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State-of-the-art of Blockchain Technology in Intelligent Transportation Systems

Literature Review

Delft University of Technology

TU Delft

State-of-the-art of Blockchain Technology in Intelligent Transportation Systems

Literature Review

by

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Preface

This literature review is written as part of the second year of the Mechanical Engineering master at the Delft University of Technology. This assignment is done within the department of Maritime and Transport Technology, for the track Transport Engineering and Logistics, within the theme of Coordination for Real-Time Logistics. This report can be used as a basis for further research into the integration of blockchain technology for transportation purposes. This review is written in an extraordinary time, where the corona-virus made a huge impact on every day life. I would like to thank my supervisor, Dr. F. Schulte, for his support and guidance along the way, even when physical meetings were not possible. Besides my supervisor, I would like to thank my house mates, who kept me focused when I was forced to work from home.

J. van Dijk
Delft, July 2020

Abstract

In recent years blockchain technology has become a popular topic for research in multiple fields of discipline. For the transport sector especially, the technology is seen as disruptive. Because the research field is young and the research on the topic is developing fast, state-of-the-art knowledge is exclusive to a select group of academics. This review aims to provide an overview of the current state of blockchain technology applications in the transportation domain. Previous reviews on blockchain and transportation have already mapped the contributions for supply chain and logistics. Studies within the transportation domain on connected systems and vehicles have not been comprehensively reviewed, while the relevance on these kind of systems is growing. The focus of this review is on Intelligent Transportation Systems (ITS), which integrates the connected transportation systems and vehicles. The demand for ITS is growing and the relevance of supporting blockchain solutions as well. The increasing amount of connected vehicles introduce security and privacy concerns. Connected vehicles share sensitive information on which other users base their behaviour, so correctness of information is very important. Next to that, the risk arises of losing complete control over the vehicle through attacks due to the remote accessibility possibilities of the vehicle. Blockchain offers a solution for these concerns by enabling a decentralized and secure way of sharing information. These features make secure and trustworthy communication between vehicles, roadside units and platoons possible, as well as secure over-the-air software updates. Privacy concerns can be mitigated via the use of pseudonyms, partitions or fresh data keys. With its decentralized characteristic, blockchain technology creates a transparent and traceable way of storing and sharing data. For ITS applications this means efficient insurance processes and liability attribution. Furthermore, the traceability feature of blockchain can be used in fraud detection for rolling wrecks and odometer fraud. Also, ITS can benefit from blockchain technology by integrating smart contracts. Processes where a third party is involved can be replaced by a smart contract, making it possible to implement vehicle-to-machine payments. This makes transactions fast, cheaper and secure. Processes like tolling payments or vehicle maintenance can then be automated. The security and privacy features of blockchain technology offer a solution for the implementation of Mobility-as-a-Service principles, which enables vehicle sharing. Furthermore, blockchain is an asset for transportation solutions in smart cities. In smart cities, blockchain technology can ensure data integrity and encourage organizations to share data enabling transparent city management. Within smart cities, blockchain can facilitate the data sharing between vehicles and infrastructure, as well as energy trading via vehicle-to-grid principles. Another way in which ITS can benefit from blockchain technology, is through the use of incentive mechanisms. Blockchain is well suited for incentive systems because it can automate direct interaction between actors. With automated payments, people can be incentivized to share reliable traffic data or to participate in efficient energy distribution for the grid. Also, safe driving behaviour and environmental friendly transportation can be rewarded. Before real life systems can benefit from the advantages of blockchain technology a lot of challenges have to be overcome. For ITS, all applications exist only in theoretical form. Challenges that have to be faced are the high energy consumption, latency and throughput constraints, and governance issues. Although the benefits of blockchain technology are multifold, the challenges have proven to be to hard to overcome up until now.

List of Abbreviations

AVs	Autonomous Vehicles
IoT	Internet of Things
IoV	Internet of Vehicles
ITS	Intelligent Transportation Systems
M2M	Machine-to-Machine
MaaS	Mobility as a Service
OTA	Over-The-Air
RSUs	Roadside Units
V2G	Vehicle-to-Grid
V2I	Vehicle-to-Infrastructure
V2M	Vehicle-to-Machine
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad-hoc Network

Contents

Preface iii

Abstract v

List of Abbreviations vii

1 Introduction 1

2 Methodology 5

3 General Blockchain Features for Intelligent Transportation Systems 7
- 3.1 Security . . . 7
  - 3.1.1 Communication . . . 8
  - 3.1.2 Software . . . 8
  - 3.1.3 Privacy . . . 8
- 3.2 Traceability . . . 9
  - 3.2.1 Insurance . . . 9
  - 3.2.2 Fraud Detection . . . 10
- 3.3 Smart Contracts . . . 10
- 3.4 Overview of Blockchain Utilization in ITS . . . 11

4 Blockchain Applications for Intelligent Transportation Systems 13
- 4.1 Mobility as a Service . . . 13
- 4.2 Connected Vehicles . . . 13
  - 4.2.1 Autonomous Vehicles . . . 14
  - 4.2.2 Internet-of-Vehicles . . . 14
- 4.3 Smart Cities . . . 15
  - 4.3.1 Vehicle-to-Infrastructure . . . 15
  - 4.3.2 Vehicle-to-Grid . . . 16
- 4.4 Incentivization . . . 16
- 4.5 Overview of Blockchain Applications in ITS . . . 17

5 Challenges for Blockchain Application 19

6 Conclusions 21

References 23

1
Introduction

In recent years blockchain technology has become a popular topic for research in multiple fields of discipline. While the implementation of the distributed ledger technology was first adopted by the financial sector, it has now found its way into various other sectors. Where the new technology meant overcoming the problem of double spending for the financial sector, it means something different for the transportation sector. To most academics and practitioners in the transportation sector, the actual state of development of blockchain technology is unknown. This literature review will map the state-of-the-art applications of blockchain technology in the transportation sector and try to shed light on the state of this research field.

The first implementation of blockchain started in 2008, when an individual under the name of Satoshi Nakamoto published a paper introducing Bitcoin, a cryptocurrency based on blockchain principles [38]. A blockchain is a cryptographically secured list of chronological blocks, each block contains information and hashed pointers to the previous block, this structure makes the blockchain irreversible [52]. In a blockchain, transactions are final when they are verified simultaneously by multiple peers in a peer-to-peer network [43]. This means peers inside the network all keep a shared ledger which is consensus-based, making the blockchain system immutable and transparent. Another characteristic of blockchain technology is that no single entity controls the data, removing a single point of failure and making the information decentralized and tamper proof. An important feature of the blockchain is the possibility to implement smart contracts. A smart contract is a computer program within the blockchain containing terms and conditions. Once the terms and conditions are met, a computer can automatically execute the rights and obligations within the contract. Because the contract is visible to all relevant parties, the amount of miscommunications is reduced. Smart contracts can automate the bureaucratically necessary processes in a fast, secure and transparent way [29]. The blockchain platform that is well known and supports smart contracts is called Ethereum, it is seen as the next major step after Bitcoin [55].

After blockchain had made its introduction in the financial sector, other sectors began to take notice of the novel technology. From 2016 onward the amount of publications regarding blockchain technology has increased significantly in different sectors. For the transport sector especially, the technology is seen as disruptive [12]. The characteristics of blockchain technology suit the needs of the transport sector well, in particular the attribute of being able to overcome trust issues. Trust is essential in supply networks and it is a important feature for smart supply chains [19]. However, the possibilities do not stop there. In fact, the spectrum of potential possibilities is very broad. The transport industry recognizes the potential of blockchain technology and several initiatives have originated to bring together the different stakeholders within the sector [4, 18]. Some initiatives have already proven to be effective, as the first blockchain container transport has successfully been shipped from China to Slovenia [11]. The possibilities also range to autonomous ride sharing and autonomous drone deliveries [16]. As a consequence of the broad spectrum many studies have been performed discovering all the various applications.

