Benefits And Risks of Blockchain Adoption In The Transport Sector

by

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Declaration

I, Livia Fraccalvieri, hereby declare that this Ph.D thesis titled "Benefits And Risks Of Block-chain Adoption In The Transport Sector" is a presentation of my original research work for the degree of Doctor of Philosophy in Economics under the guidance and supervision of Prof. Elena Maggi and Prof. Jianyi Lin. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions.

I affirm that this work has not been submitted previously in the same or similar form to another examination committee at another department, university or country.

Signed: Livia Fraccalvieri

Date: 14-11-2024

A spider conducts operations that resemble those of a weaver, and a bee puts to shame many an architect in the construction of her cells. But what distinguishes the worst architect from the best of bees is this, that the architect raises his structure in imagination before he erects it in reality.

KARL MARX (1818 – 1883)

Imagination is more important than knowledge. For knowledge is limited to all we now know and understand, while imagination embraces the entire world, and all there ever will be to know and understand.

ALBERT EINSTEIN (1879 – 1955)

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Abstract

The thesis explores the potential of implementing blockchain technology across various transportation sectors, including supply chain, logistics, motorways, shipping, smart cities, and public urban transport systems. These sectors are increasingly considering blockchain to leverage its features such as distributed networks, advanced cryptography, data immutability, and decentralized consensus. Special attention is given to examining blockchain's potential in electronic toll collection systems for highways. Additionally, the study aims to assess the impact of expanding the highway network and introducing blockchain-based payment systems on European economic growth. Overall, the research contributes to bridging the gap between theoretical knowledge of blockchain technology and its practical implementation in transportation.

The contributions of this thesis are presented across three distinct chapters. Chapter 2 reviews the literature on the diffusion of blockchain technology in the transportation sector and potential barriers to its widespread adoption. Chapter 3 proposes and implements a theoretical model of Bitcoin blockchain technology for integrated payments among companies managing different sections of the same highway lane. Chapter 4 develops a macroeconomic model that studies the effects of highways and Bitcoin blockchain infrastructure on economic growth through a panel model.

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Chapter 1

General Introduction

Numerous cities worldwide are experimenting with blockchain initiatives as part of broader efforts to shape the urban future. Domains like supply chains, logistics, motorways, shipping, smart cities, and public urban transport systems are increasingly exploring blockchain solutions to harness the benefits of distributed networks, advanced cryptography, data immutability, decentralized consensus, and other features offered by blockchain technology.

In Chapter 2, we present a state-of-the-art systematic review of the literature, emphasizing the potential benefits and challenges of blockchain implementation in the transportation sector. Key findings from the literature suggest that blockchain can bring disruptive innovation to sectors like agri-food, pharmacy supply chains, logistics, smart cities, and traffic management. Common features of blockchain systems include peer-to-peer communication, transparent transaction processing, decentralized transaction history, and immutability of records. We identify several barriers to adoption, including scalability, integration complexity with existing systems, lack of standardization, and data privacy regulation. While technological barriers may diminish over time, challenges related to integration and privacy regulation remain significant concerns that need to be addressed for widespread adoption.

Companies globally are increasingly adopting blockchain technology to enhance the traceability of goods and services, thereby strengthening transparency and trust in business arrangements between organizations. In the highways sector, a few companies, such as Indra and Iota, have developed blockchain applications, albeit limited to specific routes.

Chapter 3 introduces a decentralized public blockchain payment model designed to involve various organizations operating on highway lanes. The Liquid blockchain emerges as a promising solution, addressing the need for swift transactions with low fees and ensuring a trustworthy exchange of monetary transfers among companies, retailers with stores on highways, and customers. This proposal is implemented in a blockchain toll payment system for Italian highway companies, aiming to enhance security, train users, and reduce operational costs in toll collection. Utilizing Bitcoin, Liquid Bitcoin, or stablecoins for payments offers advantages such as simplicity, user anonymity, no intermediary disruptions, and lower transaction fees compared to credit or debit card transactions.

In Chapter 4, we delve into the ramifications of highway extension and the adoption of the Bitcoin blockchain for digital payments on the economic growth of the 27 EU member countries. Blockchain stands out as a transformative innovation in digital payments, prompting a comparison of its effects on economic growth with those of traditional digital payment methods. Employing a robust random effects panel model, our investigation yields limited support for assertions of a substantial increase in productivity stemming from heightened infrastructure extension. Specifically, our analysis indicates that boosting the rate of highway extension investment would likely have minimal or negligible impact on annual real GDP growth from 2001 to 2021.

The Bitcoin blockchain, offering secure digital payments and serving as a hedge against inflation and currency depreciation, exhibits a favorable influence on growth, as demonstrated by its trade volumes. In contrast, other digital payment systems play a marginal and insignificant role. However, bitcoin fees associated with daily digital transactions, being lower than those of other digital methods, can foster economic growth. From 2003, the year in which Bitcoin reached parity with the dollar, to 2011, both Bitcoin volumes and fees appear to have a positive effect on the real GDP growth rate. Debit card transactions start to show significance in growth, indicating their potential to stimulate real GDP growth through consumption, while the role played by their fees appears to be insignificant.

Chapter 2

A Systematic Review of Blockchain Technology in Transportation Industry

Abstract:
Numerous cities worldwide are launching blockchain initiatives as part of the overall efforts toward shaping the urban future. Various domains including supply chain, logistics, motorways, shipping, smart cities, and public urban transport systems are increasingly considering blockchain to leverage distributed networks, advanced cryptography, data immutability, decentralized consensus, and other features offered by blockchain technology. This study provides a systematic literature review, highlighting the potential gains and obstacles of blockchain implementation in the transportation sector.

2.1 Introduction

Since 2017, Bitcoin and blockchain technologies have garnered widespread interest, primarily in the information technology (IT) and financial sectors. According to the 2019 Gardner IoT Implementation Trend survey (Litan and Lheureux, 2019), “a majority (75%) of U.S. respondents implementing Internet of Things (IoT) technologies have already implemented blockchain or will do so by the end of 2020” (Kandaswamy et al., 2019). Originally developed as a financial technology, blockchain has expanded its adoption to public administration, transport, supply chain, and logistics.

Moreover, blockchain can complement or work with other digital technologies, including artificial intelligence (AI), the Internet of Things (IoT), data analysis and big data, cloud computing, robotics, and additive manufacturing. The industry gained momentum after Nakamoto introduced Bitcoin in 2009. However, the enterprise environment only took off in 2015 with permissioned blockchains, generally referred to as enterprise blockchains. In

September 2015, nine financial companies, including Goldman Sachs, Barclays, and J.P. Morgan, collaborated to build a new blockchain-based infrastructure for financial services (Underwood, 2016). Consequently, blockchain technology is less than 10 years old as of this writing, and enterprise blockchains are less than 5 years old.

Despite its youth, interest in this emerging technology is growing across various sectors of economic activity. A recent paper from the University of Sheffield and Transport Systems Catapult (TSC) Carter and Koh (2018) highlights the disruptive potential of blockchain in the transport industry. TSC is urging the government and industry to explore the technology's potential uses in transport to ensure the UK stays ahead of the latest developments. The report acknowledges that while the technology is still some years away from full maturity, synergies exist in areas like Freight and Logistics, Autonomous Vehicles, and Mobility as a Service, where the technology could be applied in the future. These areas involve multiple businesses with potentially competing interests that require trust and transparency to share data and collaborate. The decentralized nature of blockchain, coupled with its transparency and security, appears to be the natural solution to these needs.

The main diffusion of blockchain technology nowadays is in the finance industry (Cuccuru, 2017; Yli-Huumo et al., 2016). However, blockchain can be applied in various fields and is attractive for several areas within the transport sector. The technology is utilized to verify transactions, create immutable records and share information in a trustworthy manner. All transactions occur in a decentralized manner through a network of participants or distributed nodes. Their validation relies on a consensus mechanism that operates within the network rather than through a third party, such as a bank or credit card company.

The goal of this article is to analyze the possibilities of using blockchain technology in the transportation sector. The study is conducted by considering academic and conference papers extracted from the Scopus Online database on the topic of blockchain in railways and roadways management, smart cities, and vehicles. The remainder of the paper is structured as follows: Section 2 provides an overview of blockchains and smart contracts. A brief analysis of existing architectures with their limitations is given in Section 3. Section

4 discusses the research methodology of the systematic review used in this study. Section 5 showcases the diffusion of blockchain applications in the transportation industry and how those applications can be grouped into particular sectors. Section 6 presents the results of the systematic review in terms of applications in different transport sectors and the costs and benefits of their adoption. Finally, Section 7 concludes this research.

2.2 Blockchain Technology

Blockchain, commonly known as distributed ledger technology (DL), functions as a shared data platform facilitating authenticated communication, digital data exchange, and the real-time diffusion of shared information among participants. It operates without the control of a central authority, eliminating the need for a trusted intermediary in the market. The technology enables credible peer-to-peer transactions, fostering trust among parties by ensuring that once digital records are stored, they cannot be manipulated.

It is essential to grasp the distinction between a distributed blockchain ledger and a traditional database. Unlike a traditional database, a distributed ledger is stored and updated independently by each node in the network. Every online node possesses a current copy of the working blockchain, providing redundancy and resilience. For instance, in the Ethereum network, a transaction is written to more than 1,600 other nodes. This decentralized nature ensures data integrity and trust among participants.

Trust is established through consensus protocols, ensuring that every new block added to the blockchain represents the agreed-upon truth among all nodes. Despite the common goal of trust and the removal of third parties, not all blockchains are equal. For instance, Ethereum and Bitcoin handle transactions differently concerning ordering and validation.

Bitcoin, the pioneering blockchain solution, emerged as an experiment aiming to introduce digital currency without centralized authority and associated high costs. It successfully removed banks from payment processes, offering benefits such as decentralization, faster transfers, and reduced risks. Bitcoin's success lies in its creation of a decentralized, peer-to-peer electronic cash system based on cryptography.

The blockchain, or distributed ledger, is the platform supporting cryptocurrencies like Bitcoin. It globally shares and secures data, ensuring immutability and transparency. Blockchain operates as a decentralized, trustless, and reliable database, allowing anyone to join the network and view all information. Additionally, blockchain systems, such as Ethereum, often incorporate “smart contracts” — code executed automatically when predefined terms and conditions are met.

A smart contract, coined by Nick Szabo in 1994, is computer code stored on a blockchain that automatically executes transactions based on predetermined conditions. Trust in smart contracts arises from their automated execution and the enforcement of agreed-upon terms and conditions.

Blockchain employs algorithms to process data with cryptography, maintaining data integrity. Each blockchain node solves complex numerical problems, producing cryptographic hashes. The sequential chaining of blocks, each containing a copy of previous and new transactions, ensures the entire transaction history’s permanence.

Blockchain’s cryptographic protection denies unauthorized access to data, enhancing security. Notable advantages for the transport industry include data integrity, behavioral integrity, security, decentralized storage, and consensus-driven consent.

1. Data Integrity: Blockchain ensures complete, correct, and contradiction-free data, crucial in handling the significant flow of information in the supply chain.
2. Behavioral Integrity: The system operates as intended, free from logical errors.
3. Security: Access to data and functionality is restricted to authorized users, enhancing overall system security.
4. Decentralized Storage: Information is transparently stored and shared with third parties with the originator’s consent, preventing data loss.
5. Consent: A consensus protocol controls network access, storage, and distribution of

information, reducing the risk of fraudulent activities through unanimous agreement among participating parties.

2.2.1 Types of blockchain for transport system

There are three distinct types of blockchains: public, private, and hybrid. Additionally, there are two fundamental operations on a blockchain: reading and writing transaction data.

Public blockchains grant read access and the right to create new transactions to all users or nodes. In these systems, anyone can join the network and access its contents. On the other hand, private blockchains limit read access and transaction creation rights to a preselected group of users or nodes. Both private and public blockchains can be further categorized as permissioned or unpermissioned.

Unpermissioned blockchains allow write access to everyone. Users can join the network without third-party approval, verify transactions, and contribute by creating and adding new blocks to the blockchain data structure. Notable examples of public unpermissioned blockchains include Bitcoin, Ethereum, and Litecoin. Ethereum and Bitcoin blockchains find widespread use in supply chain management, logistics, and smart cities. This blockchain architecture comprises a chain of blocks on which peer-to-peer transactions occur. Every user with a computer and internet connection can register as a node and access the entire blockchain network. The significant advantage is the establishment of a high level of trust between parties without the need for third-party control, supervision, or intermediation (Ahram et al., 2017). However, this type of blockchain requires substantial electrical power and presents a trade-off between transparency and privacy defense.

Permissioned blockchains, such as Hyperledger Fabric and Ripple, impose strict rules on network data access. Participants are identified through credentials that grant them varying levels of authority for specific actions. In a permissioned blockchain, participants decide who can transact and which nodes can validate, participating in the consensus mechanism. Only the nodes with write access are permitted to verify transactions and partake in the distributed consensus procedure.

Private blockchains are characterized by efficient verification and validation of transactions, ensuring higher transaction speed, better scalability, and improved consensus. The smaller number of nodes contributes to the increased speed, as organizations control the addition of nodes based on demand, addressing scalability issues. Private blockchains typically have fewer nodes and employ a different consensus algorithm. However, the drawback of permissioned private blockchains is their inability to provide a decentralized system for secure transactions and an immutable database. It's worth noting that not all permissioned blockchains are private; for instance, an organization may deploy a permissionless private blockchain based on Ethereum.

Lastly, there are consortium or federated blockchains, representing a blend of public and private blockchains. These semi-decentralized blockchains are not granted to a single entity but to a group of approved members. Only specific members with required permissions are allowed to join the network. Consortium blockchains share some information and transactions publicly but are generally faster, not requiring proof of work for consensus. In the transportation industry, private or hybrid blockchains are more prevalent than public ones. Consortium blockchains are often adopted in supply chain management and logistics, although their accuracy and reliability are still subject to clarification.

2.3 Research methodology

This study employs a systematic literature review, following the methodology outlined by Kitchenham et al. (2009) and adhering to specific guidelines for systematic reviews in supply chain management proposed by Durach et al. (2017). A systematic literature review serves as a comprehensive exploration of the research area related to the adoption of blockchain technology in the transportation sector, shedding light on the existing research evidence supporting its adoption.

The systematic literature review process initiates with the formulation of key research questions:

1. How is blockchain being utilized in the transportation industry?
2. In what ways can blockchain technology reduce costs and enhance business performance in the transport and logistics industry?
3. How might blockchain technology facilitate the development of integrated platforms to improve the efficiency of the entire transport system?
4. Can blockchain be instrumental in creating an integrated urban public mobility system?
5. What are the primary obstacles or barriers hindering the widespread adoption of this new technology?

These questions provide a structured framework for the review, guiding the analysis of existing literature to glean insights into the current state, applications, benefits, and challenges associated with the integration of blockchain technology within the transportation sector.

2.4 Review methodology

The literature review on the application of blockchain systems in the transportation industry adheres to the framework outlined in Figure 2.1. Similar methodologies are frequently employed in the literature, as demonstrated in studies such as Astarita et al. (2019); Kamble et al. (2018); Mishra et al. (2018). This structured approach provides a systematic and comparable basis for examining the diverse aspects of blockchain applications in transportation, contributing to a cohesive and insightful analysis.

