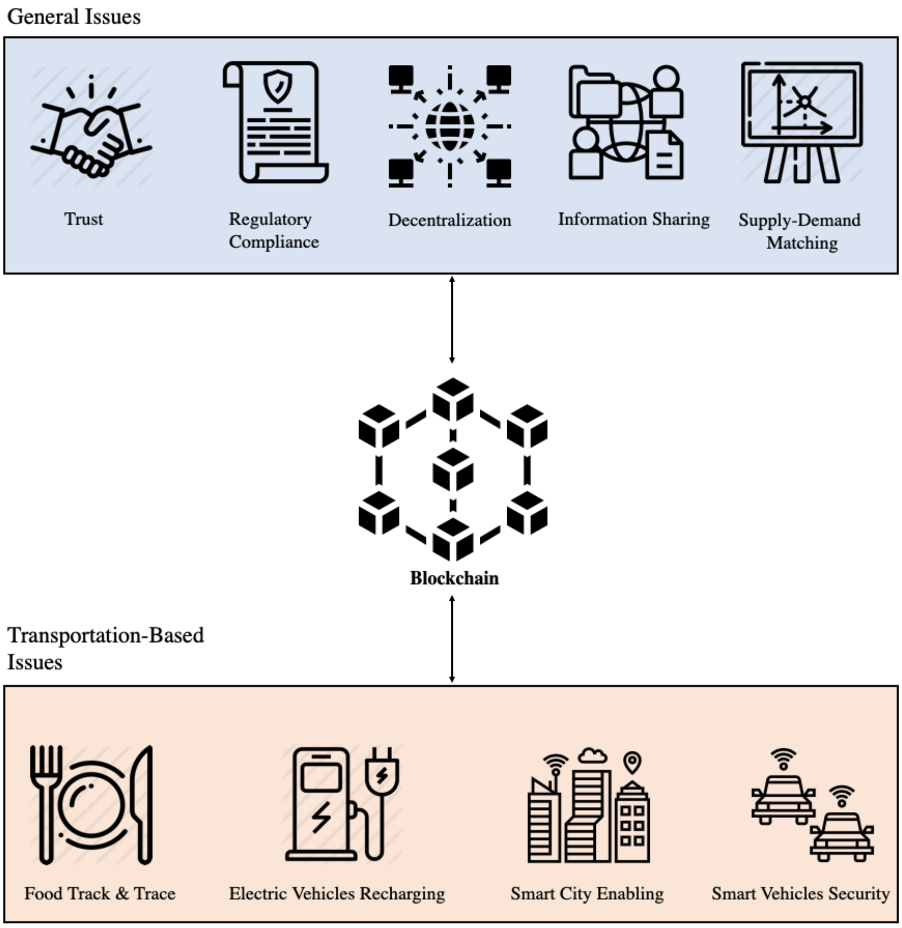

Figure 6. General and transportation-based emerging issues in the application of blockchain technology.

- *Electric Vehicle Recharging*: Electric vehicles are becoming more widespread, as are the stations for recharging them. The application of blockchain technology in this area is something new and little explored. One of the main purposes concerns the right matching between energy demand and supply. On the one hand, there is a group of motorists who, on the basis of their geographical location, show the need for a recharge within a certain time window, and on the other, a set of energy suppliers able to decide prices, based on demand and competitors. This mechanism could favour both parties because drivers could choose, each time, the cheapest offer in their area, and suppliers could dynamically vary their prices, maximising the expected profit. In fact, the use of smart contracts could enable auction mechanisms. However, important efforts are needed to make the blockchain-based architectures sufficiently scalable [88]; in fact, over the years the number of motorists and suppliers who could decide to join the electric vehicle ecosystem could dramatically grow. The functionalities offered by the blockchain (e.g., secure payments through cryptocurrency) could, however, constitute the trigger to give a definitive impulse to the spread of electric cars.
- *Smart City Enabling and Smart Vehicles' Security*: Many cities are defined "smart" when the following features are present: broadband connectivity, a knowledge workforce, and digital inclusion. One of the main goals of smart cities is to improve the services offered to citizens, reducing administrative costs through the use of technology. Considering that the use of IoT, although very useful, leads to security problems in data management, the introduction of blockchain technology could solve this important issue. In the near future, almost all vehicles produced and marketed will be called smart; in fact, they will be able to connect to the internet and communicate with each other. Additionally, in this case, the main problems concern privacy and security [51]; in fact, the use of centralised infrastructures poses the alarming issue of data control by a single entity. Implementing blockchain technology could mean making drivers more secure in sharing

information about: real-time position, traffic conditions, and any unexpected events, such as road accidents. However, even in this case there is a great need for practical experiments: there is a lack of real implementations within smart cities and the propensity of drivers to share very confidential information (e.g., geographical location) should also be strongly evaluated and analysed (e.g., some questionnaires could be submitted to drivers, in order to have a complete picture). It is important to note that traffic congestion is one of the main problems of modern cities and one of the main causes of air pollution; its reduction is a big challenge nowadays. Traditional efforts to solve congestion problems have been centred in attempts to move the demand on the transit system [96] and on a better management of road traffic using tools such as traffic simulation [97–102], dynamic network loading equilibria, and dynamic models [103,104] for the simulation and management of user route choice [105–109]. New technologies such as intelligent transportation systems and co-operative intelligent transportation systems (C-ITS) have also been considered for an increase in road traffic sustainability [110–112], though the true innovation is possibly coming from the future generation of vehicles that will be electric, "connected," and "autonomous." New vehicles are considered by many the key to completely transform traffic networks in terms of reduced energy consumption, improved safety, and reduced pollution. The future introduction of autonomous vehicles and the switch from fuel-based technologies to electric vehicles has the potential, in fact, to completely change the road traffic sector: goods and people will be moved by driver-less autonomous vehicles in smart cities. Human driven taxi services will be substituted by autonomous vehicles and new business models will emerge where mobility as a service could take the place of the current car-ownership paradigm. In this future scenario, vehicles will have also to refuel autonomously and the current paradigm of the credit card-based transaction could become inadequate for the exchange of services and energy between machines. The trust management problem in vehicular networks [113] could be solved by blockchain technologies, and new, secure systems based on blockchain technology could support the development and deployment of an electric and autonomous mobility where all transactions are "broadcasted" and stored on a secure, open, and unalterable data base. The development of smart cities, where the above-listed services and technologies are implemented, can create demand for blockchain technology. As an example, blockchain systems could satisfy the future needs of citizens and authorities to exchange and store personal data safely.