Many of these studies have been on the topic of supply chain and logistics. Previous reviews in this field have already mapped most of these contributions [44, 46, 65, 66]. However, the studies within the transportation domain on connected systems and vehicles have not been comprehensively reviewed, while the relevance on these kind of systems is growing [78]. The research field is mentioned by Astarita et al. [1], but this study only indicates the current state and direction of research. The study stays very much on the surface of the different applications and implications for the transportation domain. In table 1.1, the literature reviews regarding transportation are listed to get an overview of work that has already been done.

The field of connected systems and vehicles is encompassed by the term Intelligent Transportation Systems (ITS). ITS are defined by the European Parliament [41] as: 'Systems in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users, and in traffic management and mobility management, as well as for interfaces with other modes of transport.' In recent years Autonomous Vehicles (AVs) have become a big part of ITS. According to Bagloee et al. [2], the interest for AVs will keep on growing in the coming years and Saranti et al. [52] states that the potential of blockchain technology for autonomous vehicles is significant. Moreover, due to a growing need for intelligent infrastructure and smart cities, the relevance of autonomous vehicles and the supporting blockchain solutions is increasing even more [70].

Because of the large number and broad spectrum of publications on blockchain technology and transportation in the recent years, it is hard to keep track of the current state of development. Figure 1.1, shows the increase of published documents per year on the subject of blockchain and transport, AVs, ITS, and Internet-of-Vehicles (IoV). The increasing amount of research can result in duplication of work and exhaustive literature studies. Furthermore, because the research field is young, misconceptions exist about blockchain and state-of-the-art knowledge is exclusive to a select group of academics. Therefore, this paper aims to capture and lay out the present state of blockchain implementation in the transportation domain. By doing so, the author attempts to contribute to future research and help academics with obtaining insight in the fast developing sectors of blockchain and transportation.

Table 1.1: Analysis of Articles published on Blockchain and Transportation Reviews

Reference	Focus				Remarks
	Supply Chain	Logistics	Smart Cities	ITS	
Astarita et al. [1]	√			√	Discusses current state of research
Pournader et al. [44]	√	√			Categorizes research in technology, traceability, trade and trust clusters
Queiroz et al. [46]	√				Looks into background of publications and gaps in literature
Shen and Pena-Mora [55]			√	√	Main focus on smart cities, also mentions the transportation domain and blockchain use cases in ITS
Tijan et al. [65]	√	√			Identifies impact of blockchain on business transparency
Wang et al. [66]	√				Shows relevance of publications to supply chain management
This paper			√	√	Main focus on the implications of blockchain technology for ITS, also discusses smart cities

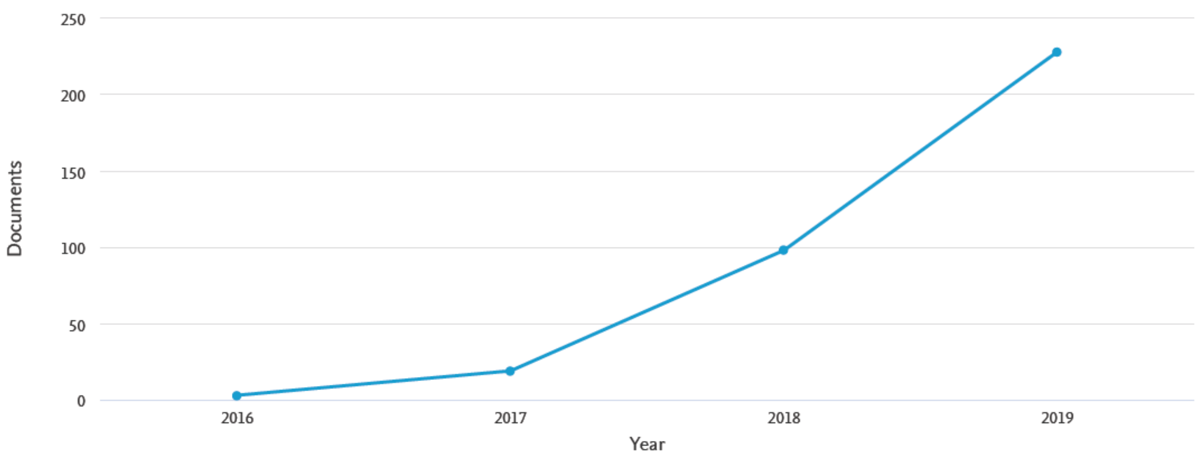

Figure 1.1: Amount of published documents on 'Blockchain and Transportation' per year [53].

Hence the main question this literature review aims to answer is:

- What is the current state of blockchain technology applications in the transportation domain?

The main question is answered by answering the following sub-question:

- How can blockchain applications in transportation be categorized?
- How can ITS benefit from blockchain technology?
- What are the implications for ITS?

The scope of the literature review is focused on applications of blockchain technology in transportation, with the exception of supply chain and logistics applications. The blockchain developments in the rail, maritime and air transport sectors are not included as well, because the technology is not emergent in these sectors [1]. Thus, focus will be on intelligent transportation systems and connected vehicles. In the context of this study, transport refers to the system of conveying people or goods from place to place by means of vehicles. This study may benefit academics and practitioners looking into the state-of-the-art applications of blockchain technology for connected systems in the transportation domain.

The report is structured as follows. Firstly, in chapter 2, the methodology and discussion of the database search are given. Secondly, in chapter 3, the general features of blockchain are discussed and their usability for transportation systems. Subsequently, in chapter 4, the implications for ITS are discussed. Hereafter, the challenges regarding blockchain technology are given in chapter 5. Lastly, the report finishes with the conclusions of the literature review in chapter 6, respectively.

2
Methodology

In order to find relevant sources for the literature review, Scopus, Google Scholar and Web of Science have been searched. These scientific research databases have been searched over a period of four weeks. Multiple databases are used to reach a complete representation of the research field. For the search, the following terms and combinations have been used: 'Blockchain AND (Transport* OR "Autonomous Vehicles" OR "Intelligent Transportation Systems")'. The results were made up of matches in the title, abstract and keywords. Via Scopus, Scholar and Web of Science a total of 347 results were found. Because the search terms were combined in one search query, there are no duplications within the results. Subsequently, from the results, relevant documents were selected. For a paper to be selected it had to meet the following criteria: no focus on supply chain or logistics, published after 2017 and written in English. These criteria were set because supply chain and logistic applications have already been reviewed extensively and publications before 2018 do not contribute to the state-of-the-art review. Furthermore, papers within the research field from before 2018 which made an impact were selected, a threshold of ten citations was used for this criterion. This criterion yielded twelve extra papers. To ensure that no topic was overlooked, the bibliographies from the most cited papers were scanned and relevant papers were included for this review. Due to this method, 38 extra papers were included in this research. Most of which would have been included by adding the search term 'Internet of Vehicles' (IoV). The added papers were then also screened via the criteria. A flowchart of the included studies can be seen in figure 2.1. .

When analyzing the results of the scientific databases search, some interesting insights can be obtained. The first documents linking blockchain technology with transport, date from 2016. That shows how young the research field is. Furthermore, the significant increase in publications is noticeable, that shows the increasing interest in blockchain technology and applications for transportation purposes. Also, up until now already 40 documents have been published on these topics in 2020 [53]. The analysis of the database search show that most of the publications are from China and very little originate from Latin America and Africa.