2.4.1 Performing research

The second phase of this mapping study involves a comprehensive search for all relevant scientific papers about the research topic, which focuses on the applications of blockchain

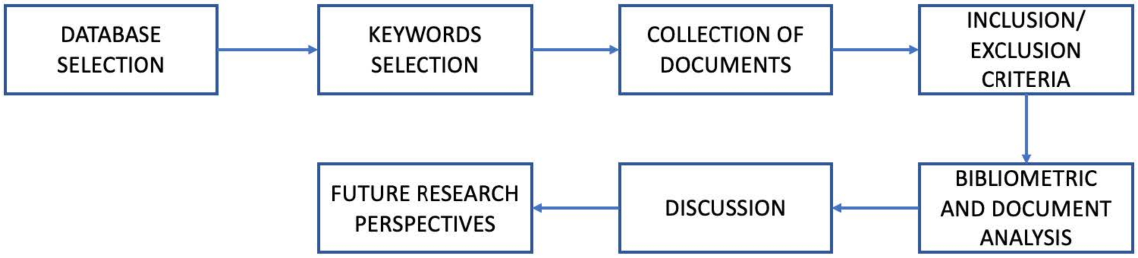

Figure 2.1: Review methodology schedule

in transportation. The keywords “blockchain” and “transportation” were employed in the online search. To refine the search, the term “blockchain” was initially queried in the selected digital library, with articles predating 2009 excluded as the first blockchain implementation occurred in that year. The chosen research papers include conference papers and proceedings, prioritizing those with full-text availability. Only high-quality papers published in reputable scientific journals and conference proceedings have been considered.

The growing popularity of blockchain technology is evident, as reflected in databases like Scopus and Web of Science. Before 2013, in Scopus only four scientific articles were related to blockchain, with a rapid increase to over 2,800 in 2018, exceeding 5,256 in 2019, and reaching 14,643 in 2020 and 69,360 in 2024. Following this pilot search, a refined query was executed using the terms “blockchain and transportation” or ”blockchain and transport”. Blockchain and transport produced 827 results from 2018 to 2024, while blockchain and transportation produced 2038 in the same period. In particular, the term “Bitcoin” was excluded from the search terms due to the substantial number of articles related to cryptocurrencies rather than the technological applications of the blockchain. Because the majority of articles found searching for the keywords blockchain and transport are present in the results obtained under the search contacted using blockchain and transportation, this work is based on the second search.

Given the broad scope of transportation, encompassing the movement of goods and persons using various means, the query results were categorized into themes such as supply chain, logistics, automotive, smart cities, smart parking, roadways, railways, tickets, and tolls. This categorization ensures a focused and organized approach to mapping the diverse applications of blockchain technology in the transportation sector.

2.4.2 Eligibility criteria

Following the application of the search protocol in scientific databases, the subsequent stage involved the selection of relevant papers aligned with the research questions. During the initial screening phase, papers were chosen based on their titles, and those not directly relevant to the research topic were excluded. For instance, some papers retrieved from the search protocol were related to blockchain in the transportation sector but focused on cryptocurrencies, Defi (Decentralized Finance), or Fintech applications, falling outside the scope of this mapping study. Consequently, these papers were not included in the literature review.

Determining the relevance of a paper based solely on its title posed challenges in some instances. In such cases, the paper was advanced to the next stage for further reading. During the second phase, the abstracts of all previously selected papers were thoroughly reviewed. This study specifically concentrated on blockchain technology in transportation, incorporating research articles and conference papers that met the predefined criteria outlined in Table 2.1. The aim was to ensure the inclusion of papers directly addressing the research questions and contributing to the mapping of blockchain applications in the transportation sector.

2.4.3 Classification of research articles

This section classifies and discusses the following aspects: (1) year of publication and (2) author nationalities.

Figure 2.2 depicts the trend of article publications from 2016 to 2024 for the query "blockchain and transportation". The graph illustrates a consistent annual increase in publications, indicating a growing interest among researchers in the application of blockchain

Criteria	Specified Criteria
Inclusion	Review, conference papers, and survey papers relevant to the use of blockchain technology in transport applications; Research articles (architecture,system design, framework, scheme, model, platform approach, protocol and algorithm) relevant to transport applications based on blockchain;
Exclusion	Thesis, books, and book chapters Non-English articles Unrelated articles

Table 2.1: Inclusion and Exclusion Eligibility Criteria

technology in the transportation sector. This upward trend suggests an expanding body of literature and a heightened focus on the integration of blockchain in transportation-related research.

In Figure 2.3, the most productive countries for the publication of articles on the application of blockchain in the transportation industry are presented. Notably, Korea, China, and the USA emerge as the most prolific contributors, with India following closely. This distribution underscores the global interest and engagement of researchers from diverse geographical regions in exploring and contributing to the discourse on blockchain applications in the transportation sector.

Finally, a co-word analysis is conducted to create a map illustrating how principal terms inserted in titles and abstracts are interconnected or linked in the selected papers. This technique, known as “Multiple Correspondence Analysis (MCA)”, involves a hierarchical cluster analysis using K-means clustering to group words that define clusters of common concepts. Words are grouped based on their homogeneity in the collection, indicating how frequently they appear together in the collected articles. The closer words are in the distribution, the more often they are cited together, thereby defining a concept.

Figure 2.4 presents four distinct clusters or concepts derived from word associations in the titles and abstracts. The first cluster includes terms such as ”supply chains,” ”supply chain management,” and ”transportation,” representing the logistics and supply chain sec-

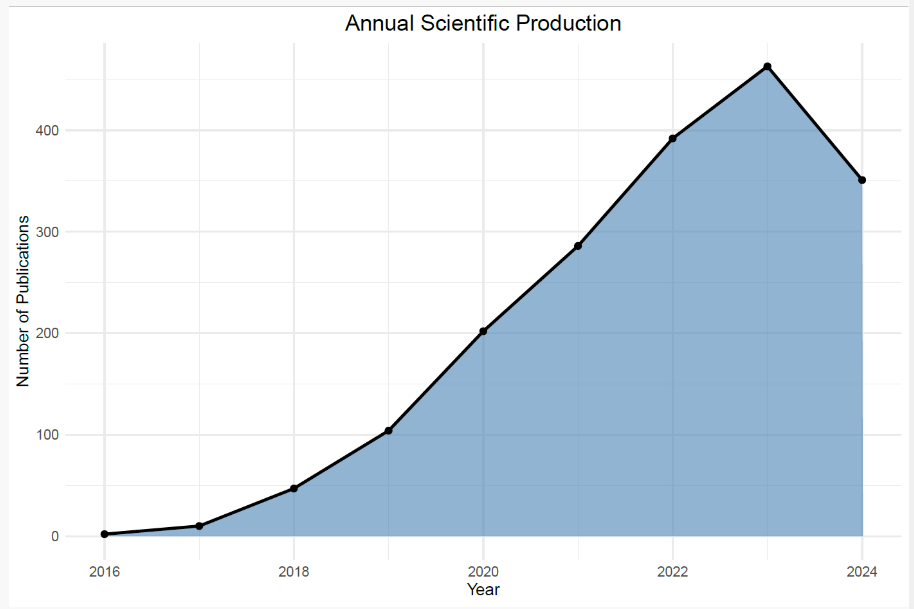

Figure 2.2: Publication Trend in Scopus

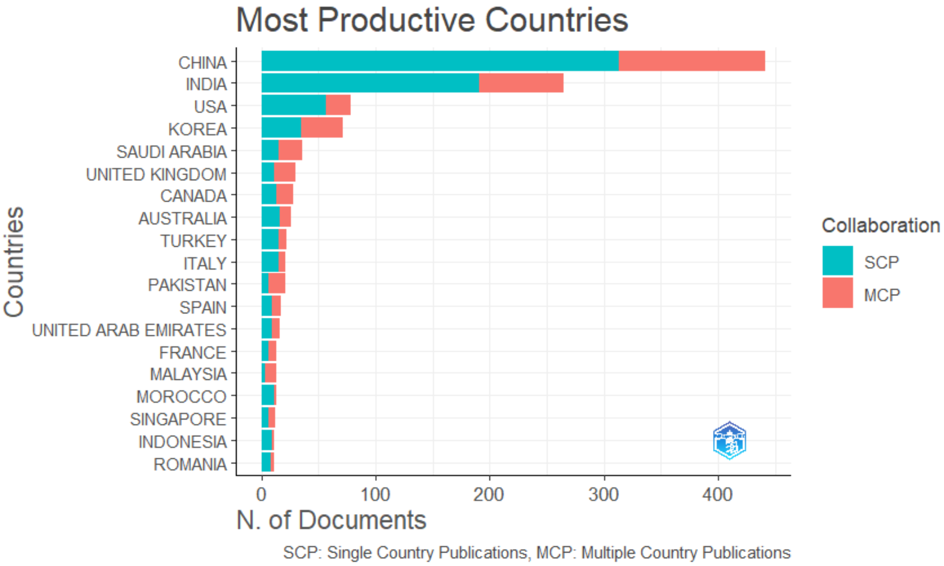

Figure 2.3: Distribution by Author Nationality

tor. The second cluster features words like ”internet of things,” ”automation,” ”Ethereum,” ”access control,” ”security,” and ”privacy,” encompassing a broad range of engineering IT applications. The third cluster focuses on terms related to roads, vehicles, traffic management, vehicular ad hoc networks (Vanet), highways, and congestion. The fourth cluster is tied to smart city technologies, intelligent transportation systems, and automation.

This figure also illustrates clusters related to ”blockchain and transport” in publications from 2016 to 2024. The initial search for ”blockchain and transportation” returned 2,034 results, which were further refined with terms like ”blockchain and supply chain,” ”blockchain and smart city or smart cities,” ”blockchain and vehicles and/or intelligent transportation system,” and ”blockchain and roads or highways or railways.” The cluster focused on blockchain and IT applications is not within the scope of this paper.

2.4.4 Detecting relevant papers

From the initial search, only papers related to the research questions were selected. Following the implementation of the search protocol in the scientific database, the subsequent stage involved the careful selection of relevant papers. During the first screening phase, papers were chosen based on their titles, and those not directly pertinent to the research topic were excluded. For instance, the search protocol generated papers related to blockchain and the transportation sector that were not strictly associated with this topic but rather focused on cryptocurrencies or other scientific fields like DeFi or Fintech applications.

Moreover, it’s essential to note that this analysis excludes blockchain applications in the logistics sector. These papers fall outside the scope of this mapping study, which primarily concentrates on the transport system related to highways, railways, and public transport in smart cities. As a result, they were not considered in the literature review.

Despite the emphasis on title-based screening, determining the relevance of a paper solely on this criterion proved challenging in some instances. In such cases, the paper was advanced to the next stage for further reading. The abstracts of all previously selected papers were then thoroughly reviewed. After identifying the relevant papers through ab-

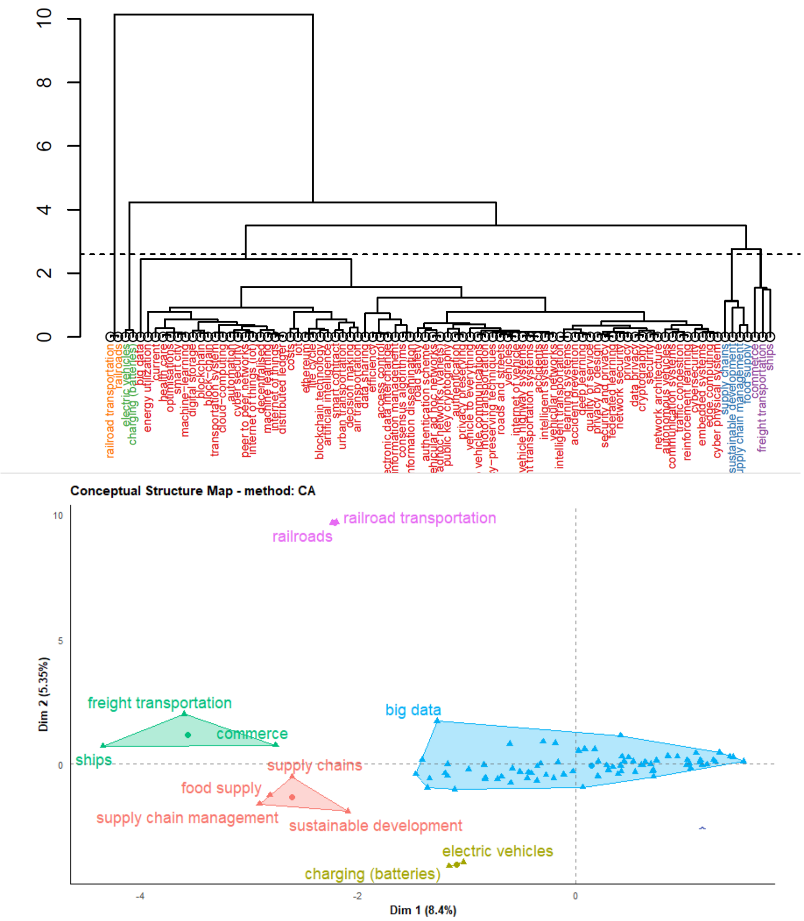

Figure 2.4: The conceptual structure of blockchain in the transportation industry

stracts, the subsequent step involved reading and selecting relevant keywords and concepts based on the contributions of each paper. This systematic approach ensures the inclusion of papers that align closely with the research questions and objectives of the mapping study.

2.4.5 Supply Chain Management

Various industrial sectors are increasingly exploring blockchain applications in supply chains, encompassing aspects such as product provenance and traceability, international shipping, cross-border flows, trade finance, anticorruption, and humanitarian aid (Chang et al., 2020; Pournader et al., 2020; Yontar, 2023). Presently, permissioned blockchains are the predominant type used in supply chains due to their capacity to provide network members with control over ledger access and node connections. Permissioned blockchains offer scalability and enterprise-level security, making them a preferred choice.

Blockchain technology has demonstrated the potential to enhance supply chain liquidity, operations, and flexibility. It aids in better freight tracking and improves monitoring, storage, and validation of data through vehicle-to-vehicle communications. The motivation for deploying blockchain often lies in its “Immutability”, signifying the ability to store an unalterable history of transactions. The permanence of historical data ensures a shared, immutable single version of truth across businesses, fostering transparency. Transparency is particularly crucial in complex supply chain networks, where consumers seek to trace and understand the origins and characteristics of products.

Blockchain’s transparency and traceability benefit sustainable practices, allowing companies to monitor the environmental performance of their vendors (Fareed et al., 2024; Kouhizadeh and Sarkis, 2018; Yontar, 2023). It supports green supply chain initiatives, enabling shared performance measurement and improving sustainable supplier development programs. In contrast to centralized systems with opaque information centers, blockchain introduces a decentralized traceability system where information is transparent, shared, and open, enhancing information credibility (Apte and Petrovsky, 2016; Bajwa et al., 2020; Cai et al., 2023; Esmaeilian et al., 2020; Fareed et al., 2024; Kouhizadeh et al., 2021; Paul et al., 2021; Rane et al., 2023; Stranieri et al., 2021; Yontar, 2023).

Traditional supply chains are often not sustainable, contributing to environmental challenges. Green Supply Chain Management (GSCM) practices aim to reduce waste, enhance productivity, and improve brand reputation. However, their implementation can be hindered by limited financial resources, a lack of skilled personnel experienced in managing green supply chains, insufficient technological capabilities, and the absence of environmental partnerships between buyers and suppliers (Stranieri et al., 2021). To address these barriers, Kumar et al. (2023); Nagariya et al. (2022); Rane et al. (2023) propose a blockchain-IoT integrated architecture. This blockchain solution enables real-time data collaboration, automates transactions through smart contracts, and enhances transparency, trust, and cooperation among stakeholders, thereby facilitating more efficient GSC adoption.

However, it is imperative to acknowledge that blockchain's veracity relies on robust audit processes to verify the accuracy of each transactional record. Regardless of whether the blockchain is public or private, there is always the potential for collusion among miners, introducing vulnerabilities. Scalability remains a challenge, with larger blockchain systems experiencing delays in transaction processing. Privacy concerns also persist, necessitating careful consideration of access rights and data privacy levels within blockchain systems.

Fareed et al. (2024) stress that blockchain adoption, particularly in developing countries, faces significant barriers that differ from those in more developed regions. Key obstacles include limited knowledge of blockchain technology, inadequate information and communication infrastructure, poor connectivity, underdeveloped financial systems, and the absence of clear regulations to encourage blockchain use. Furthermore, there is a shortage of trained professionals with blockchain expertise. Overcoming these challenges requires collaboration between industry, academia, and government to develop and disseminate blockchain-related skills and knowledge

As noted in Khan et al. (2023), blockchain technology has the potential to revolutionize supply chains by improving transparency and efficiency. However, the widespread adoption of blockchain technology has been impeded by a range of barriers, including inadequate information sharing, challenges in trust management, outdated technological infrastructure, ineffective organizational policies, communication gaps among supply chain partners, concerns over data security and privacy, high initial investment costs, a lack of technical resources, the complexity of blockchain adoption frameworks, and insufficient knowledge about blockchain itself.