With reference to the previously analysed transportation-based issues, we can see a great closeness between the two terms blockchain and sustainability:

- The greater effectiveness of traceability systems could minimise the number of lots that are recalled from the market in the event of food scandals, limiting food waste.
- The use of smart contracts could stimulate the growth of the electric car market, with consequent benefits for the environment, considering the reduction of exhaust gas emissions.
- The information sharing among motorists, stimulated by rewarding mechanisms through an appropriate cryptocurrency, could reduce traffic in overcrowded urban areas, improving the quality of life.
- The blockchain technology could lead to a continual increase in the number of smart cities, favouring sustainable urban development.

Other potential applications of blockchain technologies may emerge from the convergence of emerging services and technologies, such as Mobility as a Service (MaaS), IoT, artificial intelligence (AI) with deep learning, 5G, and distributed smart objects. This convergence may be able to create a fertile ground for blockchain technologies and may determine the conditions for the development of blockchain applications in the other transportation sectors that have not been yet extensively covered in the literature: transit, rail, maritime, and air transportation. Blockchain technologies might be introduced in these sectors when the level of the development of the transportation systems reaches that of what is clearly envisioned for road transportation and that involves the future adoption of autonomous and connected vehicles. As for now, the literature analysis, which was carried out in this paper, tells us that blockchain innovation in the context of rail, maritime, and air transportation is not seen as an emergent topic.

In general, however, there are some "obstacles" for adopting blockchain in the transportation sector. Some barriers for using blockchains in sustainable supply chains have been detected in [114]. They have been categorised into: intra-organisational barriers (e.g., lack of knowledge and expertise; financial constraints), systems-related barriers (e.g., immaturity of technology; hesitation to adopt blockchain technology, due to negative public perception), inter-organisational barriers (e.g., cultural differences of supply chain partners), and external barriers (e.g., lack of government policies and lack of external stakeholders' involvement). Other significant limitations are: lack of willingness of the actors of the chain to share information [115], limits on the number of transactions per unit of time, compared to other players such as Visa or Mastercard (i.e., performance and scalability issues) [116], and regulatory uncertainty [47]. Moreover, trading on a blockchain system could be expensive, because any mistake is irreversible and increases the transaction costs [117]. These barriers are only some among those debated in the literature; additional information can be found in [118–120]. Basically, this technology is still immature and not ready for large-scale dissemination.

6. Conclusions

In this review, we focused on scientific papers that are directly connected with the transportation sector. Therefore, we did not take into account documents specifically centred on: trust issues, internet of things, trade, and general business.

It must be noted that the majority of scientific papers examined in the transportation sector are centred on potential applications. There are very few real blockchain systems in the literature. The relevance of blockchain technology for the logistics sector is claimed for traceability and for a better integrated supply chain management. Blockchain technologies can improve trust and data sharing among supply chain actors. The introduction of blockchain technologies is often related to the diffusion of the Internet of connected systems and devices (i.e., IoT). The blockchain databases have to be connected with the physical world, and in many works it is foreseen that this connection will be carried on by IoT devices. The "connected" vehicle will become a part of the IoT, and this is the reason for a growing popularity of blockchain technologies in road traffic management and smart cities. Cooperative data sharing, transactions, and any other data (or currency) exchanges that will be possible between "autonomous" and "connected" vehicles, may be facilitated by the use of blockchain technologies that can guarantee specific features that cannot be guaranteed by traditional databases.

Blockchain technologies applied to the transportation sector are in an early phase of development, and while many authors advocate the use of this technology, there are also some concerns about practical applications, since some early blockchain projects have failed in the first years of deployment. The debate will go on until many applications have been deployed and used, and until the specific applicative field of blockchain technologies is properly "framed." The positive and objective view, which emerges from our review, is that there is a growing interest in the scientific world, in blockchain applications in the transportation sector. However, much effort is still needed, mainly on the part of transportation engineering researchers, so that this promising technology can reach its final degree of maturation.

Author Contributions: Conceptualisation, V.A. and V.S.; methodology, G.M. and V.S.; software, G.M. and V.S.; validation, V.A. and V.P.G.; formal analysis, V.A. and V.P.G.; investigation, V.A., V.P.G., G.M. and V.S.; resources, G.M. and V.S.; data curation, V.A., V.P.G.; writing—original draft preparation, V.A. and V.S.; writing—review & editing, V.A., G.M. and V.S.; visualization, V.A., V.P.G., G.M. and V.S.; supervision, V.A. and G.M.; project administration, V.A. and G.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Some icons have been retrieved from the Flaticon website (www.flaticon.com).

Conflicts of Interest: The authors declare no conflict of interest.

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