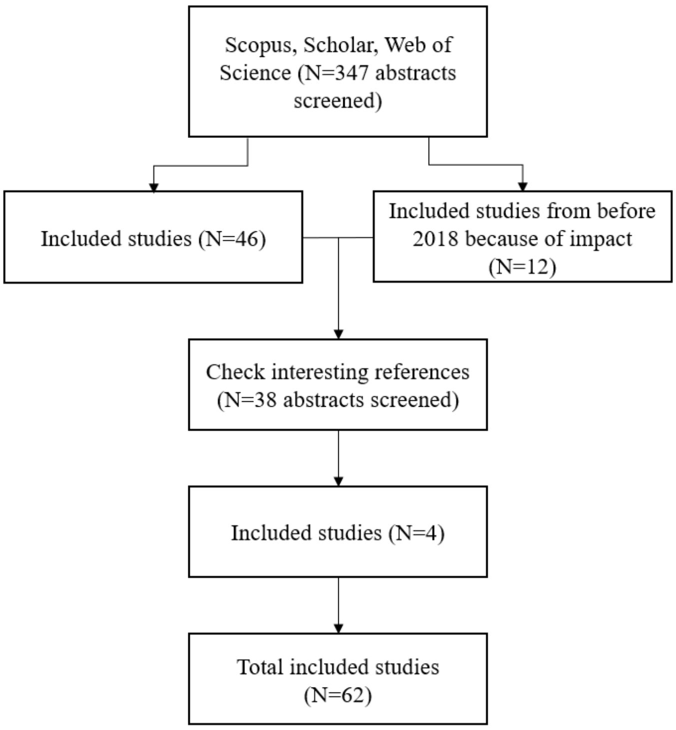

Figure 2.1: Flowchart of included studies.

3
General Blockchain Features for Intelligent Transportation Systems

This chapter will give the main blockchain features which are currently used for intelligent transportation applications. The aim is to give a indication of how transportation can utilize the specific benefits blockchain offers. Blockchain is getting increasingly relevant for transportation purposes as more and more vehicles will be connected with the internet and communicate with each other. The road transportation development has taken is depicted in figure 3.1, as can be seen the journey has arrived at a digital age. This development introduces security and privacy concerns [1]. In the following section the security and traceability benefits of blockchain technology are mentioned. Subsequently the highly useful ability of implementing smart contracts is discussed.

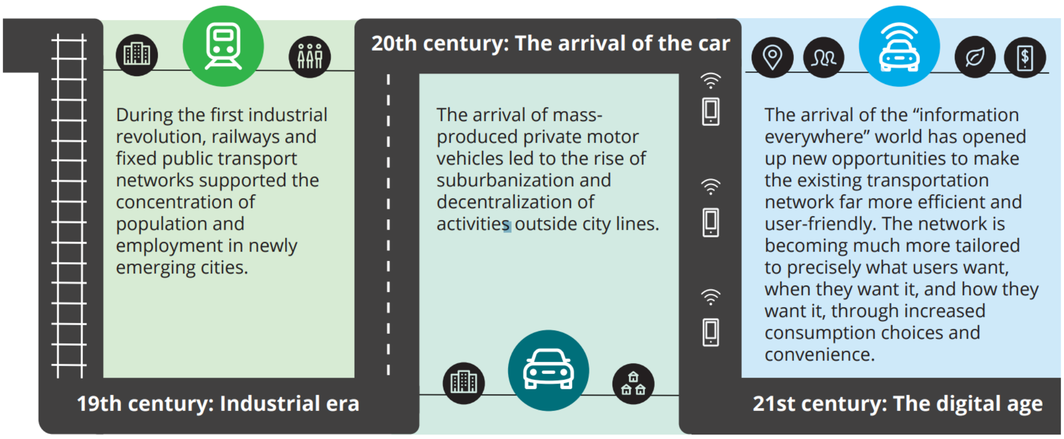

Figure 3.1: Road of development for transportation [20].

3.1. Security

Blockchain technology is well known because it offers a very secure way of sharing information. Part of the security comes from the fact that the technology is distributed, meaning no third party controls the data. Furthermore, it means that multiple nodes will validate a transaction. The transactions themselves are secured as well, via a encrypted digital signature. Because of this signature, information cannot be forged by adversaries. Furthermore, for information to be read, the correct digital key is required. The security blockchain offers, is widely implemented by the transportation sector. These days, connected vehicles can make use of an increasing amount of online services. This connectivity and services introduce threats that were earlier irrelevant to the transportation domain, think of tracking or remote hijacking [17]. Furthermore, the distributed nature of ITS presents a number of security challenges that have to me mitigated. Challenges are introduced by the amount of attack surfaces, the amount of sensor data and the difficulty level of post-security audits [62]. In the following sections the current applications and relevance of the security features for transportation are given.

3.1.1. Communication

Communication between multiple nodes in a transport system is essential for efficient functioning of the system. According to the U.S. Department of Transportation, Vehicle-to-Vehicle (V2V) communication can address up to 82% of crashes in the U.S. involving unimpaired drivers [32]. In future transportation systems, not only communication between different vehicles but also communication between vehicles and Roadside Units (RSUs) and communication between multiple modes of transport will contribute to the system. For a broad acceptation of these communication systems, a high level of security is a prerequisite [9]. The information that can be transmitted between different actors can be sensitive, such as identification, position and speed. Multiple studies refer to blockchain technology as a way to introduce the required security levels in connected vehicle communication. Buzachis et al. [9] investigates the feasibility of applying blockchain technology to road intersections in order to ensure the correctness of communication between vehicles. Furthermore, Singh and Kim [58] proposes an blockchain based secure environment for peer-to-peer communication between intelligent vehicles without disturbing other intelligent vehicles. Lei et al. [34] suggests using a blockchain based key management system to secure vehicle communication. Blockchain technology is effective because it provides a secure and real-time communication method. In decentralized blockchain transport systems, vehicles can jointly and securely collaborate without having to go through a central computing node authority.

Blockchain technology for communication can also be utilized for V2V communication within platoons. In a platoon of vehicles, messages are send between the platoon members. The behaviour of members inside the platoon is adjusted based on the information in the messages, thus forming an entry point for attacks [10]. Because blockchain is distributed over all platoon members and relies on logically consistent series of data in the chain, it is difficult to change the original data for one of the blocks [15]. Therefore, blockchain offers a secure and adequate platform for communication between platoon members, as Ying et al. [75] concludes as well. Blockchain in communication can also be used for data transmission to request the acquisition of lane property rights [50]. In section 4.2, platooning will be further elaborated on.

3.1.2. Software

With the growing interest in intelligent software in vehicles and the financial benefits associated with over-the-air (OTA) updates [33], vehicles have become more susceptible to attacks. Intel [26] identifies fifteen areas in a connected vehicle most likely to be attacked, as seen in figure 3.2. OTA software updates are beneficial for both the car manufacturers as well as the vehicle owner, as service centers do not have to perform software updates anymore [61]. For these systems, a secure platform is extremely important because when vehicles are accessible remotely, adversaries can take control of the complete vehicle [48]. Furthermore, updates require full access to the embedded control systems, making them an even bigger target and more susceptible [17]. Steger et al. [61], uses a proof-of-concept implementation of a wireless software update system and shows the applicability of an blockchain architecture as well as its benefits compared to a certificate-based system. Dorri et al. [17], sees an application of blockchain technology for remote software updates as updates demand a distributed security method while maintaining the vehicle owner's privacy.

3.1.3. Privacy

The identity and behaviour of individuals can be easily determined from vehicle data streams. With the rise of applications like Waze and Google Traffic, more and more information is being gathered, some of which can be sensitive to certain individuals [24]. Information that is being recorded by- or can be determined from vehicle data include: identity, phone numbers, text messages, call logs, driving habits and addresses [56]. This information is important to be protected [40]. Even when information is being send anonymously, the identity of individuals can be determined by linking pieces of data. According to Dorri et al. [17], this risk can be mitigated by using a fresh data key for each interaction. An offline encrypted blockchain-based storage of sensitive data for a cluster of cars is proposed by [24]. Furthermore, Shi et al. [56] and Oham et al. [40] also propose using blockchain technology to hide the real identity of users. Shi et al. [56] does so by introducing a trusted authority which, as the only one, knows the association between each entity's personal information and their pseudonym. Oham et al. [40] introduces partitions of information which are only accessible to intended entities and makes use of fresh signing keys at every transaction.