One significant obstacle to blockchain adoption is the complexity of its frameworks. Organizations face various challenges when trying to integrate blockchain into their operations. There is a lack of standardized protocols and best enterprise practices, and each industry satisfies its needs with its own specific solutions. Additionally, interoperability poses a significant hurdle; integrating blockchain with existing systems can be particularly complex, especially when navigating disparate technologies. This multifaceted challenge is highlighted by Yadav et al. (2023), the need for clearer guidelines and standards to facilitate smoother integration.

Governance issues can also arise. Establishing governance rules for a blockchain network is a complex process, especially in environments with limited regulatory frameworks. Moreover, cultural shifts within organizations are necessary for successful blockchain adoption. Cai et al. (2023); Yadav et al. (2023) Employees must be equipped with the necessary skills and motivated to embrace this new technology.

Most of the identified barriers can be categorized into technical, organizational, and environmental barriers. Moretto and Macchion (2022) discuss two main groups of barriers to blockchain adoption in the fashion industry. There are technology-specific barriers that are related to the high investment costs associated with developing blockchain systems, which are often perceived as expensive compared to traditional traceability methods.

This concern is heightened by the potential for increased product costs, leading to resistance from marketing and sales teams to adopt blockchain technology unless they can clearly see the value of the customer.

In addition, the complexity of blockchain technology can make it difficult for organizations to understand and trust this new approach. Some stakeholders struggle to understand how blockchain operates, and challenges persist around deciding what data should be shared and how to establish trust in the technology.

Moretto and Macchion (2022) underline that also trust issues are important obstacles. The intricate nature of blockchain technology poses challenges for organizations in terms of understanding and trusting this new practice.

Yen-Ting et al. (2022) identify two main barriers: the complexity of information and acceptance of this technology within the supply chain (supply chain buy-in).

They define complexity as comprising three key elements: process complexity, the virtual-physical link, and the diversity of data modeling. Process complexity, which refers to the extent of alterations goods undergo during processing, can hinder traceability, especially for perishable items Tracking and tracing the provenance of specific perishable goods makes their traceability challenging.

The virtual-physical link is the reliability of the digital record. For high-value goods like diamonds, luxury items, and scarce minerals, it's crucial to ensure that the physical items match their blockchain records. This is especially challenging at remote sources like mines, forests, or oceans. How can data entry be verified in these locations?

Data modeling and structural diversity refers to the wide range of methods companies use to store data internally. Data modeling and structural diversity refers to the wide range of methods companies use to store data internally. This variety complicates the establishment of a unified data format for the blockchain. The ability to communicate across different systems, known as interoperability, presents a significant challenge in supply chain IT. Finally, the article discusses other factors that influence companies' adoption of blockchain technology in supply chains. These factors include the ability to handle information, comfort with sharing data, and the size of the supply chain.

Despite these challenges, blockchain-based applications hold the potential to enhance visibility, optimize processes, and improve demand management. The literature underscores the primary advantage of blockchain technology in supply chain networks as increased transparency and accountability, enabling more flexible and efficient value chains (Ahram et al., 2017; Kshetri, 2017, 2018). Additionally, research by Schmidt and Wagner (2019) indicates that blockchain reduces the impact of environmental uncertainty in transactional relationships, leading to lower transaction costs and facilitating more market-oriented governance structures in supply chains.

2.4.6 Logistics

Logistics, as a science and technology, encompasses the management and control of various flows, including materials, information, finance, and services. Within the supply chain context, logistics is responsible for overseeing stocks and physical product flows to the final

Challenges/issues	References	%
Immutability	Apte and Petrovsky (2016); Bajwa et al. (2020); Caro et al. (2018); Esmaeilian et al. (2020); Kouhizadeh et al. (2021); Tian (2016); Yontar (2023)	90%
Transparency	Apte and Petrovsky (2016); Bajwa et al. (2020); Cai et al. (2023); Caro et al. (2018); Chang et al. (2020); Esmaeilian et al. (2020); Kouhizadeh et al. (2021); Paul et al. (2021); Pournader et al. (2020); Stranieri et al. (2021); Tian (2016); Yontar (2023)	90%
Trust	Apte and Petrovsky (2016); Bajwa et al. (2020); Caro et al. (2018); Chang et al. (2020); Esmaeilian et al. (2020); Hull et al. (2016); Kouhizadeh et al. (2021); Paul et al. (2021); Pournader et al. (2020); Tian (2016)	90%
Identity	Bajwa et al. (2020); Chang et al. (2020); Pournader et al. (2020); Tian (2016)	90%
Accountability	Ahram et al. (2017); Bajwa et al. (2020); Caro et al. (2018); Hull et al. (2016); Kshetri (2017, 2018); Paul et al. (2021); Tian (2016)	90%
Insurance	Bajwa et al. (2020); Tian (2016)	90%

Table 2.2: Challenges/issues related to blockchain adoption in Supply Chain Management, along with the percentage of cited papers that emphasize each challenge.

Unsolved weakness	References	%
Lack of knowledge, lack of technical expertise, and lack of supportive culture	Bajwa et al. (2020); Cai et al. (2023); Fareed et al. (2024); Khan et al. (2023); Moretto and Macchion (2022); Stranieri et al. (2021); Tian (2016); Yadav et al. (2023); Yen-Ting et al. (2022); Yontar (2023)	10%
Lack of laws and regulatory conditions	Bajwa et al. (2020); Fareed et al. (2024)	10%
Scalability	Bajwa et al. (2020); Hull et al. (2016); Tian (2016); Yadav et al. (2023)	30%
Interoperability	Bajwa et al. (2020); Hull et al. (2016); Yadav et al. (2023); Yen-Ting et al. (2022)	90%
Expansive costs	Caro et al. (2018); Khan et al. (2023); Moretto and Macchion (2022)	10%
Governance	Chang et al. (2020); Moretto and Macchion (2022); Pournader et al. (2020); Yen-Ting et al. (2022)	60%
Privacy	Hull et al. (2016)	10%

Table 2.3: Unsolved weakness related to blockchain adoption in Supply Chain Management, along with the percentage of cited papers that emphasize each weakness.

customer. However, traditional logistics information systems often fall short of providing essential features such as transparency, shared trust, traceability, and auditability.

A notable study by Caro et al. (2018) emphasizes the challenges faced by agri-food supply chains when relying on centralized infrastructures. In response, they introduce "AgriBlockIoT", a fully decentralized, blockchain-based traceability solution for agri-food supply chain management. This solution integrates IoT devices throughout the chain, producing and consuming digital data. The study compares two blockchain implementations, Ethereum and Hyperledger Sawtooth, in a "from farm to fork" project. Hyperledger Sawtooth emerges as a potential solution, addressing Ethereum's CPU-intensive consensus algorithm and proving more suitable for computationally limited devices like edge gateways and IoT devices.

In logistics, blockchain finds applications in various areas such as identifying counterfeit products, reducing paperwork processing, enabling origin tracking (Hackius and Petersen, 2017; Kennedy et al., 2017; Lee and Pilkington, 2017; Toyoda et al., 2017), and facilitating direct transactions between buyers and sellers without intermediary manipulation. Additionally, blockchain-based applications in supply chain networks and logistic contribute to enhanced security (Dorri et al., 2017), robust contract management mechanisms between third and fourth party logistics (3PL, 4PL) (Polim et al., 2017), improved tracking mechanisms, traceability assurance (Apte and Petrovsky, 2016; Düdder and Ross, 2017; Heber et al., 2017; Lu and Xu, 2017; Tian, 2016, 2017), better information management (O'Leary et al., 2017; Turk and Klinc, 2017), food safety assurance (Ahmed and Broek, 2017), intellectual property protection (Herbert and Litchfield, 2015; Holland et al., 2017), enhanced customer service through advanced data analytics and recommender systems (Frey et al., 2016), improved inventory and performance management across complex supply chains (Madhwal et al., 2017), and advancements in smart transportation systems (Lei et al., 2017; Leiding et al., 2016; Yuan and Wang, 2016). Rathore et al. (2022) explores the challenges faced by the logistics sector in adopting disruptive technologies (DTs) such as blockchain, IoT, AI, drones, and 3D printing. All these DTs show the following Key barriers to their diffusion: lack of top management support, legal and regulatory frameworks, insufficient infrastructure and cultural resistance to change

Tangsakul and Sureeyatanapas (2024) explores the integration of Blockchain and IoT for improving sustainability and security in logistics and supply chains. This paper outlines the critical factors for successful BIoT adoption, while for policymakers, it underscores the importance of regulatory and infrastructural support for emerging technologies in logistics.

Kumar et al. (2023) explore the potential of integrating blockchain and IoT (BIOT)to enhance sustainability and security in logistics and supply chains. They suggest that technological, organizational, and environmental factors influence blockchain adoption. The research identifies key enablers, including technology maturity, top management commitment, and customer awareness, within these dimensions. They find that a ”sustainability focus,” ”emphasis on emerging technology,” and ”technology maturity” are the top three enablers for blockchain adoption. Ultimately, BIoT success depends on improving its scalability, throughput, storage, and latency on a network

2.4.6.1 Ports Logistics

In the Central Baltic Sea Region (CBSR), a consortium comprising enterprises, universities, and organizations has collaborated to apply blockchain technology in the supply chain and logistics field. The project, named the “Smart Logistics and Freight Villages Initiative (SMARTLOG)”, operates under the European Union’s Interreg Central Baltic program. The consortium members include Kouvola Innovation Oy (Finland), leading the initiative, Region Orebro County (Sweden), Valga County Development Agency (Estonia), Sensei LSC (Estonia), Tallinn Technical University (Estonia), and Transport and Telecommunication Institute (Latvia).

The primary objective of the consortium is to reduce cargo transit times on transport corridors, aligning with EU policy objectives. As noted by Queiroz et al. (2019), the implementation of blockchain and IT in the CBSR transport corridors enhances the transparency of shipment progress, leading to improved efficiency. These technologies also foster greater trust through the indelible recording of transactions, ensuring accuracy and lowering logistic management costs.

Notably, a joint project initiated by IBM and Maersk in 2016 utilized blockchain to enhance workflow and visibility in cargo shipment. Multiple stakeholders, including trading partners, government authorities, and logistics companies, collaborated within this blockchain network. The detailed visibility of cargo progress and real-time access to original supply chain events and documents contributed to improved transparency and efficiency.

In the maritime sector, blockchain applications show promise for digitalizing the exchange of shipping documentation, bill of lading, and compliance. Gausdal et al. (2018) found that blockchain innovations could improve financial, documentation, and asset management for Norwegian Maritime Companies, leading to better documentation and control systems. The public, traceable nature of blockchain transactions also contributes to reducing corruption risks.

Studies by Jabbar and Bjørn (2018) and Hackius et al. (2019) delve into the challenges and advantages of integrating blockchain into existing shipping information infrastructures. The intersection of blockchain technology and traditional shipping information systems creates an “infrastructural grind”, characterized by consolidation, permeability, and velocity. Privacy concerns, digital proficiency requirements, and the disclosure of partners and subcontractors emerge as potential barriers.

In the aviation industry, Madhwal et al. (2017) explored the role of blockchain in Aviation Supply Chain Management. They found that blockchain could enhance the traceability of aircraft parts, establishing the authenticity of spare parts and lowering the cost of doing business in global aircraft parts supply chains.

Nguyen et al. (2023) examines the challenges and strategies surrounding blockchain technology adoption in the container shipping industry. Based on interviews with experts from container shipping service providers (CSSPs), including shipping companies, terminal operators, and freight forwarders, the study identifies key barriers to adoption, such as technological complexity, data privacy concerns, insufficient legal frameworks, and lack of governmental support. They highlight the differing perspectives among CSSPs on these barriers, with larger shipping companies being early adopters, while terminal operators and freight forwarders show more caution. Notably, the research emphasizes that successful adoption depends on addressing these barriers through industry collaboration, the development of legal standards, and education on blockchain's benefits and risks.

The study recommends several strategies for enhancing blockchain adoption. These include promoting sustainable applications, developing gradual adoption pathways, emphasizing digitalization and standardization, and fostering collaborative efforts across the industry. Finally, the article concludes that blockchain's potential in container shipping remains significant, but achieving widespread adoption will require a combined effort across technological, regulatory, and cultural dimensions within the industry.

Guan et al. (2023) explore barriers to blockchain adoption in the seaport industry, using a fuzzy DEMATEL analysis to identify and analyze these obstacles. The study reveals four key barriers: lack of management support, supply chain collaboration issues, external stakeholder resistance, and high costs. Despite blockchain's potential for enhancing transparency, efficiency, and security in port operations, these barriers complicate its adoption. Using a mix of expert interviews and fuzzy DEMATEL methodology, the authors classified the barriers into cause-and-effect groups, with management commitment and external stakeholder involvement identified as major causes impeding blockchain adoption. The research emphasizes the critical role of management in advocating for blockchain, as organizational commitment can significantly impact decision-making and drive adoption. High costs were another significant obstacle, particularly for ports lacking resources for large initial investments. Furthermore, collaboration challenges within the supply chain, including coordination and communication, pose considerable hurdles to blockchain implementation. Finally, external stakeholders, such as customers and regulatory bodies, often resist adoption due to a lack of understanding or involvement in blockchain initiatives. The study suggests that overcoming these barriers requires a targeted approach, including strategic investment in technology, robust organizational policies, and enhanced engagement with external stakeholders. By addressing these areas, ports can leverage blockchain technology to improve operational efficiency, security, and sustainability in maritime logistics.

Tsiulin et al. (2023) discusses the key challenges in implementing blockchain technology within the maritime sector. It identifies and categorizes these challenges into four primary areas:

1. **Human Factor:**
    - Dependency on manual input for documentation, which complicates integration with blockchain systems.
    - Reluctance among companies to change business processes and adopt new technology, as the integration of blockchain demands significant expertise and resources.
    - The existing level of trust in current systems may be seen as sufficient, making blockchain adoption less appealing.
2. **Operational Challenges:**
    - A wide variation in digitalization levels across ports, with some focusing on expanding physical infrastructure over digital solutions.
    - Blockchain systems designed for tracking are seen as potentially redundant, as current centralized systems can fulfill similar roles.
    - Costs and benefits of blockchain implementation remain unclear, and its role often overlaps with existing Port Community Systems (PCS).
3. **Organizational Challenges:**
    - Diverging priorities among ports, particularly in terms of land expansion versus digital investments.
    - Difficulties in incorporating customs and other transport sectors (e.g., middle- and last-mile logistics) into a blockchain network.

    - Projects that claim decentralization might still be developed and controlled by a single entity, compromising true decentralization.

4. **Technological Challenges:**
    - Scalability issues, with difficulties in managing blockchain's security and governance on a large scale.
    - Confusion regarding responsibility and data ownership within a decentralized system.
    - Low maturity and long-term implementation experience in the maritime sector, which has led to a lack of case studies and technical documentation.

The study concludes that while blockchain offers potential benefits, the technology is still immature in the maritime sector. Overcoming these challenges will require cooperation among industry stakeholders, digital literacy improvements, and regulatory alignment.

Overall, the integration of blockchain technology in transportation and logistics holds significant potential for efficiency, transparency, and cost reduction across various sectors.

2.4.7 Smart Cities and Internet of Vehicles

The concept of a smart city is broad, defined by the use of Information and Communication Technologies (ICT) to address urban challenges and provide services. With a focus on "blockchain and smart cities", a search yielded 540 articles, but the selection was narrowed to those within the specific area of interest. The research concentrates on applications and benefits derived from optimizing urban resources such as space, transportation, and mobility services. Attention is particularly given to the efficient use of urban assets and the reduction of transaction costs, encompassing energy savings, congestion reduction, and pollution control.