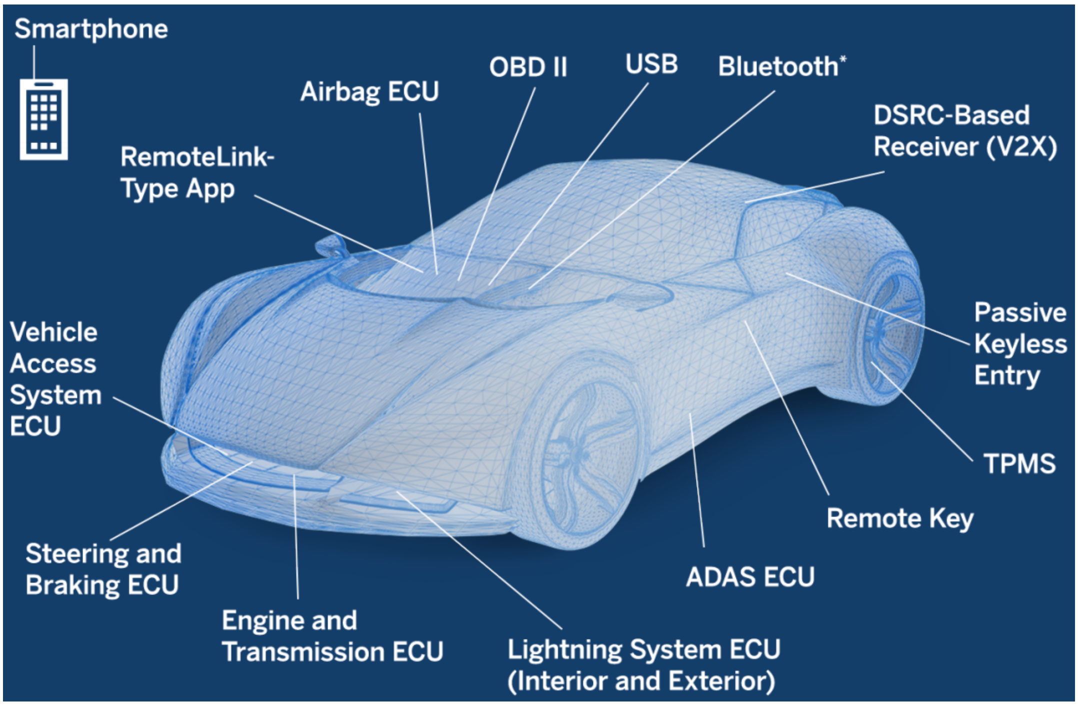

Figure 3.2: Attack surfaces of a connected vehicle [26].

3.2. Traceability

Next to securing transactions and information, blockchain provides the possibility to trace back information. These features are already used in supply chain applications. Because blockchain functions as a shared ledger it helps track the origin and transformation that a product undergoes in the supply chain. A formal registry is created, enabling the identification and the tracking of possession of a good throughout the supply chain [43]. By tagging and scanning products and sharing this information via blockchain with other stakeholders, the provenance of a product can be easily determined, as well as the conditions it went through. In this way, foodborn outbreaks can be traced back to its source and other affected products can be removed from stores. Furthermore, because the provenance of products is stored on the blockchain, counterfeit products can easily be identified. For pharmacy supply chains this can resolve the problem of selling fake drugs. The tagging and scanning of products is being done more and more because of the implementation of Internet of Things (IoT). Through the use of IoT systems, an electronic bill of lading can be generated, removing the need for paper and removing the ability to tamper with the bill of lading [63]. Moreover, blockchain can play a role in storing data from the IoT sensors in a immutable and accessible way [65]. These applications of blockchain technology in supply chain have been extensively reviewed in the past years but the application of the traceability property is also known outside of supply chain applications. In the following sections these applications are discussed.

3.2.1. Insurance

In the transportation domain, the traceability attribute of blockchain technology can be used for insurance purposes and liability attribution. The issue of assigning blame to the responsible parties in case of an accident is becoming more complicated with the introduction of smart and autonomous vehicles. Liability cannot always be assigned to the driver, it is shared by the manufacturer as some driving decisions are made by the vehicle. There could be multiple entities that might have incentives to alter accident related information to avoid punitive penalties [21]. Blockchain technology offers a secure and private platform in which the untampered forensic evidence collected by the vehicles and RSUs can be send to legal authorities and the governmental transport authorities to processes and to make liability decisions [13, 17, 21, 40, 48]. This can settle disputes in an efficient way and with the use of smart contracts the compensations for damages and injuries on behalf of the client can be automatically payed [40]. Furthermore, when required, the vehicle data can be securely shared with the insurer to file an accident claim. By making use of the blockchain structure, the insurance company can ensure the privacy sensitive data has not been modified since the event [17].

Next to assigning liability and settling insurance claims efficiently, the traceability feature offers more benefits to clients of insurance companies. Because insurance companies can monitor driving patterns, the companies can adjust insurance fees based on the driving behaviour. Making insurance fees lower for clients who have a safe driving behaviour [12, 17, 40]. Furthermore, with all vehicle data being recorded and safely shared with the insurance company, the blockchain ensures no false and invalid insurance claims [7, 48].

3.2.2. Fraud Detection

The traceability and transparency features can overcome trust issues between the stakeholders in the automotive industry. For the used-car market, for example, blockchain technology can mean overcoming various types of frauds, such as odometer fraud and putting up wrecked or salvaged vehicles for sale [7, 39]. Almost every third car is affected by odometer fraud, resulting in billions of extra costs for consumers [7, 23]. By securing the odometer data in the blockchain and sharing it with relevant parties, tampering is made impossible. Worse than odometer fraud are the frauds with rolling wrecks. Vehicles that have experienced severe damage and are put back on the roads are cause for severe accidents. By using blockchain technology, the amount of rolling wrecks can be reduced, saving consumers and companies a lot of money. When an insurance company declares a vehicle as wrecked, the owner will transfer the property of the vehicle to the insurance company. The insurance company will then take care of destroying the vehicle [7].

3.3. Smart Contracts

Another way of using blockchain for transportation is through smart contracts. Smart contracts can automate processes in a transparent, secure and efficient way. Processes which earlier required lots of paperwork or intermediaries, can now be automatized, reducing the process duration and making it tamper proof. A smart contract contains a lot of information, for example: state transition functions, conversion rules, trigger conditions and interaction methods. Blockchain measures the state of an asset in real time and executes the smart contract automatically when the trigger conditions are met [80]. For physical assets delivery, the traceability property and smart contracts can be used to confirm the receiving of an item by a transporter or buyer [22]. When the contract detects that the asset has been truly received it can automatically initiate the next phase of transport and it can settle the payment. An overview of a smart contract working principle can be seen in figure 3.3. Other processes that can benefit from smart contracts are processes that involve placing orders and processes that involve giving or denying rights to participants. Almost any process where a third party is involved can be replaced by a smart contract. Without the need for third parties it is possible to implement machine-to-machine (M2M) and vehicle-to-machine (V2M) payments, through smart contracts and cryptocurrency wallets.

For V2M systems, smart contracts can automatically be triggered based on change in location, service, or parts failure [47, 48]. In ITS these methods can be used for connected vehicles when toll payments are re-

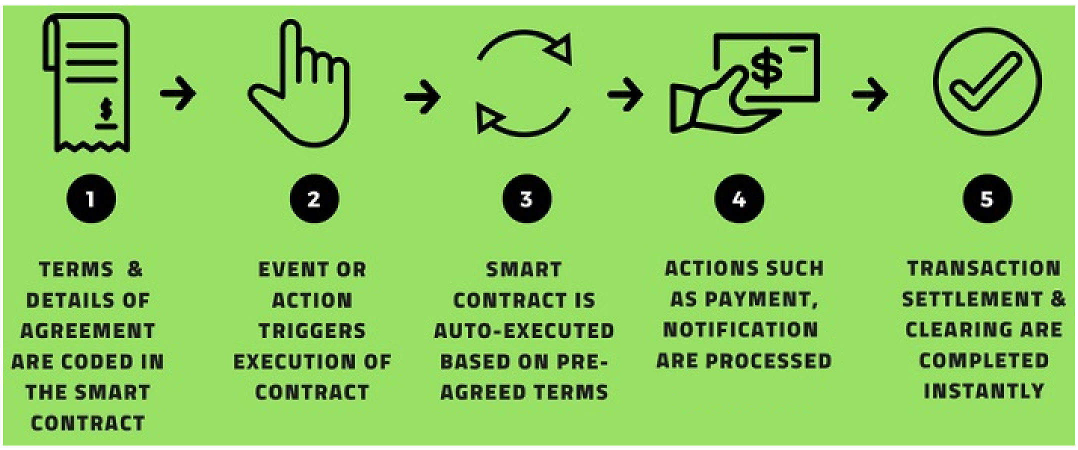

Figure 3.3: Smart Contracts explained (adapted from [5]).

quired. By making use of blockchain technology, the transactions can be made more efficient, secure and cheaper, as no third party is involved [47]. Furthermore, by implementing cryptocurrency wallets, credit card data does not have to be stored in the vehicle anymore. Besides tolling payments, the blockchain can be used for automated vehicle registration renewals and vehicle maintenance service bookings. With the vehicle continuously monitoring its state, it can automatically invoke a smart contract to book an appointment for vehicle service. Payments can then be automatically deducted, with cryptocurrency wallets [48]. In this way vehicles can interact without friction with other installations or RSUs. The potential of smart contracts in the transportation sector has been recognized, seen from the amount of research within the sector that refers to smart contracts [15, 22, 45, 47, 48, 55, 60, 76, 80]. In chapter 4 the specific consequences for AVs and ITS will be further discussed.

3.4. Overview of Blockchain Utilization in ITS

Table 3.1 shows the main blockchain features that are leveraged in each article. Important to note is that most of the articles utilize all features blockchain technology offers, albeit sometimes to small extends. Articles that mention the use of blockchain technology in general and articles with a focus on logistics are not represented. Furthermore, articles presenting a survey or review are not included. As can be seen, most publications utilize blockchain technology for its excellent safety features. Oftentimes the security feature is utilized to mitigate privacy concerns.

Table 3.1: Overview of Main Utilization of Blockchain Features

Reference	Focus	Leveraged Blockchain Feature		
		Security	Traceability	Smart Contracts
Bai et al. [3]	Driver behavior data sharing while maintaining privacy	√		
Brousmiche et al. [7]	Monitor vehicular life-cycle	√	√	
Buzachis et al. [8]	Secure intersection management	√		
Buzachis et al. [9]	Secure data exchange at intersections and check correctness of communication	√		
Calvo and Mathar [10]	Secure inter-vehicular communication	√		
Cebe et al. [13]	Forensics application for connected vehicles		√	
Chaudhary et al. [14]	Secure energy trading in V2G networks	√		
Chen et al. [15]	Payment mechanism for urban platoon formation			√
Dorri et al. [17]	Secure data exchange and privacy for automotive services	√	√	
Guo et al. [21]	Event recording system for AVs		√	
Hasan and Salah [22]	Proof of delivery of physical assets	√		√
Hîrtan and Dobre [24]	Privacy preservation in ITS	√		
Hîrţan et al. [25]	Reputation for road events in ITS	√	√	
Jaffe et al. [27]	Cycling incentive system			√
Jindal et al. [28]	Secure energy trading in V2G networks	√		
Kang et al. [30]	Secure electricity trading in V2G networks	√		
Kaur et al. [31]	Authentication mechanism for VANETs	√		
Lei et al. [34]	Secure key management for V2V and V2I communication	√		
Lei et al. [35]	Certificate revocation for V2V and V2I communication	√		
Leiding et al. [36]	Smart contract managed VANETs			√
Li et al. [37]	Secure privacy conserving incentive mechanism	√		
Newman [39]	Fraud prevention through blockchain		√	
Oham et al. [40]	Liability attribution for AVs		√	
Pedrosa and Pau [42]	Facilitate M2M transactions at vehicle charging stations	√		√
Pustišek et al. [45]	Charging station selection via smart contracts			√
Ramaguru et al. [48]	Security for IoV and smart contracts for automated payments	√		√
Rathee et al. [49]	Secure connected vehicles against attacks	√		
Ren et al. [50]	Perform lane acquisition right requests via smart contracts			√
Ren et al. [51]	Traffic condition sharing in ITS	√		
Sharma et al. [54]	Secure architecture for ITS	√		
Shi et al. [56]	Private multimedia sharing in VANET	√		
Shivers et al. [57]	Secure ride-hailing	√		
Singh and Kim [58]	Provide security and reliability of communication	√		
Singh and Kim [59]	Reliability in peer to peer networks	√		
Singh et al. [60]	Parking management via smart contracts			√
Steger et al. [61]	Secure automotive software updates	√		
Su et al. [62]	Attack mitigation in ITS	√		
Tan and Chung [64]	Authentication and key management in VANETs	√		
Wang et al. [67]	Secure energy delivery in V2G networks	√		
Xie et al. [71]	Security framework for vehicular IoT services	√		
Yang et al. [73]	Consensus mechanism for traffic event validation		√	
Yao et al. [74]	Prevent database attacks for VANETs	√		
Ying et al. [75]	Secure communication in platoons, utilize smart contracts for payments within platoon	√		√
Yuan and Wang [76]	Secured and trusted architecture for ITS	√		
Zhang et al. [77]	Secure architecture for VANETs	√		
Zhang et al. [79]	Secure data sharing for IoV	√		
Zhang and Wang [80]	Adaptive traffic signal control	√		√

Abbreviations: V2G (Vehicle-to-Grid), AVs (Autonomous Vehicles), ITS (Intelligent Transportation Systems), VANETs (Vehicular Ad-hoc Networks), V2V (Vehicle-to-Vehicle), V2I (Vehicle-to-Infrastructure), M2M (Machine-to-Machine), IoV (Internet of Vehicles), IoT (Internet of Things)

4

Blockchain Applications for Intelligent Transportation Systems

According to Yuan and Wang [76], blockchain has the full potential of establishing a decentralized ITS. The way in which blockchain can reach this potential is discussed in this chapter. The implementation of blockchain in ITS exists primarily out of the main blockchain features mentioned in chapter 3. In other words, security, traceability and smart contracts will play a big role in future ITS. First, in chapter 4.1, a closer look is taken into initiatives that already implement ITS ideas and how they can benefit from blockchain technology. Subsequently, ITS and blockchain applications in connected vehicles and smart cities will be discussed.

4.1. Mobility as a Service

The ideas surrounding Mobility as a Service (MaaS) have been around for quite some time. MaaS is becoming more and more of a reality with the implementation of ITS. The aim of the MaaS ideas are to make individual end-to-end transport more efficient by sharing and connecting multiple modes of transport. By doing so, the potential of the transport network can be utilized optimally. Consumers need to be able to access the shared and connected multimodal transport options via a digital platform which have to include features such as digital payment, ticketing, planning and management [12]. This is where blockchain can play an important role. For Maas a decentralized and transparent system is required to provide consumers with on-demand access to bicycles and road vehicles. Blockchain can offer such a platform.