Sun et al. (2016) showcases blockchain's application in sharing services, emphasizing the crucial link between privacy and trust. Anonymity becomes essential to protect citizens'

Challenges/issues	References	%
Immutability	Caro et al. (2018); Gausdal et al. (2018); Jabbar and Bjørn (2018); Nguyen et al. (2023)	90%
Transparency	Caro et al. (2018); Czachorowski et al. (2019); Gausdal et al. (2018); Guan et al. (2023); Hackius et al. (2019); Jabbar and Bjørn (2018); Madhwal et al. (2017); Nguyen et al. (2023); Queiroz et al. (2019); Rathore et al. (2022)	90%
Trust	Caro et al. (2018); Czachorowski et al. (2019); Gausdal et al. (2018); Guan et al. (2023); Jabbar and Bjørn (2018); Madhwal et al. (2017); Nguyen et al. (2023); Queiroz et al. (2019); Rathore et al. (2022)	90%
Identity	Czachorowski et al. (2019); Hackius et al. (2019); Jabbar and Bjørn (2018)	90%
Interoperability	Czachorowski et al. (2019); Jabbar and Bjørn (2018); Madhwal et al. (2017); Queiroz et al. (2019)	90%
Accountability	Caro et al. (2018); Gausdal et al. (2018); Guan et al. (2023); Jabbar and Bjørn (2018); Nguyen et al. (2023); Queiroz et al. (2019)	90%
Insurance	Gausdal et al. (2018)	90%

Table 2.4: High challenges/issues related to blockchain adoption in Ports Logistics, along with the percentage of cited papers highlighting each challenge.

Unsolved weakness	References	%
Lack of knowledge, lack of technical expertise, and lack of supportive culture	Di Gregorio et al. (2017); Gausdal et al. (2018); Guan et al. (2023); Hackius et al. (2019); Nguyen et al. (2023); Queiroz et al. (2019); Rathore et al. (2022); Tsiulin et al. (2023)	60%
Lack of laws and regulatory conditions	Di Gregorio et al. (2017); Guan et al. (2023); Nguyen et al. (2023); Rathore et al. (2022)	10%
Expansive costs	Caro et al. (2018); Guan et al. (2023)	10%
Governance	Chang et al. (2020); Fareed et al. (2024); Guan et al. (2023); Tsiulin et al. (2023)	
Privacy	Dorri et al. (2017); Hackius et al. (2019); Rathore et al. (2022)	45%

Table 2.5: Unsolved weakness related to blockchain adoption in Supply Chain Management, along with the percentage of cited papers that emphasize each weakness.

privacy in scenarios like direct renting of apartments, office space, or Wi-Fi routers. The study highlights examples like Enigma and the German startup (Slock.it UG). Brousmiche et al. (2018) propose a Blockchain-backed Vehicles Data and Processes Ledger to digitize the vehicle life cycle, fostering secure sharing of data among stakeholders. Lazaroiu et al. (2020) emphasize how blockchain aids in sharing data about the consumption and recharge of electric vehicles, contributing to real-time control and efficient planning.

Blockchain finds applications in smart parking systems, as discussed by Kim and Kim (2020), ensuring transparency and addressing privacy concerns present in centralized systems. Badr et al. (2020) propose a decentralized parking system using blockchain to ensure integrity, privacy, and an anonymous payment method. In smart cities, smart vehicles that communicate with each other and third parties are envisioned. Chiasserini et al. (2020) propose a blockchain-based architecture for decentralized vehicular applications, addressing scalability challenges. Mohammadzadeh et al. (2019) introduce DMap, a blockchain-based platform for sharing data in an anonymous distributed manner, improving online mapping services and addressing privacy concerns.

Cebe et al. (2018) introduce a blockchain forensic framework for resolving disputes after car accidents, connecting vehicles, maintenance service providers, manufacturers, law enforcement, and insurance companies. Lei et al. (2017) propose a blockchain project to transfer and verify vehicle heterogeneous keys, enhancing the security of Vehicle-to-Infrastructure (V2I) communications in Vehicular Communication Systems (VCS). The study stresses the need for more research to resolve privacy issues.

Biasin and Delle Foglie (2024) examines the impact of blockchain in the context of smart cities, focusing on creating inclusive and sustainable communities. The research highlights challenges such as the lack of practical applications of distributed ledger technologies in urban contexts and the need for solutions to improve scalability and energy sustainability.

Al Mahfuj Shaan et al. (2022) examine the potential of blockchain in smart cities, discussing both opportunities and limitations such as security, interoperability, standardization and regulatory barriers. The authors propose a future research agenda to tackle these challenges and enhance the integration of blockchain in urban infrastructures.

Looking ahead, as smart cities become a reality, security and privacy concerns will grow. Blockchain, with its cryptographic structures and shared information, can play a crucial role. The future, with electric, connected, and autonomous vehicles, envisions a world where blockchain ensures trustful and inviolable digital records of transactions, enabling secure exchanges without intermediaries. The democratic vision of blockchain, eliminating central entities and relying on the "democracy of computing power", remains a key aspect for the future evolution of smart cities and connected vehicles.

2.4.8 Public Transport

In every city, the efficiency of public transport significantly influences the quality of life for its residents. The process of purchasing and utilizing tickets, especially for multimodal journeys involving various transportation modes, can often be fragmented, time-consuming, and frustrating. Consider an individual undertaking a journey involving multiple train lines, a bus, and a bike for the last stretch. In such cases, at least four transactions, multiple visits to ticketing counters or machines, and waiting in line multiple times may be necessary. A blockchain-powered platform has the potential to streamline this process, offering a one-stop shop for such transactions.

In Madrid, a partnership between Banco Santander, a leading Spanish bank, and Vottun, a blockchain certification startup, is set to introduce a unified digital payment system powered by blockchain for city transport users. Vottun's protocol facilitates interoperable platforms, enabling the development of blockchain applications that can interact with various public or private blockchain networks. This initiative, named Madrid in Motion, led by the Municipal Transport Company of Madrid (EMT), aims to digitalize the city's transit system and simplify the services provided by various transport companies under the EMT umbrella.

Currently, Madrid residents can use multiple modes of transportation such as metro, buses, taxis, e-scooters, bikes, and car rentals, but the payment processes are separate for each. Users need to install and register in different applications, resulting in redundant processes. The integration of tickets in smart cities and the efficient implementation of this through blockchain remain understudied.

Blockchain technology can enhance the integration of public buses into the Vehicle Communication (VC) system, contributing to monitoring bus maintenance conditions and ensuring citizens' safety. The European Union's Mobility as a Service (MaaS) Alliance aims to create a single mobility service accessible on demand. Blockchain could facilitate the MaaS model by providing a unified platform managing ride-sharing, public transportation, and logistics. It can replace centralized paper-based record systems with a digital system for ticketing, receipts, confirmations, and payments. Additionally, blockchain can track bus movements in real-time, addressing the common concern of passengers wondering whether their bus has already passed.

Hîrţan et al. (2020) propose integrating travelers and public transport as a transportation continuum, developing a secure reputation system based on users' behavior and history regarding the data they contribute to the system. The existing literature lacks an in-depth exploration of these public transport issues in the context of blockchain technology. Further study and research are warranted to delve into the aspects discussed above and explore the potential benefits of blockchain in enhancing public transportation systems.

2.4.9 Smart Mobility

Blockchain technology is increasingly finding applications in the mobility sector, particularly in the realm of asset-sharing and bike-sharing programs. The rise of the sharing economy and collaborative consumption, which rely heavily on trust, can benefit from the decentralization and transparency that blockchain provides.

In the context of asset-sharing platforms like Uber and Airbnb, blockchain has the potential to eliminate the need for intermediaries, providing a truly peer-to-peer (P2P) asset-sharing service. This can enhance efficiency and reduce costs. A specific use case explored in the literature is bike-sharing. Guo et al. (2018) designed a blockchain-based platform for bike-sharing, aiming to combine user privacy protection with measures against vandalism. The blockchain serves as a trust mechanism, ensuring real-time monitoring of users' data and triggering smart contracts after transactions. This system addresses issues related to trust, privacy, and data processing.

Another challenge in the bike-sharing domain is deposit management. Zhao et al. (2020) propose a blockchain solution to directly and transparently supervise user deposits through smart contracts. This helps overcome issues of asymmetric information, reducing risks associated with deposit management in shared bicycle enterprises.

The implementation of blockchain in bike-sharing programs is particularly relevant for cities moving towards sustainable practices. Top bike-friendly cities, including Amsterdam, Portland, Copenhagen, Tokyo, and Barcelona, can leverage blockchain to reward riders with tokens or tickets for using public transportation, including bicycles. This incentivization system can encourage more sustainable commuting practices.

The core components of a bike-sharing blockchain system involve smart contracts, coins or tokens, and software. Guo et al. (2018) emphasize that such a system can operate in both business-to-consumer (B2C) and consumer-to-consumer (C2C) modes. In the B2C model, rental bicycle providers can rent sharing bikes to ordinary users, while the C2C model allows cycling enthusiasts to rent high-quality bicycles to others through blockchain records and smart contracts.

Jaffe et al. (2017) delve into the motivation aspect of urban cycling, emphasizing that despite the growing number of cyclists and infrastructure improvements, bicycles are not yet considered a mainstream means of transportation. They propose a blockchain protocol supporting a financial incentives system for cyclists, with GPS-collecting sensor devices linked to the blockchain network. This system enables cyclists to connect and receive financial rewards for their cycling activity, ultimately aiming to increase the prevalence of urban cycling for improved public health and reduced pollution.

Dungan and Pop (2022) underline that blockchain technology has demonstrated its value in securing data for cryptocurrencies. However the use of blockchain technology is important to enhance sustainability in smart mobility systems. Smart cities integrate Internet of Things (IoT) technology to manage resources efficiently, aiming to improve citizens' quality of life. As urban populations grow, ensuring secure, sustainable transportation becomes crucial. Blockchain can serve the safety and security requirements that are specific to intelligent transportation systems (ITS). By using blockchain, traffic data from sensor networks can be securely stored, ensuring system integrity and safety. The study proposes a conceptual model for sustainable smart mobility that leverages blockchain for decentralized ride-sharing, vehicle-to-everything (V2X) communication, and autonomous vehicle transactions. The authors propose a model that emphasizes blockchain's potential to protect privacy, facilitate transparent digital payments, and promote energy-efficient transportation solutions, such as car-sharing and the integration of renewable energy within transportation systems. They conclude that blockchain can significantly improve data security for smart mobility systems, suggesting future research on integrating blockchain with various traffic-specific sensors for enhanced security, trust, data integrity and sustainability.

In summary, blockchain technology holds promise in revolutionizing bike-sharing programs, addressing issues of trust, privacy, deposit management, and incentivizing sustainable mobility practices. Ongoing research and development in this area aim to create efficient, secure, and transparent systems for urban commuters.

2.4.10 Railways and Highways

The applications of blockchain technology in the transportation sector, particularly in railways and roadways, showcase a range of benefits from improved efficiency to enhanced security and transparency.

In the railway sector, blockchain has been successfully implemented for tracking daily passengers, as seen in Russian railways, providing an added layer of transparency and traceability. The system also allows for the creation of customized offers tailored to specific travelers, enhancing the user experience. Additionally, blockchain ensures transparency and traceability for both freight and passenger transport within the railway network. The

Challenges/issues	References	%
Immutability	Badr et al. (2020); Brousmiche et al. (2018); Dungan and Pop (2022); Hîrţan et al. (2020); Lazaroiu et al. (2020)	90%
Transparency	Badr et al. (2020); Brousmiche et al. (2018); Cebe et al. (2018); Chiasserini et al. (2020); Dungan and Pop (2022); Guo et al. (2018); Hîrţan et al. (2020); Kim and Kim (2020); Lazaroiu et al. (2020); Lei et al. (2017); Sun et al. (2016); Zhao et al. (2020)	90%
Trust	Badr et al. (2020); Brousmiche et al. (2018); Cebe et al. (2018); Dungan and Pop (2022); Hîrţan et al. (2020); Jaffe et al. (2017); Kim and Kim (2020); Lazaroiu et al. (2020); Lei et al. (2017); Mohammadzadeh et al. (2019); Sun et al. (2016); Zhao et al. (2020)	90%
Identity	Brousmiche et al. (2018); Guo et al. (2018); Hîrţan et al. (2020); Lei et al. (2017); Zhao et al. (2020)	90%
Interoperability	Cebe et al. (2018); Dungan and Pop (2022); Guo et al. (2018); Jaffe et al. (2017); Kim and Kim (2020); Lazaroiu et al. (2020); Mohammadzadeh et al. (2019); Zhao et al. (2020)	90%
Accountability	Brousmiche et al. (2018); Cebe et al. (2018); Jaffe et al. (2017); Lazaroiu et al. (2020)	90%
Insurance	Jaffe et al. (2017)	90%

Table 2.6: High challenges/issues related to blockchain adoption, along with the percentage of cited papers that emphasize each issue.

Unsolved weakness		%
Lack of knowledge, lack of technical expertise, and lack of supportive culture	Di Gregorio et al. (2017)	0%
Lack of laws and regulatory conditions	Lei et al. (2017)	1%
Scalability	Chiasserini et al. (2020); Guo et al. (2018); Lei et al. (2017)	20%
Expansive costs	Caro et al. (2018)	1%
Governance	Cebe et al. (2018); Chiasserini et al. (2020); Lazaroiu et al. (2020)	30%
Privacy	Badr et al. (2020); Guo et al. (2018); Mohammadzadeh et al. (2019); Sun et al. (2016)	30%

Table 2.7: Unsolved weakness related to blockchain adoption, along with the percentage of cited papers that emphasize each weakness.

decentralized nature of the technology enhances data security by preventing tampering, while also facilitating interconnected information that is secure and trustworthy. One key advantage is the decentralization of traffic control, which allows for collaborative management on a transparent platform. Prototypes of blockchain-based decentralized railway control systems have been introduced, enabling self-aware participants, route optimization, and the use of transparent smart contracts. Furthermore, digital ticketing platforms powered by blockchain offer secure, efficient, and paperless solutions. Blockchain's integration with big data for asset management ensures the verification and security of data, benefiting both trackside staff and Rail Operations Centers. Despite these benefits, challenges remain, particularly regarding scalability and the speed of blockchain transactions. There is also a need for rail companies to familiarize themselves with the technology to enable broader adoption.

In roadways, blockchain applications have similarly transformative potential. In toll collection systems, for example, blockchain reduces the need for third-party intermediaries, cutting costs and improving efficiency through direct payments. The integration of blockchain with intelligent toll gates ensures that transactions between vehicle owners and governing authorities are both secure and transparent. Blockchain-enabled smart highways offer advantages like reduced credit card fees, faster transaction times, and incentives for better traffic management. Within intelligent transportation systems, blockchain enhances trust in toll-collection processes by ensuring the transparency and traceability of financial transactions. Privacy concerns are addressed through blockchain's secure transaction methods, which preserve the confidentiality of users. Another innovative application is the Leadership Incentives for Platoons (LIPs) protocol, which uses blockchain to create a secure environment for untrusted vehicles to interact safely on the road, particularly in vehicle platoons. Additionally, blockchain and IoT are being integrated into automated service provider systems to offer seamless assistance in cases of accidents or vehicle breakdowns. However, like in railways, road transportation faces challenges in adopting blockchain technology. Issues of interoperability and scalability require further research and development to ensure effective integration into existing systems.

Dungan and Pop (2022) explore the use of Ethereum blockchain technology for automated road toll collection on highways. Traditionally, tolls are collected manually or through Radio Frequency Identification (RFID), which is limited by centralization, additional fees, and potential security vulnerabilities. The authors propose a blockchain-based system employing smart contracts to securely and efficiently manage toll payments. This decentralized approach enables vehicles to automatically pay tolls without intermediaries, reducing costs and increasing data security.