Smart contracts can be implemented in MaaS-systems such that travel delay compensation in public transport can be automatically processed and executed, even when the delay is due to multiple transport operators. Furthermore, blockchain can play a role in the sharing economy where MaaS advocates for. With blockchain technology, vehicles can be used in a usership-based model instead of a ownership-based model, enabling a Connected Vehicles as a Service system [47, 49]. Currently, third parties control commissions on ride hailing services, while with blockchain the intermediary is cut out and drivers can set their own fares and transact with customers directly [12]. In this way decentralized blockchain ride-hailing allows owners of connected vehicles to add their vehicle to a community driven fleet when not in use or to share their empty seats with others traveling the same route [57]. Blockchain integration in ITS also enables a solution for riders to switch between several vehicles on their way to destinations, creating a better coverage of the MaaS-system [76]. The decentralized architecture of blockchain is ideal for this purpose because of its fault tolerance. Furthermore, blockchain can play a role in car sharing by offering an immutable and trusted communication channel to securely exchange mileage, location, keys to unlock the car and payment details of the user [17].

4.2. Connected Vehicles

Vehicles are a big part of ITS. With the implementation of information and communication technologies in vehicles, vehicles can be made intelligent, making them a valuable asset for efficient transport systems. Connected vehicles can transform the current traffic networks in ways of reduced energy consumption, improved safety and reduced pollution [1]. Furthermore, besides that blockchain offers the possibility of sharing a connected vehicle with other users, it enables automated processes for transport services through the secure communication and smart contract abilities. In the following sections, the contribution of autonomous vehicles to ITS are discussed and the role of blockchain technology is discussed. Furthermore, the concept of

IoV for ITS is introduced with the possible blockchain implementations.

4.2.1. Autonomous Vehicles

Autonomous and connected vehicles can add value to an ITS by sharing all sorts of data, driving behaviour and road conditions information, for example. Bai et al. [3] proposes the use of blockchain technology to provide tamper proof and secure road condition information to other vehicles, where third party certification is not required. By sharing driving behaviour and road conditions, road users can be warned for dangerous driving behaviors [3]. Furthermore, with the secure communication and smart contract features that blockchain offer, platooning in a free-flow traffic state is made possible. With platooning, the capacity of the road is enlarged and fuel efficiency increased. Moreover, by implementing platooning possibilities in ITS, the amount of accidents is reduced. Blockchain can play a role in platooning by offering a secure communication network and by avoiding malicious and false automated payments to the platoon head [15].

For autonomous vehicles, ITS real-time traffic information can be combined with a planned route and car battery status to find the best charging station. Charging stations can then bid for the best price and a transaction can be automatically executed by blockchain based smart contracts. Due to blockchain, an autonomous charging station selection is enabled [45]. When electric charging stations become unmanned, the contracts and transactions will be mainly M2M. For M2M transactions in autonomous vehicle charging scenarios, blockchain offers the required flexible, tamper proof and scalable technology [42].

4.2.2. Internet-of-Vehicles

Due to the increase in vehicle connectivity, the system of Vehicular Ad-hoc Networks (VANETs) has emerged. A VANET is a subset of Mobile Ad-hoc Networks and consists of stationary and moving vehicles and RSUs, connected via a wireless network [49, 74]. Within a VANET, each vehicle or RSU is a node and can share data with other nodes in the network [80]. Because of the good connectivity and communication abilities of a VANET, they are considered to have a significant role in ITS [31, 49, 74, 80]. However, in a traditional VANET the nodes are random, temporary and unstable with a local range, hindering global and sustainable services to customers. Furthermore, VANET lack the processing capacity for handling global information, so there is a need for an open and integrated network system, like IoV [72].

When combining the networking capabilities of VANETs with vehicle intelligence, the IoV can be realised. Vehicle intelligence integrates technologies like network computing, advanced sensing, data acquisition, deep learning and intelligent planning [3, 72]. Furthermore, IoV is accelerated by integrating distributed cloud servers, which can manage the interaction between multiple VANETs [64]. With the integration of computation and communication, IoV obtains large scale data to improve the capabilities of a VANET systems. Thus, IoV goes beyond VANETs by intelligent integration of vehicles, humans, environments, sensors, and mobile devices into a global network. In this way various services can be delivered to people on board and around vehicles, even in the range of a whole country. By doing so, IoV aims to reduce social cost, promote the efficiency of transportation, improve the service level of cities, and increase user satisfaction [72]. These are features which are very much aligned with the goals of ITS, and which benefit ITS implementation.

The connectivity, high mobility and cloud computing that are associated with IoV, introduce a lot of challenges concerning security and privacy of communication [54]. Furthermore, threats can arise from attacks by malicious entities sending false information, which might be used by another vehicle for decision-making [48, 80]. Next to that, the risk arises of losing complete control over the vehicle through attacks due to the remote accessibility possibilities of the vehicle. Multiple studies propose the use of blockchain technology in overcoming these challenges introduced by the VANETs and IoV. Zhang et al. [77] presents a method based on signatures and threshold secret sharing, and designs a mechanism to prevent the acceptance of a fake message and mitigate the throughput limitations of blockchain technology. Zhang and Wang [80] proposes the use of blockchain technology to break the central control of traffic signals for VANETs. In the paper of Ramaguru et al. [48], a blockchain platform with artificial intelligence capabilities is proposed to offer solutions for the IoV ecosystem. Furthermore, Sharma et al. [54] proposes a blockchain architecture based on vehicle networks, to support the privacy and security features of VANETs. Leiding et al. [36] proposes implementing a smart contract system with VANETs to create self-managed VANETs. To prevent malicious information from interfering with traffic, Xie et al. [71] introduces a blockchain trust management system for a 5G software-defined-network based VANET. Bai et al. [3] proposes a group signature strategy to optimize encryption and ensure privacy security while maintaining traceability, for a blockchain-based traffic conditions and driving behaviors warning scheme in the IoV. Blockchain technology is selected to overcome all these issues because of its distributed, immutable, transparent, consensus based features. Furthermore, because data is decentralized, it reduces communication overhead between domain managers, making blockchain technology especially suitable for the delay-sensitive vehicular applications [74].

4.3. Smart Cities

Because of the growing population and urbanisation, as depicted in figure 4.1, transportation systems have been under pressure. The risk of congestions is growing and cities are struggling to get people to use public transport [6]. Furthermore with the urbanisation it is hard to maintain a good quality of life and a steady economical growth [69]. The concept of smart cities can solve the urban transportation problems with the implementation of ITS. A smart city is defined by Washburn et al. [68] as: The use of Smart Computing technologies to make the critical infrastructure components and services of a city -which include city administration, education, healthcare, public safety, real estate, transportation, and utilities- more intelligent, interconnected, and efficient. According to Xie et al. [70], blockchain has a huge potential to promote the development of smart cities. Blockchain technology can ensure data integrity, encourage organizations to share data and perform joint decision making, enable transparent city management, and promote the implementation and deployment of a trusted, and secure smart city [70]. In the following sections the implementation of ITS for smart cities is discussed and the integration of blockchain technology in these solutions.

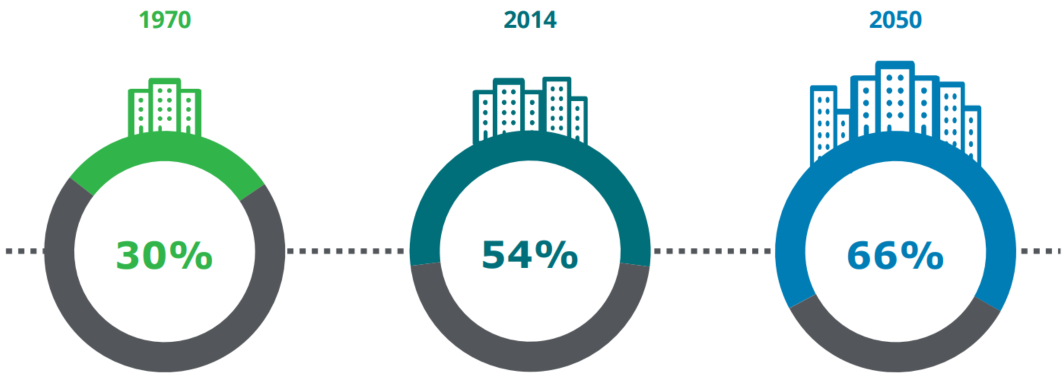

Figure 4.1: Percent of population living in urban areas [20].

4.3.1. Vehicle-to-Infrastructure

Transportation is an essential city sector for smart cities [55]. By making the transportation within a smart city intelligent, the city becomes more intelligent. Transportation can be made more intelligent by adding infrastructure to vehicle communication networks, resulting in Vehicle-to-Infrastructure (V2I) communication. Traffic information can be shared within the network, such as car accidents warnings, road construction notices and driver route changes to reduce traffic congestions earlier [73]. Furthermore, whole intersections can be added to the network. A critical aspect of managing vehicles is their behaviour near intersections [9]. In such a network, the intersection can coordinate particular behaviors of vehicles by gathering information on traffic and road conditions. V2I communication allows the intersection to determine the ideal velocities and accelerations of vehicles and inter-vehicle distances based on traffic conditions, which could significantly reduce overall emissions and fuel consumption [8]. Also, by making use of smart contracts, intelligent traffic signal control can be realised. A green light duration can be allocated according to a vehicle's length. In this way, congestions can be prevented on certain road sections [80].

Again for the secure and distributed communications protocols, blockchain can be used. To prevent collisions, a high exposure of data is required, such as speed, position and identification [8]. Next to providing a consensus based and tamper proof method, blockchain offers a method to ensure correctness of event notifications. Each vehicle can effectively verify- and give feedback on a notification when received, providing traceable events and trust verification [73]. Trust verification can also be handled via smart contracts. Vehicles can receive credit value when sending reliable information. When information is forged, the smart contract can deduct credit value. In this way malicious responses can be effectively prevented [80]. Furthermore, blockchain technology can be adjusted to handle a high amount of data while doing it in real time for V2I communication [59].

With blockchain technology, intermediaries are no longer required and a single point of failure is removed. This offers a solution for parking management. Current systems are centralized, which makes drivers depend on the service providers for accessing parking services. By integrating the parking infrastructure with vehicle communications, a driver can independently find a parking lot suited to their requirements [60]. Making the service more efficient and cheaper.

4.3.2. Vehicle-to-Grid

Smart grids offer an intelligent solution for energy distribution to smart cities. With the current power grid, electricity is transported through a mesh of cables, resulting in high losses and low efficiency [30]. By combining smart grids with the potential of electric vehicles to transport energy, energy can be transported over large geographical areas with reduced losses. Such a system can efficiently allocate the electricity to various areas with different electricity loads through the movement of electric vehicles [67]. Furthermore, when the vehicle is not in use it can serve as a temporary energy storage or source for the smart grid, balancing electricity demand and supply [30, 45]. In smart cities the cooperation between vehicles and grid can be combined with V2M transactions, including auctions and payments, leading to reduced prices for electric vehicle charging [45]. Furthermore, suppliers can benefit as well, because their prices could be varied dynamically, maximising the expected profit [1].

Current electricity trading relies on a centralised third party, making it vulnerable to privacy leakage and posing a single point of failure [30]. Furthermore, the system is vulnerable to attacks by adversaries [67]. Multiple studies suggest using blockchain technology to overcome the difficulties surrounding energy trading among electric vehicles. Wang et al. [67] develops a consensus protocol in a permissioned blockchain while enhancing the security of energy nodes and an incentive mechanism is developed to schedule charging processes. Chaudhary et al. [14] presents a secure blockchain-based energy trading scheme, while making use of an software defined network architecture. Kang et al. [30] proposes using a permissioned blockchain based on local aggregators to verify energy transaction between vehicles. Jindal et al. [28], designs a blockchain based consensus mechanism for secure energy trading in a edge-as-a-service and a Vehicle-to-Grid (V2G) environment. Moreover, Jindal et al. [28] concludes that computation costs are small, so real world application is feasible.

4.4. Incentivization

ITS can benefit from the blockchain feature of a secure and fast incentive system. Blockchain is well suited for incentive systems because it can automate direct interaction between peers. The decentralized features of blockchain offer an accessible, transparent and scalable system. The robust and secure features are beneficial as well, as personal data and financial transactions are being recorded. Furthermore, blockchain transactions are faster and cheaper than current financial transactions [27].

For electric vehicles such an incentive mechanism can be used to stimulate vehicles to participate in energy delivery to achieve a regional energy balance [30, 67]. The incentive mechanism can also be used for promoting sustainable and environmental friendly transportation methods. Shen and Pena-Mora [55], proposes to use crypto tokens for such a system. Jaffe et al. [27] proposes a system where cyclists can receive financial compensation by sharing their activity and location with organisations that would like to sponsor cycling activities. In this way sustainable transportation can be encouraged. With such a system, it is also possible to reward good driving practices [48].

With an incentive mechanism, vehicles can be motivated to participate in event validation, for insurance purposes for example. The blockchain based system could raise a vehicle's credit score to lower an insurance premium [21]. Incentive mechanisms can be used as well to employ penalties to enforce actors to act honestly in validation scenarios [22]. Li et al. [37] advocates the use of a blockchain based system called CreditCoin to incentivize users to share traffic information, while preserving privacy and security. By using a distributed blockchain network, region wide vehicle announcement messages can be broadcast without the need of a trusted entity. To encourage vehicle participation for broadcasting the messages, vehicles can be rewarded by some cryptocurrency [79]. Singh and Kim [58] proposes a points system to ensure reliable intelligent vehicle communication. A blockchain enabled incentive mechanism can be beneficial as well for the forming of platoons, by offering members of a platoon an incentive to become a platoon leader [15, 75].

4.5. Overview of Blockchain Applications in ITS

Table 4.1 shows an overview of the suggested field of blockchain application by each article. The field which suits the article best has been indicated by the check mark. Articles that present a review or survey are not included in the table. As can be seen the VANET solutions are classified as smart city applications, this is because of the inclusion of RSUs in VANETs. Therefore, VANETs are a key part of V2I systems. The table shows that only a few studies link blockchain for ITS to the sharing economy of MaaS. In this area a lot of progress is still possible.