In this model, smart contracts manage transactions, deducting toll fees directly from drivers' accounts as they pass through toll plazas. Blockchain maintains a secure and transparent record of all transactions, which enhances trust and minimizes the potential for fraud. The article suggests that using blockchain for toll collection could improve traffic flow by diverting vehicles to less congested routes, as well as offer substantial savings by eliminating additional service fees commonly charged by credit or debit card companies. The authors recommend future research into integrating incentive mechanisms within this system for further traffic management and vehicle control on highways.

In conclusion, blockchain technology offers numerous advantages to the transportation sector, from increased efficiency and enhanced security to better user experiences. Its applications in railways and roadways demonstrate the potential for transforming transportation systems. However, challenges such as scalability and interoperability must be addressed for blockchain to achieve widespread and effective adoption across the sector.

2.5 Discussion and future research perspective

This summary highlights the key findings from the identified clusters of blockchain applications in different sectors, with a focus on supply chain and logistics, maritime shipping, traffic management, and smart cities. Here's a breakdown of the main points:

1. Supply Chain and Logistics:

Challenges/issues	References	# of Refs	%
Immutability	Ceccarelli et al. (2020); Das et al. (2022); Dayana et al. (2019); Dungan and Pop (2022); Figueroa-Lorenzo et al. (2021); Gulyi (2020); Kuperberg et al. (2019); Ledbetter et al. (2019); Preece and Easton (2019); Qian et al. (2021); Rajbhandari et al. (2018); Xiaodong et al. (2020); Yadav et al. (2021); Ying et al. (2020)	1550	90%
Transparency	Badr et al. (2020); Brousmiche et al. (2018); Cebe et al. (2018); Chiasserini et al. (2020); Dungan and Pop (2022); Guo et al. (2018); Hîrţan et al. (2020); Kim and Kim (2020); Lazaroiu et al. (2020); Lei et al. (2017); Sun et al. (2016); Zhao et al. (2020)	1550	90%
Trust	Ceccarelli et al. (2020); Dayana et al. (2019); Dungan and Pop (2022); Figueroa-Lorenzo et al. (2021); Gulyi (2020); Huang et al. (2021); Kuperberg et al. (2019); Ledbetter et al. (2019); Naser (2018); Preece and Easton (2019); Qian et al. (2021); Rajbhandari et al. (2018); Tanveer and Javaid (2019); Xiaodong et al. (2020); Yadav et al. (2021); Ying et al. (2020)	1550	90%
Identity	Ceccarelli et al. (2020); Das et al. (2022); Gulyi (2020); Huang et al. (2021); Kuperberg et al. (2019); Ledbetter et al. (2019); Naser (2018); Preece and Easton (2019); Qian et al. (2021); Rajbhandari et al. (2018); Tanveer and Javaid (2019); Xiaodong et al. (2020); Yadav et al. (2021); Ying et al. (2020)	1550	90%
Interoperability	Dayana et al. (2019); Dungan and Pop (2022); Gulyi (2020); Kuperberg et al. (2019); Naser (2018); Preece and Easton (2019); Rajbhandari et al. (2018); Zhang et al. (2019)	1550	90%
Accountability	Ceccarelli et al. (2020); Das et al. (2022); Dayana et al. (2019); Gulyi (2020); Huang et al. (2021); Kuperberg et al. (2019); Ledbetter et al. (2019); Naser (2018); Preece and Easton (2019); Rajbhandari et al. (2018); Xiaodong et al. (2020); Yadav et al. (2021)	1550	90%
Insurance	Das et al. (2022); Gulyi (2020); Kuperberg et al. (2019); Rajbhandari et al. (2018); Yadav et al. (2021)	1550	90%

Table 2.8: High challenges/issues related to blockchain adoption, along with the percentage of citations that emphasize each challenge.

Unsolved weakness	References	%
Communication Complexity	Ceccarelli et al. (2020); Dayana et al. (2019); Figueroa-Lorenzo et al. (2021); Huang et al. (2021); Kuperberg et al. (2019); Naser (2018); Preece and Easton (2019); Rajbhandari et al. (2018); Tanveer and Javaid (2019); Xiaodong et al. (2020); Yadav et al. (2021); Ying et al. (2020)	90%
Lack of knowledge, lack of technical expertise, and lack of supportive culture	Ceccarelli et al. (2020); Kuperberg et al. (2019); Naser (2018); Preece and Easton (2019); Rajbhandari et al. (2018); Xiaodong et al. (2020)	30%
Scalability	Tian (2016); Yadav et al. (2021)	5%
Expansive costs	Gulyi (2020)	1%
Governance	Ceccarelli et al. (2020); Kuperberg et al. (2019); Ledbetter et al. (2019); Preece and Easton (2019); Tanveer and Javaid (2019); Zhang et al. (2019)	20%
Interoperability	Ceccarelli et al. (2020); Figueroa-Lorenzo et al. (2021); Kuperberg et al. (2019); Qian et al. (2021); Xiaodong et al. (2020); Yadav et al. (2021)	20%

Table 2.9: Unsolved weakness related to blockchain adoption, along with the percentage of citations that emphasize each weakness.

   (a) Real-time Traceability: Blockchain provides real-time traceability of products in the supply chain, addressing information asymmetry issues.
   (b) Application Areas: Explores applications in cross-border digital integration, product traceability, financial settlements, process automation, and contract management.
   (c) Trust and Transparency: Blockchain enhances trust through data security, transparency, and information reliability, addressing legal disputes and fraud issues.
   (d) Disintermediation: The technology enables peer-to-peer asset or money transfer, reducing transaction costs and eliminating the need for third-party authentication.

2. Maritime Shipping:
   (a) Workflow Improvement: Blockchain solutions are explored to enhance the workflow and visibility in maritime shipping, reducing documents and intermediaries.

   (b) IBM and Maersk Collaboration: A joint venture in 2016 aimed to improve shipment workflows, but interoperability challenges remain.
   (c) Mass Adoption Challenges: Blockchain's potential depends on mass adoption, and current challenges hinder widespread implementation.

3. Traffic Management and Infrastructure:
   (a) Efficiency Gains: Blockchain applications in traffic management show efficiency gains, especially in roads, streets, highways, railways, and congestion management.
   (b) Strengths: Data immutability, trust, transparency, real-time data flows, and interconnectedness between people and devices are highlighted.
   (c) Complex Tasks and Computational Resources: Successful applications require integrated blockchain systems with IoT to perform complex tasks that demand significant computational resources.

4. Smart Cities:
   (a) Blockchain Characteristics Impact: Studies focus on how blockchain characteristics like transparency, trust, and decentralization impact vehicular movements and city services in smart cities.
   (b) Challenges: Addressing challenges such as scalability, cost efficiency, flexibility, real-time information availability, privacy, and security of vehicular networks is crucial.
   (c) Future Vehicle Trends: Blockchain's utility is emphasized for connected, autonomous, environmentally efficient, and driverless vehicles, addressing threats like data integrity and security.

5. Cross-cutting Themes:

   (a) Barriers to Diffusion: Barriers include a lack of knowledge and expertise, regulatory challenges, and the need for new legal standards.
   (b) Interoperability Challenges: Addressing interoperability challenges and the potential elimination of the need for traditional financial intermediaries (banks, credit cards) are key research areas.
   (c) Cost Management: The cost of managing large amounts of data on blockchain networks is a potential concern.
   (d) Regulatory Challenges: Blockchain development requires regulatory frameworks to ensure legal validity and enforceability of smart contracts.
   (e) Consortium Systems: Exploring the expansion of blockchain consortium systems in the transport industry, especially in terms of increasing the number of participating actors.

6. Advice for Further Studies:
   (a) Investigate how to improve interoperability in blockchain applications.
   (b) Examine whether traditional financial intermediaries will still be required in various sectors.
   (c) Explore the potential cost implications of managing significant data on blockchain networks.
   (d) Address regulatory challenges and establish legal standards for smart contracts.
   (e) Investigate the expansion of blockchain consortium systems to include more actors in the transport industry.

This comprehensive summary provides insights into the current state, challenges, and potential directions for research in blockchain applications across diverse sectors.

2.6 Conclusions

This work examines the diffusion of blockchain technology across various transportation industries, relying on academic literature as a credible source of information. The study identifies blockchain's potentially disruptive impact on agri-food, pharmacy supply chain, store supply chains, logistics, smart cities, and traffic management. The key features highlighted in the selected studies include peer-to-peer communication without a central authority, transparent transaction processing, decentralized transaction history, and immutability of records.

The following are some of the key observations and findings:

1. Integration of Digital Technologies:
    - The integration of digital technologies in modern societies, including the transport sector, necessitates mechanisms for accurate user identification and certification of personal attributes.
    - Blockchain serves as a decentralized security architecture that can enhance the security of interconnected IoT devices and the flow of personal information.
2. Trust Enhancement:
    - Blockchain, while not guaranteeing information reliability, preserves information integrity, transparency, and security, ultimately enhancing trust.
    - Trust is considered a crucial factor driving interest in blockchain technology, as highlighted by the literature.
3. Early Phase of Blockchain Adoption:
    - Blockchain technology in the transportation industry is still in its early phase, and the literature signals its potential for disruptive innovation.
    - Barriers to adoption are acknowledged, but technological barriers are expected to break down over time.

4. Challenges and Barriers:
    - The study does not extensively discuss specific barriers to blockchain adoption in the transportation sector.
    - Notable challenges like scalability, integration with legacy systems, complexities in building and deploying solutions, and lack of standardization are not thoroughly addressed.
5. Blockchain Consortium Proposals:
    - Some articles propose the formation of Blockchain Consortia to address challenges related to standardization, interoperability, and tailoring systems to specific user needs.
6. Data Privacy Regulation:
    - Data privacy regulation is recognized as a critical concern, emphasizing the need to decide how privacy should be defended within a transparent and trusted blockchain network.

Future research could explore the unaddressed challenges, including scalability, integration complexities, and lack of standardization, to provide a comprehensive understanding of blockchain adoption in transportation. Further investigations into the formation and expansion of Blockchain Consortia could shed light on collaborative approaches to overcome challenges and promote interoperability. Addressing the ethical and regulatory aspects of data privacy within blockchain networks could be a crucial area for future studies.

Chapter 3

Implementation of Blockchain Technology in the Highway Sector

Abstract:
Numerous companies worldwide are increasingly adopting blockchain technology to enhance the traceability of their goods and services, thereby reinforcing transparency and trust in business arrangements between organizations. In the highways sector, a handful of companies, such as Indra and Iota, have developed blockchain applications, albeit limited to specific routes. This article introduces a decentralized public blockchain payment model that involves various organizations operating on highway lanes. The Liquid blockchain emerges as a promising solution, addressing the need for swift transactions with low fees and ensuring a trustworthy exchange of monetary transfers among companies, retailers with stores on highways, and customers.

3.1 Introduction

The development of a country's transportation infrastructure has historically paralleled periods of rapid economic growth (Duranton et al., 2014; Hasselgren, 2018; Heintz et al., 2009; Zhang and Cheng, 2023). However, economic growth is not solely dependent on infrastructure; technological innovation also plays a crucial role. While traditional infrastructure comprises surface roads, bridges, railways, and terminals, a contemporary perspective considers the physical networks facilitating the flow of vehicles, people, information, and money Tiffin (2007). Blockchain emerges as a revolutionary method to connect people, roadway agencies, and infrastructures.

The recent development of fifth-generation communication technology (5G), which leverages the Internet of Things (IoT), allows a large number of sensors to establish communications between vehicles and infrastructure devices, as well as other networked devices.

In many countries, the costs of maintaining highways roads (including – but not limited to – for example, highway lines, bridges, and tunnels) are covered by the collection of toll payments from their users. Blockchain technology can be used in traffic signal control mechanisms, traffic flow forecasts, and traffic information systems in the transportation field (Astarita et al., 2020; Fujihara, 2018, 2020; Li et al., 2019). Real-time toll collection through electronic toll collection (ETC) allows low latency, improves the user's quality of experience (QoE), and fewer queue-buildups at the Intelligent Toll Gates (ITGs). However, it suffers from problems of security, privacy, and location-based attacks on customers' sensitive data, especially in possible Internet-of-Vehicles (IoV) ecosystems (Shukla et al., 2020). Blockchains can face these problems and offer workable solutions.

Blockchains are distributed ledgers that work in a decentralized manner enabling direct transactions between users without dependence on centralized actors while providing transparency, persistency, security, and data privacy guarantees. Moreover, they offer an elevated level of cyber security. Blockchains enable and realize the so-called ”smart contracts”, which are protocols (i.e., computer communication rules) that allow transactions to take place credibly without significant intervention of third parties. We argue that, based on these features, the open-source protocols and smart contracts driven by blockchains enable a transparent and immediate profit distribution among multiple highway companies, and offer edge service providers independence from a central authority. Compared to currently implemented and deployed systems, we claim that blockchain technology offers features for data security, openness, and transparency that are not present in commonly used database systems today. Therefore, the research questions are as follows:

1. How could blockchain technology be effectively adopted in a highway toll collection system?
2. Is decentralized technology suitable for a highway toll architecture?
3. What could the architecture of a highway toll system utilizing blockchain technology be like?

4. Is using blockchain technology in a highway toll system justified and convenient in economic terms?

To provide answers to these questions, the key issues to investigate are the eco-system of a road tolling system: what actors participate in such an ecosystem, what kinds of equipment are applied, and what kind of data is generated and transferred in the system. The novelty of this work is a model of a unique blockchain-integrated system of payments between different actors: highway concession companies, vehicle drivers, retail companies that have stores on the lines of the highway, and possible intermediaries in collecting and redistributing toll fees (i.e., "Telepass" Company in Italy).

The few articles that investigate the application of a blockchain payment system in toll collection adopt blockchains that lack the capability and efficiency to function as versatile operating systems able to support the multiple applications needed in a broad commercial setting. This work, different from the main literature, finds a solution in the adoption of a Liquid blockchain, a sidechain that is public, decentralized, and similar to a federated blockchain.

A federated blockchain, also known as a consortium blockchain, is a type of blockchain network that is jointly maintained and governed by a group of organizations or entities. Unlike public blockchains where anyone can participate, a federated blockchain restricts access to a predetermined set of trusted participants. These participants, often forming a consortium, work together to validate and confirm transactions, ensuring a more controlled and private environment compared to public blockchains. The collaborative governance structure allows for increased efficiency, scalability, and tailored consensus mechanisms suitable for specific use cases.

The Liquid Network is a sidechain project developed by "Blockstream", designed to enhance the functionality of the Bitcoin blockchain. A sidechain is a layer two solution for Bitcoin. This is a secondary set of protocols or a mechanism built on top of the existing Bitcoin blockchain system to address scalability issues and to faster and cheaper Bitcoin transactions. Users initiate the process by sending bitcoins to a special address on the main Bitcoin blockchain. This process is known as ”locking” bitcoins. Once the bitcoins are locked on the main chain, they become temporarily inactive on the Bitcoin blockchain. Simultaneously, a corresponding amount of a sidechain’s native asset (e.g., Liquid Bitcoin or other tokens) is generated on the sidechain. Users can now transact with the native assets on the sidechain. These transactions are typically faster and may include additional features not available on the main Bitcoin blockchain.

When users want to move assets back to the main Bitcoin blockchain, they initiate a process called ”peg-out.” The native assets on the sidechain are locked, and an equivalent amount of bitcoins is released on the main chain. This system does not require a hard fork or alteration of the fundamental rules of the main Bitcoin blockchain. Even if, like other sidechains, it does not require changes to the underlying Bitcoin protocol, it develops its own changes in terms of additional protocols and mechanisms to enable the interaction between the main Bitcoin blockchain and the sidechain.

The Liquid sidechain enhances confidential transactions because the amounts and types of assets in transactions are encrypted such that only the sender and the recipient can see them. In the Liquid Network, a federation of functionaries (known as the Liquid Federation) is responsible for maintaining the sidechain. Transactions are validated between 2.5 minutes with a ”zero proof knowledge”.