Table 4.1: Overview of suggested Blockchain Application in ITS

Reference	Focus	Blockchain Application Field			
		MaaS	Connected Vehicles	Smart Cities	Incentives
Bai et al. [3]	Secure data exchange for road conditions		√		
Brousmiche et al. [7]	Allow sharing of vehicle life-cycle data		√		
Buzachis et al. [8]	Autonomous intersection management based on V2I communication		√	√	
Buzachis et al. [9]	Intersection management for AVs in ITS		√	√	
Calvo and Mathar [10]	Enable secure communication for connected vehicles		√		
Cebe et al. [13]	Forensics application for connected vehicles		√		
Chaudhary et al. [14]	Energy trading platform in ITS			√	
Chen et al. [15]	Enable platooning for autonomous vehicles		√		√
Dorri et al. [17]	Exchange keys for automotive services	√			
Guo et al. [21]	Event recording for autonomous vehicles		√		√
Hasan and Salah [22]	Incentive mechanism to enforce honest acting				√
Hîrtan and Dobre [24]	Privacy preservation in ITS		√	√	
Hîrţan et al. [25]	Reputation for road events in ITS		√	√	
Jaffe et al. [27]	Incentivize urban cycling				√
Jindal et al. [28]	Secure energy trading in V2G environment			√	
Kang et al. [30]	Enable electricity trading among electric vehicles			√	√
Kaur et al. [31]	Authentication in VANETs		√	√	
Lei et al. [34]	Secure key management for V2V and V2I communication		√	√	
Lei et al. [35]	Certificate revocation for V2V and V2I communication		√	√	
Leiding et al. [36]	Self managed VANETs through smart contracts		√	√	
Li et al. [37]	Incentivize to share traffic information				√
Oham et al. [40]	Liability attribution for AVs		√	√	
Pedrosa and Pau [42]	Enable M2M transaction for electric charging		√	√	
Pustišek et al. [45]	Autonomous charging station selection in V2G environment		√	√	
Ramaguru et al. [48]	Secure environment for IoV		√	√	√
Rathee et al. [49]	Security mechanism for connected autonomous vehicles services	√	√		
Ren et al. [50]	Perform lane acquisition right requests via smart contracts		√	√	
Ren et al. [51]	Traffic condition sharing in ITS		√	√	
Sharma et al. [54]	VANET architecture in smart city		√	√	
Shi et al. [56]	Private multimedia sharing in VANET		√	√	
Shivers et al. [57]	Ride-hailing platform for autonomous vehicles	√	√		
Singh and Kim [58]	Reward based intelligent vehicle communication		√		√
Singh and Kim [59]	Solve communication challenges in V2V and V2I communication		√	√	
Singh et al. [60]	Smart contract based parking management			√	
Steger et al. [61]	Secure automotive software updates		√		
Su et al. [62]	Attack mitigation in ITS		√	√	
Tan and Chung [64]	Key management in VANETS		√	√	
Wang et al. [67]	Incentive scheme for energy delivery in vehicular network			√	√
Xie et al. [71]	Trust management in VANETs		√	√	
Yang et al. [72]	Network model for IoV		√	√	
Yang et al. [73]	Traffic event validation in VANETs		√	√	
Yao et al. [74]	Authentication for VANET services		√	√	
Ying et al. [75]	Secure communication for platoons		√	√	√
Yuan and Wang [76]	Presents case study for ride-sharing	√			
Zhang et al. [77]	Secure VANET architecture		√	√	
Zhang et al. [79]	Encourage data sharing in IoV		√		√
Zhang and Wang [80]	Adaptive traffic signal control for ITS			√	

Abbreviations: MaaS (Mobility as a Service), V2I (Vehicle-to-Infrastructure), AVs (Autonomous Vehicles), ITS (Intelligent Transportation Systems), V2G (Vehicle-to-Grid), VANETs (Vehicular Ad-hoc Networks), M2M (Machine-to-Machine), AVs (Autonomous Vehicles), IoV (Internet of Vehicles), V2V (Vehicle-to-Vehicle)

5

Challenges for Blockchain Application

Before blockchain technology can be implemented in ITS, a number of challenges have to be overcome. A lot of research has been done on the topic of ideas, concepts and potential applications of blockchain technology in ITS, but there are very few documents that implement a real blockchain. According to Astarita et al. [1], this is because the technology is still immature and not ready for large-scale dissemination.

One of the challenges that requires more research is overcoming the large energy consumption. Maintaining a blockchain requires great computational resources [1, 39, 50, 51]. The safest consensus mechanisms used in blockchain systems, rely on computational redundancy, which is not energy efficient. While the security of other consensus mechanisms have not been rigorously analyzed yet [70]. Next to increased cost due to energy consumption there is also the increased cost of making a erroneous transaction, which cannot be reversed [44].

Furthermore, blockchain systems can suffer from latency and throughput issues, especially when faced with more and more connected devices. Currently, the amount of transactions per minute is much lower than that of Visa and Mastercard [1, 47], this can become a problem when all vehicles are using smart contracts and automated payments. Moreover, Pournader et al. [44], Ren et al. [50, 51], Singh et al. [60] all share concerns considering latency and throughput issues in real blockchain applications. Xie et al. [70] also recognizes that schemes need to be designed to increase transaction throughput for smart city applications while maintaining security. Latency can also become an issue for event validation, when the number of vehicles is to large, a congestion in the wireless network can arise. According to Yang et al. [73], a solution could be to reduce the information exchange frequency. However this solution is not an option for communication between intersections and vehicles. Therefore Buzachis et al. [9] concludes that with today's computational capabilities it is not possible to ensure a real-time application of intersection management. High latency is not acceptable when collisions need to be avoided. In an intersection deadlock situation, Singh and Kim [59] proposes to decrease the mining time of a block and to split the blockchain into multiple chains to overcome latency issues.

Other challenges surrounding blockchain implementation originate from the complicated governance aspects. For data sharing among different entities standards and formats need to be agreed, while considering data quality and integrity [23, 70]. Also, it would be a contradiction of the blockchain premise if a single interested entity should rule all the nodes and manage a blockchain [1]. That also makes that blockchain initiatives must come from multiple stakeholders. Often within transport networks there are trust issues and there is a lack of willingness to share information [1], hindering cooperation between stakeholders. Furthermore, there is the question of who is going to pay the set-up and development costs [39]. Before universal adoption these hurdles need to be overcome.

6
Conclusions

The aim of this literature study was to map the current state of blockchain technology in the transportation domain. The focus was on ITS, because it is a fast developing research field and the topic has not been reviewed extensively. In order to map the state of blockchain technology for transportation, first a look has been taken into the most widely adopted use cases of blockchain. These use cases have been categorized in security, traceablility and smart contract applicabilities. Furthermore, the implications for ITS have been discussed. ITS can benefit from blockchain technology since the technology offers a secure, decentralized and transparent platform for infrastructure, connected vehicles and smart cities. Blockchain offers a solution for communication, software and privacy concerns. These features benefit the sharing economy of MaaS and the implementation of connected vehicles. It is noticeable that very few studies investigate the possibilities of using blockchain technology for car sharing purposes. Furthermore, blockchain can make liability attribution transparent, which can be crucial for AV implementation. The applicability of smart contracts brings a whole load of other benefits to ITS. Such as removal of third parties, V2M payments and electricity trading. Moreover, blockchain technology offers a way to incentivize users to utilize transport in a more sustainable manner. Because blockchain enables efficient communication and transactions, V2I and V2G interaction is possible, serving the smart city realisation.

However, before blockchain technology will be widely adopted a number of challenges have to be overcome. Very few system are really using blockchain technology, research on the topic has predominantly been on the potential applications. Furthermore, the network requirements are a topic of concern. A blockchain system requires a lot of energy and with widespread adoption of the technology, the network capacity has to increase in order to provide low latency. High latency is not acceptable at decentralized intersections. Another challenge that has to be faced is the efficient governance of a blockchain systems. A lot of parties have to be involved and all need to be ready to share information. Also, the question of who will take the lead in a blockchain network development project, raises more concerns.

The conclusions can be summarized as follows:

- Blockchain has a huge potential for ITS through:
  - Secure communication
  - Privacy preservation
  - Traceability of events
  - Smart contract application
- Blockchain enables a sharing economy
  - Still a lot of uncharted potential in utilizing blockchain for sharing purposes in transportation
- Blockchain massively benefits the implementation of connected vehicles
- Blockchain can play a key role for transportation in a smart city environment
- Blockchain implementation faces a number of challenges:

- Large energy consumption
- Latency and throughput concerns
- Complicated governance

Altogether this literature review shows that the potential for blockchain in intelligent transportation is huge, albeit from the theoretical perspective. In practice, the research field is to young and the hurdles have proven to high to have resulted in successful real life applications. The benefits of blockchain technology do make it worth the effort to overcome the challenges, because successful implementation would provide an excellent basis for efficient and sustainable transport systems.

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