Instead of relying on the costly decentralized proof-of-work (PoW) consensus used in the Bitcoin blockchain, the Liquid Network employs a federation of functionaries for consensus. This federation is a group of trusted entities or independent companies selected to validate transactions. The federated functionaries collect digital signatures from each other, indicating their consensus on the validity of the transaction. They apply dedicated cryptographic tools and highly secure functionary hardware called ”Liquid functionary” to sign blocks and secure their private keys. With their signature, they can validate transactions and create new blocks. A predefined threshold of signatures, known as a quorum (a two-thirds majority between functionaries), is required for a transaction to be considered valid. Once the quorum is reached, a new block is created, and the validated transactions are included in that block. Only after a transaction is included in a block and committed by the federation, it is considered final and cannot be reversed. The Liquid Network not only facilitates efficient and confidential transactions but also supports the creation and transfer of various digital assets. One such asset class that has gained significant attention is Non-Fungible Tokens (NFTs). Unlike traditional cryptocurrencies, NFTs represent unique digital items, making them particularly valuable for applications that require distinct identifiers, such as digital art or property rights. In the following section, we explore how the Liquid Network enables the secure and private transfer of these non-fungible assets, further broadening its utility beyond simple monetary transactions

The Liquid Network allows users to create and transfer not only cryptocurrencies or digital money but also other assets confidentially, like stablecoins, native tokens assets that users can create, or Non-Fungible Tokens (NFTs). ”Non-fungible” means something unique and can’t be replaced. NFTs are a type of digital asset that represents a property right or a proof of authenticity of artworks or photos, videos, audio files, virtual real estate, and other digital formats or pieces of them. Ownership is recorded on the blockchain. Each NFT is distinct and has unique attributes or information that differentiate it from other tokens. They are cryptographic assets that use blockchain technology, often on platforms like Bitcoin, Ethereum, or other blockchain networks, to provide a transparent and secure way of verifying ownership and authenticity. Their ownership and authenticity are recorded on the blockchain and NFTs cannot be divided into smaller units like cryptocurrencies and as whole tokens. However, they can be traded on the blockchain.

Highway companies may need to store data not necessarily of a financial nature. This choice excludes the adoption of blockchains like Iota[1]. The need for higher transparency

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[1] Iota is a decentralized, open-source distributed ledger technology specifically designed for the Internet of Things and focused on feeless microtransactions. This technology is known as Tangle. The complexity of the Tangle does not allow, until now, user-friendly interfaces and tools. IOTA has experienced security-related incidents in the past. For example, in 2017, it was subjected to a vulnerability related to the use of the Curl hashing function.

excludes the adoption of private blockchains like Hyperledger[2] and Corda[3] widely used in the literature.

In comparison, Bitcoin is completely public and decentralized, however, it offers many similarities to a software application with high fees and scalability problems. Ethereum blockchains continue to demonstrate many characteristics of an operating system, such as the ability to program smart contracts and the provisions of a programming language. However, Ethereum blockchains show insufficient system interfaces, lack customization in some modules and are not synchronized with normal computers.

Finally, this article is new to the proposal of a blockchain payment system for Italian highways. The next step would be to examine why this blockchain technology would offer the best services in terms of these requirements, and what properties are desired to develop an efficient electronic toll payment system for highways.

This paper is organized as follows: in Section 3.2 we describe the relevant literature, in Section 3.3 we offer an overview of the economic model employed, in Section 3.4 we present the payment methods, in Section 3.5 we describe the Telepass and Italian Highways system, in Section 3.6 we extensively describe the implementation of the proposed blockchain model, Section 3.7 reports our main results, and in Section 3.8 we draw our conclusions.

3.2 Literature Review

Blockchain technology has emerged as a promising solution for improving the efficiency and security of Electronic Toll Collection (ETC) systems. In China, Huang et al. (2021) developed a decentralized framework aimed at mitigating attacks that threaten traditional ETC systems, offering a secure and scalable way to trace transactions. Similarly, Ying et al. (2020) designed a blockchain-based toll collection paradigm for autonomous vehicle

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[2] An open-source collaborative project under the Linux Foundation where people can come and work on the platform to develop blockchain technologies that are not pubblic

[3] Corda is not a traditional public blockchain but rather a distributed ledger technology(DLT)designed to address the specific needs of the financial sector. Corda is often implemented in private or consortium settings. The access to the network is controlled, and participants are known entities.

platoons within intelligent transportation systems. This platform ensures that only trusted vehicles can participate, enhancing the reliability and reducing the time required for toll collection.

Xiao et al. (2019) extended these ideas by proposing a blockchain-based toll system that reduces transaction costs and times, while also accelerating the adoption of the Internet of Things (IoT). Their system offloads computational tasks from the cloud to the network edge, using an off-chain instant payment protocol to bypass the need for Ethereum's energy-intensive proof-of-work process. This reduces gas fees and transaction times, making the system more efficient.

Further improvements to toll systems using blockchain include the Blockchain-based Automated Toll-Tax Collection System (BATCS) presented by Das et al. (2022), which uses smart contracts to collect tolls without stopping vehicles. This solution ensures transparency, trust, and privacy in ETC transactions. Soner et al. (2021) also demonstrated how blockchain could enhance toll security, protect personal information, and maintain participant anonymity.

In Mexico, the Indra company[4] developed a blockchain-based toll payment system for the Monterrey-Saltillo highway. Their solution, based on the Quorum platform, focuses on transaction integrity, operator clearing, and fraud control. Quorum's permissioned blockchain model provides a more private and secure system compared to public blockchains like Ethereum.

Blockchain is also being leveraged for loyalty programs, as shown by Sönmeztürk et al. (2020), who introduced Ethereum-based tokens that can be converted into Ether. Agrawal et al. (2018) highlighted the versatility of these tokens for business promotions, demonstrating their exchangeability across customers and industries, further showcasing blockchain's potential beyond ETC.

Building on the advancements of blockchain in Electronic Toll Collection (ETC) systems, we now turn to the economic implications of implementing blockchain technology

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[4] https://www.indracompany.com

within toll systems. While blockchain has shown promise in enhancing efficiency and security across various case studies, understanding the economic feasibility and potential transaction cost reductions is critical. To explore these aspects, we introduce a simplified toll collection model that incorporates blockchain's cost advantages.

3.3 The Model

In this section, we introduce a simplified toll collection economic model. Consider a route consisting of multiple links, each managed by a distinct operator. The travel demand and supply volumes are assumed to be influenced by the monetary transaction costs associated with using the highway. Importantly, this model excludes the presence of public financing or financial support to alleviate toll fees. The underlying cost structure follows the framework proposed by de Rus and Romero (2004), with the incorporation of monetary transaction costs.

3.3.1 Highways demand

A simplified demand function for highways can be expressed as

$$q_{i,j} = a_{i,j} - b_{i,j}\ \tau_{i,j} - TTC_{i,j} \tag{3.1}$$

where $q_{i,j}$ is the number of vehicles at a certain instant of time on the highway i. j is an index that identifies vehicles, $a_{i,j} > 0$ is a constant, $\tau_{i,j}$ is the toll rate charged on entrance of highway i for the vehicle j, and $TTC_{i,j}$ is the travel time cost on highway i for vehicle j . Variants of the above expression have been presented in linear and non-linear forms by (Board et al., 2012; Gousios et al., 2007). Equation (3.1) takes into account two basic factors that determine the demand. These are the toll rate charged and the travel time cost. However, it does not take into account other significant factors such as traffic conditions, and transaction costs when paying tolls with credit cards. We expand term TTC of (3.1) as a function of travel time and cost related to traffic conditions. Thus, we express TTC explicitly as:

$$TTC_{i,j} = d_{i,j}T_{i,j} + \gamma_{i,j}\ q_{i,j} \tag{3.2}$$

where $d_{i,j}$ is a constant parameter, $T_{i,j}$ is the travel time, and $\gamma_{i,j}\ q_{i,j}$ measures the cost related to traffic conditions which depend on the number of vehicles ($q_{i,j}$. If we sum over j the equation (3.4), it is possible to obtain the average daily traffic in highway section i. We consider $0 \leq \gamma_{i,j} \leq 1$ and $T_{i,j} \geq 0$.

Incorporating a monetary transaction cost into our demand and supply functions, we aim to highlight the potential reduction in transaction costs facilitated by blockchain technology, which minimizes reliance on centralized institutions. Chen and Bellavitis (2019) emphasized that centralized payment networks, such as Visa, Mastercard, and PayPal, often impose relatively high fees for their services.

Various fees are typically associated with each transaction within centralized payment systems, with costs varying depending on the type of credit card accepted. Merchants accepting credit card payments must handle interchange fees, assessment fees, and processing fees, which are distributed to the card's issuing bank, the card's payment network, and the payment processor. These fees collectively constitute processing fees. Forbes reports that per-transaction fees can range from 0.18% plus 0.10 to 0.50% plus 0.10 (Forbes, 2023). Debit card payments also incur fees, typically lower than credit card fees. In some instances, businesses may pass these fees to consumers through surcharges to offset their additional costs.

According to Coingate, merchants accepting blockchain-based payments through a reliable provider may incur processing costs of not more than 1%, significantly lower than credit card processing fees (Coingate, 2023). Blockchain technology also enables cross-border payments without exchange rate fees.

In the traditional cross-border payment landscape, a payment from abroad could take 3-4 days, passing through multiple intermediaries and incurring extra fees before reaching the final highway company's current account. For MasterCard and Visa, the international transaction credit card fee is 1%, while other payment networks usually charge between 2% and 3% of the transaction amount. British residents face fees ranging from 1.15% to 1.5%, according to the U.K. Payment System Regulator (Payment System Regulator, 2023).

Therefore, we express the monetary transaction cost associated with using highways as a significant consideration in evaluating the potential advantages offered by blockchain technology as

$$MTC = f_{i,j}\ g_{i,j}\ m_{i,j} \tag{3.3}$$

where $f_{i,j})$ is a positive constant, $m_{i,j}$ is the number of vehicle j's monetary transactions during the travel on highway i, and $g_{i,j}$ is the unitary fee on monetary transactions faced by vehicle j on highway i.

Our demand function for highway travel taking into consideration the expanded travel time cost and the additional monetary transaction cost is given by:

$$q_{i,j} = a_{i,j} - b_{i,j}\ \tau_{i,j} - d_{i,j}T_{i,j} - \gamma_{i,j}\ q_{i,j} - f_{i,j}\ g_{i,j}\ m_{i,j} \tag{3.4}$$

By aggregating (3.4) for vehicle j, we obtain the following:

$$q_i = A_i - b_i\ \tau_i - d_i\ T_i - \gamma_i\ q_i - f_i\ g_i\ M_i \tag{3.5}$$

where $A_i = \sum_j a_{i,j}$ reflects the aggregate demand for highway i that would be present if there was no toll rate imposed and no monetary transaction fees and b depicts the sensitivity of the toll rate to demand. $M_i = \sum_j m_{i,j}$ is the aggregate number of monetary transactions for vehicles running highway i. Rearranging the terms in (3.5) gives

$$q_i = \frac{A_i}{1+\gamma_i} - \frac{b_i}{1+\gamma_i}\ \tau_i - \frac{d_i}{1+\gamma_i} T_i - \frac{f_i}{1+\gamma_i}\ g_i\ M_i \tag{3.6}$$

Consumption is affected by prices and the direct perceived costs of using a good. The term is usually limited to monetary costs but can also include non-monetary factors. For example, the price of highway travel includes the toll amount and fees associated with the payment method but also driving time on highway lines and perceived risks associated with congestion. Factors such as discomfort and perceived risk due to traffic on the carriageways can be incorporated into the driver travel unit cost or the willingness to pay off the marginal road user. Under stationary traffic conditions, homogeneous drivers face an aggregate inverse demand function in highway section i given by

$$\tau_i = \frac{A_i}{b_i} - \frac{1+\gamma_i}{b_i}\ q_i - \frac{d_i}{b_i} T_i - \frac{f_i}{b_i}\ g_i\ M_i \tag{3.7}$$

The toll and monetary transaction fee elasticities on traffic demand are respectively given by:

$$\eta_{\tau}^{q} = \frac{dq_i}{d\tau_i}\ \frac{\tau_i}{q_i} = -\frac{b_i}{1+\gamma_i}\ \frac{\tau_i}{q_i} \tag{3.8}$$

$$\eta_{M}^{q} = \frac{dq_i}{dM_i}\ \frac{M_i}{q_i} = -\frac{f_i}{1+\gamma_i}\ g_i\ \frac{M_i}{q_i} \tag{3.9}$$

Optimal road pricing

In this simplified model there are N highways companies. Each company manages one highway segment of the country highway network and maximizes its profit as a monopolistic producer of travel. All the companies are price makers. In equilibrium, the travel demand equals travel supply in each highway segment market. Each segment has q_i travels demand or users. Each driver travels the same distance in an identical vehicle but has a different willingness to pay for the trip. Each highway company maximizes its profit by the difference between its total toll revenue and its costs. To produce travel services each company has an identical technology and production function.

$$z_i = A\ K_i^{\alpha}\ I_i^{\nu}\ \overline{L}_i^{1-\alpha} \tag{3.10}$$

where $\alpha + \nu > 1$ and $0 < \alpha < 1$. To simplify the labor supply is perfectly elastic and the labor demand is fixed to $\overline{L_i}$. K_i is the total capital invested in road capacity and I_i is the total Information Technology (IT) capital needed for the ETC. There are increasing returns to scale total capital invested in road capacity and IT capital. There are no alternative uses of capital. Capital can not be borrowed or rented. In equilibrium, each travel demand function equals the travel supply.

$$z_i^* = q_i^* \tag{3.11}$$

The annual total cost of segment i is the sum of the costs of gathering the tolls for the road owner (firm i) and the infrastructure cost. It can be expressed as:

$$TC_i(\tau) = K_i\ CFI(K)_i + \delta_i\ q_i + I_i\ CFI(I)_i + \psi_i\ \mu_i\ q_i \tag{3.12}$$

The highway i infrastructure costs are equal to all the infrastructure fixed costs per year $CFI(K)_i$ times the units of road capacity (K_i). $CFI(K)_i$ includes construction costs, fixed maintenance, and operating costs. The other cost component $\delta_i\ q_i$ is a cost variable with traffic flows and it is the result of multiplying the number of vehicles by the operating costs per vehicle (δ_i). The IT infrastructure costs are equal to all the infrastructure fixed costs per year $CFI(I)_i$ times the units of digital network capacity (I_i). To simplify we assume that IT-impaired capital is immediately replaced so that its deterioration rate is negligible. The other component is a monetary cost variable with the number of transaction fees paid on each payment received by each vehicle and it is the result of multiplying the number of vehicles by the payment system operating costs per vehicle (μ_i).

Road owners (operators-i) attempt to maximize their profit (π_i), which is the sum of the tolls gathered from the segments or the links of their road, minus the costs of gathering the tolls ($CFI(I)_i$) for road owner (firm i) and the infrastructure cost. Each highway company manages just one link of a highway route. Each company maximizes its profit function for toll amount, and infrastructure cost. The company profit function is given by the following equation:

$$\begin{aligned}\pi_i &= \tau_i\ q_i - TC_i \\ &= \tau_i\ q_i - K_i\ CFI(K)_i - \delta_i\ q_i - I_i\ CFI(I)_i - \psi_i\ \mu_i\ q_i \\ &= (\tau_i - \delta_i - \psi_i\ \mu_i)\ q_i - K_i\ CFI(K)_i - I_i\ CFI(I)_i\end{aligned} \tag{3.13}$$

The optimal solutions can be found by solving the following Lagrangian:

$$\begin{aligned}\Lambda_i = (\tau_i - \delta_i - \psi_i\ \mu_i)\ q_i - K_i\ CFI(K)_i - I_i\ CFI(I)_i + \\ \lambda\ (A\ K_i^{\alpha}\ I_i^{\nu}(I)\ \overline{L_i}^{1-\alpha} - q_i)\end{aligned} \tag{3.14}$$

First-order conditions yield:

$$\frac{\partial \Lambda_i}{\partial q_i} = (\tau_i - \delta_i - \psi_i\ \mu_i) + \frac{\partial \tau_i}{\partial q_i}\ q_i - \lambda = 0 \tag{3.15}$$

Given $\frac{\partial \tau_i}{\partial q_i} = -\frac{1+\gamma_i}{b_i}$, after some simple calculus (3.15) can be written as

$$(\tau_i - \delta_i - \psi_i\ \mu_i) - \frac{1+\gamma_i}{b_i}\ q_i^* - \lambda = 0 \tag{3.16}$$

Rearranging the terms in the previous equation gives

$$q_i^* = \frac{b_i}{1+\gamma_i}\ (\tau_i - \delta_i - \psi_i\ \mu_i - \lambda) \tag{3.17}$$

The capital first-order condition is the following:

$$\frac{\partial \Lambda_i}{\partial K_i} = CFI(K)_i + \lambda\ \frac{\partial z_i}{\partial K_i} = 0 \tag{3.18}$$

where $\dfrac{\partial z_i}{\partial K_i} = \alpha\ A\ K_i^{\alpha-1}\ I_i^{\nu}(M)\ \overline{L}_i^{1-\alpha}$ is the marginal product of capital. At equilibrium

$\frac{\partial z_i}{\partial K_i} = \frac{\partial q_i}{\partial K_i} = \alpha \; \frac{q_i^*}{K_i}$. Thus, the first capital order condition can be written as

$$CFI(K) = -\lambda \; \alpha \; \frac{q_i^*}{K_i} \tag{3.19}$$

It is possible to rewrite this condition as

$$\lambda = \frac{CFI(K)_i \; K_i}{\alpha \; q_i} = \frac{AFCK_i}{\alpha} \tag{3.20}$$

In the last expression, AFCK is the average fixed cost of physical capital or road capacity. Under equilibrium condition

$$q_i^* = \frac{b_i}{1+\gamma_i} \; \left(\tau_i - \delta_i - \psi_i \; \mu_i - \frac{AFCK_i}{\alpha}\right) \tag{3.21}$$

This condition states that the firm will set its optimal toll taking into account congestion (γ_i), the travel demand, and the marginal costs of its physical and technological infrastructure. A more efficient ETC could decrease the parameter ψ. A cost reduction in the payments system can favor a reduction in highway tolls. Given that q_i^* is the optimal demand of highway travels after some computing it is possible to rewrite the optimal toll level as

$$\tau_i^* = \frac{A_i}{2b_i} + \frac{1}{2}\left(\delta_i + \psi_i \; \mu_i + \frac{AFCK_i}{\alpha}\right) - \frac{d_i}{2b_i}T_i - \frac{f_i}{2b_i} \; g_i \; M_i \tag{3.22}$$

Equation (3.22) underlines that a reduction in the customers' payment fee can increase the highway travel demand and for this reason, can raise the toll level that companies apply even if for very negligible amounts. Finally, the first order condition on IT investment is the following

$$\frac{\partial \Lambda_i}{\partial I_i} = CFI(I)_i + \lambda \; \frac{\partial q_i}{\partial I_i} = 0 \tag{3.23}$$

The first-order condition on IT capital can be rewritten as

$$CFI(I) = -\lambda \, \frac{\partial q_i}{\partial K_i} \tag{3.24}$$

From the last expression, indicating with MPI the marginal product of IT capital it is possible to write

$$-\lambda = \frac{CFI(I)_i}{MPI_i} \tag{3.25}$$

After some manipulation, it is possible to get

$$\frac{CFI(I)_i}{MPI_i} = \frac{CFI(K)_i}{MPK_i} \tag{3.26}$$

Rearranging these terms

$$\frac{CFI(I)_i}{CFI(K)_i} = \frac{MPI_i}{MP(K)_i} \tag{3.27}$$

In equilibrium, the ratio between the marginal product of physical and IT capital should be equal to the ratio of their marginal costs.

In a more general parametric form, setting the following parameters $\beta_0 = \frac{A}{2b_i} + \frac{\delta_i}{2}$, $\beta_1 = \frac{1}{2}$,$\beta_2 = \frac{1}{2\alpha}$,$\beta_3 = -\frac{d_i}{2(1+\gamma_i)}$,$\beta_4 = -\frac{f_i}{2(1+\gamma_i)}$, the last one can be written as

$$\tau_i^* = \beta_0 + \beta_1 \; \psi_i \; \mu_i + \beta_2 \; AFCK_i + \beta_3 \; T_i + \beta_4 \; g_i \; M_i \tag{3.28}$$

Let us define $FC = \psi_i \; \mu_i$ as the firm's financial cost of each monetary transaction,$TFC = \psi_i \; \mu_i \; q_i$ as the total financial cost of all transactions, the average financial transactions cost for the company i is given $AFTC = \frac{\psi_i \; \mu_i}{q_i} \; q_i$ An alternative way to write the previous formula is the following:

$$\tau_i^* = \beta_0 + \beta_1 \; AFTC_i + \beta_2 \; AFCK_i + \beta_3 \; T_i + \beta_4 \; g_i \; M_i \tag{3.29}$$

The high costs associated with electronic toll collection (ETC) for vehicles have the potential to limit individuals' financial flexibility. When electronic payment fees are introduced, individuals may find it more advantageous to avoid these additional charges by opting for cash payments using low-fee digital cards, or even reducing their highway usage.

For individuals with extensive commutes or frequent toll road usage, cumulative toll expenses can significantly accrue over time, and elevated electronic payment fees only amplify these costs. Moreover, when the expenses tied to electronic vehicle payments are already considerable, the additional toll expenses can exacerbate the overall financial outlay for transportation. In such scenarios, the demand for highway travel may decrease, logically leading to a decrease in the equilibrium toll amount. In specific cases, the cost of using highways could be marginally higher for credit card users, factoring in fees imposed by credit card companies.

Toll systems commonly offer various payment alternatives, including credit cards, debit cards, and other rechargeable digital cards through electronic toll collection systems like RFID (Radio Frequency Identification) transponders. Each payment method could incur distinct processing charges.

If the charges associated with credit card usage are higher compared to alternative payment methods, toll authorities may implement measures to encourage users to opt for lower-fee options. This might involve adjusting toll rates proportionally or negotiating with credit card companies to secure reduced transaction fees, potentially based on transaction volume or other pertinent factors. Reduced fees could result in a less pronounced impact on the overall travel expenses for credit card users.

In certain cases, toll authorities might choose to transparently present credit card processing fees as a separate component during the payment procedure. This practice aims to inform users about the itemized breakdown of the total cost, enabling them to make well-informed decisions regarding their preferred payment mechanism.

Furthermore, highways incur costs for the banking services they utilize to manage the financial aspects of projects and ensure efficient cash flow management. These services may include automated clearing house (ACH) transfers, wire transfers, and electronic funds transfers, collectively falling under the category of "Cash Management Services." There are also costs related to "Merchant Services" if the highway company collects tolls electronically, using services provided by banks to process credit card transactions and manage electronic payments. These services typically come with processing fees. Additionally, there are costs associated with "Foreign Exchange Services" that banks provide when dealing with foreign currencies, involving currency conversion fees and foreign exchange rate spreads. A blockchain payment system has the potential to reduce these financial costs for highway companies.

Highway companies may incur various types of fees paid to banks and financial institutions based on their financial arrangements and needs, which can impact the toll amount.

3.4 Payment Methods

The issue closely tied to scalability is the enormous dependence of blockchain on computing power and, consequently, electricity. In 2022, the average energy consumption for a single Bitcoin transaction could equal several hundreds of thousands of VISA and Mastercard transactions. According to Statista (2022), one VISA transaction consumes about 0.0014863 kWh of electricity on average. In comparison, Digiconomist estimates that one Bitcoin transaction takes 1418.05 kWh to complete. This is equivalent to approximately 48.60 days of power for the average U.S. household.

The energy consumption figures for Mastercard also show a significant contrast. One Mastercard transaction consumes about 0.0007 kWh according to the Mastercard sustainability report in 2017 and Digiconomist (2022). In contrast, Bitcoin uses 550,000 times as much electricity per transaction as Visa, according to Digiconomist.

For a more detailed comparison, Coinbase states that a single Bitcoin transaction requires 1719.51 kWh, equivalent to about 59 days' worth of power consumed by an average U.S. household. On average, 240,000 Bitcoin transactions are sent over the network each day. In comparison, one Ethereum transaction takes 0.02591 kWh to complete, according to Digiconomist (2022). This is more than 42 times the energy consumption of Mastercard and 20 times that of Visa.

The Solana network, as of March 2022, published its energy consumption per transaction as 2,707 Joules, equivalent to 0.0007519444 kWh.

Iota, according to its blog, estimates an energy consumption per transaction of approximately 0.00018 kWh, making it 10 times more efficient than Visa/Mastercard.

These figures highlight the varying energy efficiency of different blockchain networks.

In summary, the energy consumption per transaction for various cryptocurrencies is as follows:

- Bitcoin: 1775 kWh
- Visa/Mastercard (100,000 transactions): 170 kWh
- Solana (100,000 transactions): 75 kWh
- Iota (100,000 transactions): 11 kWh

All cryptocurrencies significantly reduce payment processing costs, which can reach up to 3-4% for every purchase with traditional methods. Credit card processing costs depend on the merchant services provider, with monthly fees ranging from €10.07 to €20.24. Per transaction fees for Visa and Mastercard can range from 1.15% plus €0.05 to 2.40% plus €0.10. Cryptocurrencies offer a cheaper alternative and reduce the risk of credit card fraud.

When comparing cryptocurrencies to credit cards, critics often highlight disparities in processing speeds. Credit card transactions involve multiple intermediaries and take several days to authorize and clear the payment. In contrast, cryptocurrency transactions completed in 10 minutes or less, providing funds directly to the merchant's wallet. The following tables provide a summary of these transaction costs and processing times:

Blockstream's Liquid Network is a sidechain created over its Elements Blockchain, expanding the capabilities of Bitcoin by allowing the creation of new digital assets, including

Cryptocurrency	Energy Consumption per Transaction (kWh)
Bitcoin	1775
Ethereum	0.02591
Solana (estimate)	0.0007519444
Iota (estimate)	0.00018

Table 3.1: Energy Consumption per Transaction (kWh)

Payment Method	**Transaction Fee**
Bitcoin	Typically ranges from $1 to $5, depending on network congestion
Ethereum (Gas Fee)	Typically ranges from $0.20 to $50, depending on network congestion
L-BTC (Liquid Bitcoin)	0.00021 L-BTC per transaction
Visa Debit Card	0.05% + €0.21 (regulated), 0.8% + €0.14 (unregulated)
Mastercard Debit Card	0.05% + €0.21 (regulated), 1.05% + €0.21 (unregulated)
Visa Credit Card	1.15% + €0.05 to 2.40% + €0.10
Mastercard Credit Card	1.15% + €0.05 to 2.50% + €0.10

Table 3.2: Comparison of Transaction Fees for Bitcoin, Ethereum, L-BTC, and Debit/Credit Cards per Transaction.

	Payments methods							
	Cash	VISA	Mastercard	BTC	ETH	SOL	IOTA	LBTC
Waiting time at tollgate (Sec.)	30-60	20-40	20-40	2-3	2-3	2-3	2-3	2-3
Energy Consum.	0	0.0015	0.0007	1775.38	0.03	0.00075	0.00016	-
Fees on One Transactions (€)	0	1.15%-2.4%	1.15% - 2.5%	0.6901	0.7955	0.00025	feeless	0.00021
Transactions per Seconds	1	24,000	5,000	3-7	9	4,109	1000	7-10

Table 3.3: Comparison between payment systems

NFTs. It is considered Layer 2 as it builds upon Bitcoin Core. The Liquid Network includes assets like stablecoins (e.g., USDT) and connects to the Lightning Network. Governance is through votes by Federation Members, a group including exchanges, wallets, and other Bitcoin service providers. There are 15 Liquid functionaries with signing authority, responsible for the two-way pegging facility. The Liquid Network has its token, Liquid Bitcoin (L-BTC), backed 1:1 with BTC. Conversion between BTC and L-BTC occurs through peg-ins and peg-outs, involving the Liquid Federation. L-BTC transactions are confirmed in 2 blocks, and fees are paid in L-BTC.

Element is an open-source blockchain-based sidechain designed for Bitcoin development. The Liquid Network is built on Elements, and its sidechain model consumes less energy compared to Bitcoin's proof-of-work. The Liquid Network's functionaries maintain its security without relying on proof-of-work or proof-of-stake. L-BTC operates like a BTC-backed stablecoin.

The introduction of the Liquid Network sidechain in October 2018 contributed to reduced energy consumption and volatility in Bitcoin, according to Bouoiyour et al. (2019). Bitcoin miners earn transaction fees, and similarly, Liquid requires fees to mine blocks. Enterprise-focused platforms, unlike Elements Blockchain, often avoid Bitcoin's proof-of-work due to its slowness and expense. Sidechains process numerous transactions without affecting the parent chain's decentralization. Liquid enables faster transactions than Bitcoin, with a higher block production frequency, leading to greater overall transaction throughput.

In the context of toll collection, traditional cash payments can have significant waiting times, such as 3 to 8 minutes in India Chauhan and Chauhan (2022). Electronic toll collection (ETC) systems dramatically reduce waiting times. For instance, in India, ETC systems require only 18 seconds, significantly faster than manual payments. Similarly, in Jakarta, ETC systems reduced transaction times from 5-6 seconds with cash to 4 seconds Karsaman et al. (2014). Electronic toll collection systems like Telepass in Italy have transaction times as low as 2-3 seconds Collura (1993). These examples showcase the efficiency gains of electronic systems in toll collection.

3.5 Telepass and Italian Highways

The Italian toll road system, particularly on the A36 Pedemontana Lombarda motorway, utilizes the Telepass electronic toll collection system. Telepass is a DSRC (Dedicated Short-Range Communication) technology that involves a transponder (On Board Unit - OBU) mounted on the vehicle's windshield, communicating wirelessly with a beacon (called BOA) at the toll gate. The system operates with an optical recognition system (CTV) that identifies the vehicle type and sends a signal to activate the BOA.

As a vehicle equipped with Telepass passes through the toll gate, the BOA receives information from the transponder, including details about the vehicle such as its type, axles, weight, and potentially other factors. Each toll gate manages transits automatically, maintains communication with the on-board terminal, and sends vehicle data to a database. The toll amount is then charged based on the length and weight of the vehicle, the number of axles, and other relevant factors.

The toll is deducted automatically from the vehicle owner's account after identifying ownership through the transmitted signal from the OBU. However, in some cases, tolls may not be paid, such as when a driver leaves the toll road without paying. Unpaid tolls can be settled at subsequent toll gates or through online payment.

To avoid issues related to payment failures or disputes, drivers can take a ticket when entering the Autostrada network. Inserting the ticket into a machine upon exit allows the driver to know the amount due. Toll companies may check photos of the vehicle entering the autostrada, along with data like the license plate number, date, and time of entry, and the ticket received at the exit. Disputes may arise if the photo is unclear or if ticket details are missing.

In Italy, the toll road network extends over approximately 7,000 km, with a significant portion managed by state-owned and private enterprises. Two major groups, the Gavio

Group and the Atlantia Group (owned by the Benetton family), control a substantial percentage of the toll road network. The toll collection system with DSRC is a common feature in many European countries that operate toll roads, ensuring efficient and automated toll payment processes.

3.6 Implementation

Consider a hypothetical scenario where drivers plan journeys from Lake Como to Milan and from Milan to Trieste. Notably, no toll stations are present before entering the ”Autostrada” due to the absence of toll booths on the ”Pedemontana.” Instead, drivers receive notifications later, capturing the toll amount through photos of their license plates. Verification of the toll payment occurs when the driver receives a credit card statement much after the trip concludes.

The Pedemontana captures vehicle data at gantries, transmitting them to a central system for processing. However, potential weaknesses lie in the video system’s success rate, affected by weather conditions and trust issues in the toll company’s accuracy.

From Milan, the same car covers 266 km on A4, incurring a toll of €51.96. Toll payments vary across highway management companies along the route. For instance, from Milano to Brescia, the toll will be paid to Autostrade per l’Italia, from Brescia to Padua, the toll is paid to Autostrada Brescia Verona Vicenza Padova, from Padua to Venice to Concessioni Autostradali Venete, and from Venice to Trieste to Autovie Venete. Along one route the highway management company changes, and this is not noticed by drivers except thanks to the vertical signs on the carriageway. At the end of the travel, the car driver will pay a unique toll.

The total toll amount collected is redistributed between companies according to the number and type of vehicles that pass on each highway section. The Electronic Fee Collection (EFC) in Italy is managed by Telepass. Vehicle data are collected by Telepass 3G OBU to the information center. The information center processes and elaborates data to detect payments, vehicle features, and positions with the help of satellite information. ETC is a part of Intelligent Transportation Systems (ITS), which are systems that use electronics, communications, and information processing to improve the efficiency and safety of surface transportation.

A typical ETC system includes a settlement center that conducts the calculation of what is due by travelers and allows bank transfers to the highway company to which the toll gate belongs. In the case of Italy, all is managed by Telepass. Toll data is transmitted from toll booths to the settlement center that processes them, computes how much is due to the companies managing the motorway lanes, and asks a clearing bank to transfer money to each highway company of the Telepass network. The entire process requires time and a clearing institution that is paid for its service. Telepass takes about a month to credit the respective revenues to the companies that manage the highway lanes.

The main disadvantage of this form of settlement is the settlement risk as well as the counterparty risk: the ETC can lose data or make mistakes if the detection mechanisms do not work well. If there are mistakes or malfunctions, the parties involved in the transactions, which are customers or other highway companies, may incur substantial financial losses. Blockchain allows directly transferring drivers' payments to the corresponding highway company, ensuring data safety and reliability. Moreover, eliminating the need for a clearing entity, blockchain reduces transaction costs, making the entire settlement process more efficient.

This work proposes, like in the traditional Telepass mechanism, an on-board unit (OBU) installed on vehicles and a roadside unit (RSU) installed on toll gates. The decentralization of the blockchain eliminates the need for a centralized ETC. A decentralized blockchain underlying platform is shared between users. There are four categories of users: Highway Companies, Payment Card Issuing Companies, Merchandise Companies, and Vehicles.

To simplify, we have four highway companies, several card-issuing companies, and one merchandising company. The platform records transaction information of RSU, users, card issuing companies, and the merchandise company. Each vehicle has on board an OBU and an IC card. OBU stores vehicle information, and the amount of IC solvency. IC cards can be issued by banks or highway companies after a prepayment. Banks' IC cards can be prepaid (in this case, tolls are scaled by credit) or not; they can be used on board or on mobile phones, or elsewhere through the internet.

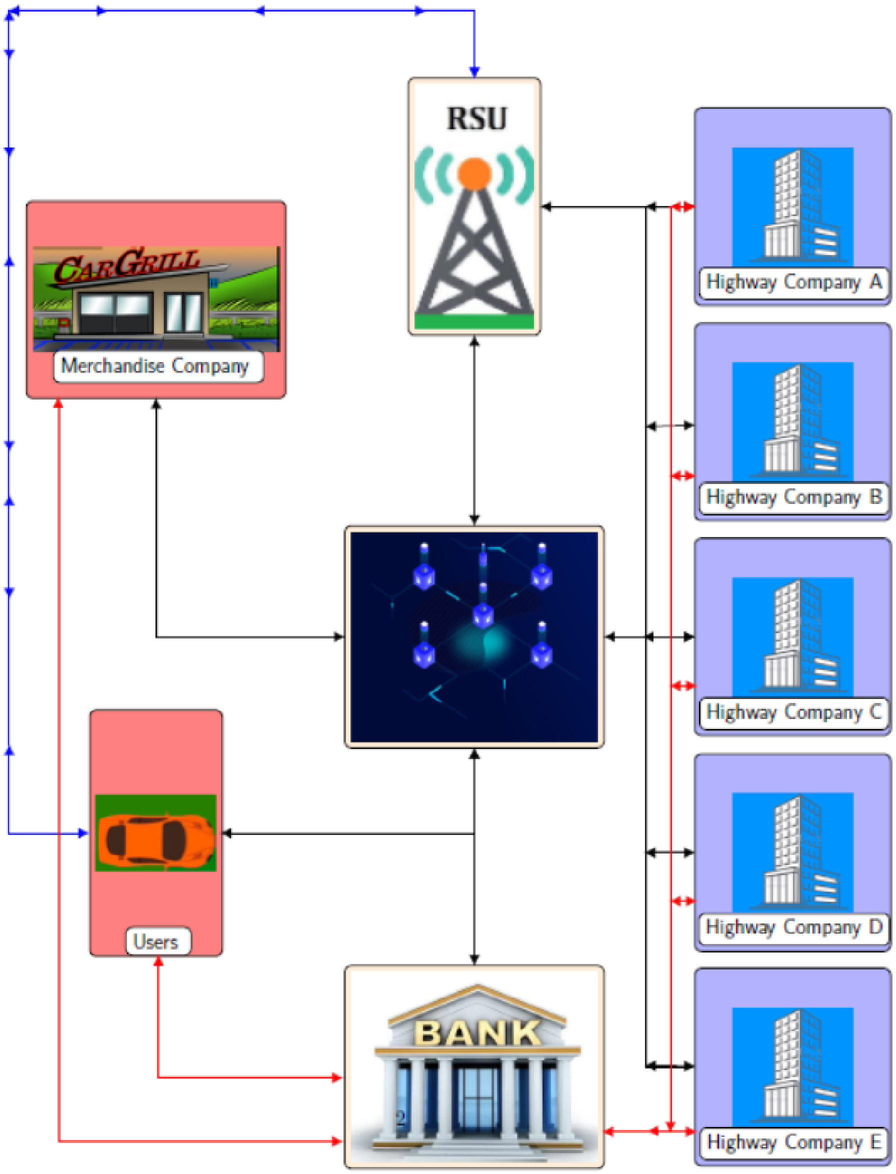

Figure 3.1: Highways integrated payment system

In this case, the On-Board Unit (OBU) also functions as a touch device that stores payment data. A Roadside Unit (RSU) is divided into an RSU entrance, a roadside RSU, and an RSU exit. The entrance reads OBU information, extracting the tag number from OBU, which serves as the car driver's public key. The identified vehicle data are stored by a central system on a cloud platform. The entrance RSU registers the vehicle passage, the ID, and the speed of the car owner, recording this information to the blockchain. In this context, one optional feature could be the use of Automatic License Plate Recognition (ALPR) software to detect, scan, and identify the vehicle number plate in real-time using video footage or photos. The scanned and processed data can be sent to local highway storage. The roadside RSU only interacts with users and does not handle monetary transactions but adds vehicle ID to the blockchain. The final RSU exit nodes verify the validity of the last block and record and facilitate payment transactions between users and card issuing companies. Each RSU can then close the block and properly link it to the blockchain. Each user possesses an individual set consisting of a private key and its corresponding public key.

The merchandise company owns a roadside RSU but also allows the use of IC card payments to purchase its goods, recording payment data on the blockchain. The merchandise roadside RSU registers the car owner's ID account, the time of arrival and departure, and the money spent with the IC card. Finally, the RSU exit registers the car driver's ID, can record their speed, and validates the overall payment to the highways. The RSU then splits the approved payments among the highway companies. The information exchanged between companies and between companies and users is recorded on the underlying blockchain platform.

Vehicle drivers choose the RSU entrance node. Let us assume, for example, that this is exactly the one that belongs to the Pedemontana highway. Each vehicle is equipped with an onboard unit that enables wireless communication with RSUs. The OBU sends out a request to enter the highway. The entrance RSU connects to the OBU and verifies user ID and/or speed identity. In practice, the OBU transmits a ciphertext to the RSU, and the RSU records the ciphertext on the blockchain. To ensure efficient communication, the entrance RSU and the roadside RSU are fixed on both sides of the lanes. Roadside RSUs can be placed at intervals of one kilometer, and at the merchandise company stores. Highways companies, users, and merchandise companies share data on a common blockchain platform. Each entity has a bank account, banks can be admitted to join the blockchain network. The architecture with these different parties is shown in Figure 3.1. Figure 3.2 explains a typical scenario of the proposed architecture. Action 1 represents the user registering an account on the highway's platform, equivalent to opening a wallet charged with a fixed minimum amount and receiving a virtual card. Transaction 1 (T1) represents the car driver's ID and the credit amount assigned by the card issuing company to the user's account.

As illustrated in Figure 3.2, the information from Transaction 1 is written in block N by the highway company. Action 2 signifies the vehicle entering the highway, leading to Transaction 2. Transaction 2 involves the entrance RSU storing the vehicle ID, its speed, wallet balance, and entrance time into the blockchain. Action 3 occurs when the vehicle passes a roadside RSU, and Transaction 3 involves the roadside RSU recording vehicle speed, type, and other data sent by the on-board OBU, such as the vehicle's status. Action 4 denotes the vehicle stopping at the merchandise company's plaza for a meal or snack. The roadside RSU near the merchandise store records the entrance and exit time of the vehicle, the amounts spent in the store using the IC card, and the credit IC residual value. Transaction 4 captures this information and is recorded in block N+3. When the vehicle reaches one of the exit RSU points, Action 5 and Transaction 5 occur. Transaction 5 involves the RSU exit charging the fee to the user, and the highway company transfers the money to its bank account according to the toll tax computed by the exit RSU.

Finally, Action 6 indicates that the vehicle leaves the highway. After each transaction is completed, a new block is created in this schematic blockchain, and the transaction information is recorded in the blocks. As shown in Figure 2, Transaction 1 information is written in block N, Action 2 in block N+1, and so on, until the last transaction ends and is stored in block N+4. This way, the blockchain can store information for all transactions.

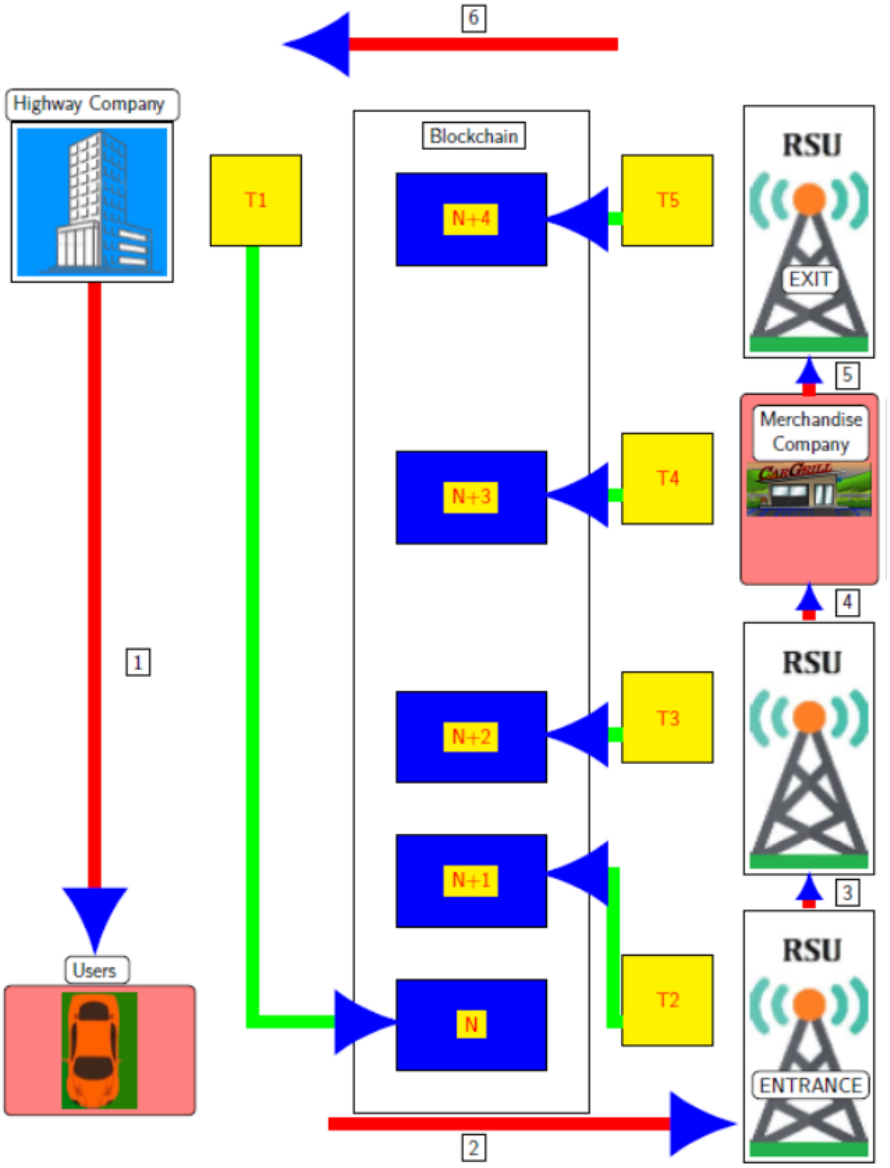

Figure 3.2: Information management system

Each highway company verifies its revenue through the blockchain and the cash amounts due to the merchandising company when vehicle owners pay with their wallets, as the highway company holds all the public and private keys of its RSUs.

Highway companies and merchandise companies apply for the exchange of the credit due by the customer with money deposits in their bank accounts. Based on information managed by the highway company, the card issuing company utilizes the RSU exit's public key (kept by the highway and merchandise company) to verify the highway and merchandising companies' credits through the blockchain. If there is a valid matching between kilometers run and charged fees, and between product prices and sells of the merchandising company, the bank approves the payments and transfers the sums directly to their bank accounts. All these procedures are carried out through a smart contract or equivalent protocol. After the checks are completed, the blockchain records the transactions described above, the exit RSU closes the block, and the payments are fulfilled on the bank accounts. It should be noted that, unlike traditional systems, this mechanism does not require any inter-bank settlements, thus reducing the time needed to process payments, which are made in real-time.

3.6.1 Driver's wallet

We utilized the Elements Core testnet to simulate the Liquid network. Figure 8 illustrates an implementation example of the proposed architecture. The first step is the development of a platform where the user can register their data, to be stored on a cloud or a database. Simultaneously, the user opens a Liquid Blockchain wallet. The wallet consists of two asymmetric cryptographic keys: a public key and a private key.

A unique address derived from SHA256+RIPEMD160 hashing and Base58 encoding of a wallet's public key is given to others to receive funds. At the time of registration, the vehicle's driver receives, for example, the following public key associated with a QR code: "tlq1qq0df7fd04dvcn9pl2pdn84g7x6t90jwjvf2ja3v9uk03r2wt4vddrrcv3vcf087hwvwqtr4k70 uuhvesgee82skn4cc93hfzv". This is the user account address.

Once the wallet is opened, an initial operation, called peg-in, is performed, i.e. some BTC are sent from the Bitcoin mainchain to the Liquid sidechain. This procedure involves sending BTC to a multisig wallet (multi-signature wallet, namely a wallet that requires multiple private keys belonging to different cosigners to authorize and execute a transaction) controlled by the Liquid Federation. Once confirmed, an equivalent amount of L-BTC can be claimed by the user who initiated the peg-in, so that thereafter, anyone can use a Liquid node to cryptographically verify that the amount of L-BTC held on the Liquid Network is equivalent to the amount of BTC held in the Liquid Federation multisig wallet.

Simultaneously, when the wallet balance is recharged, the user can choose to exchange some amount of L-BTC with a certain amount of a stable coin generated by Liquid. A stable coin is a cryptocurrency whose market value is backed by a reserve asset and its price is typically fixed to the value of a strong fiat currency, such as US dollars and Euros, or gold. The presence of a stablecoin is justified by the need not to expose the user to the high volatility of bitcoin. Therefore, the wallet contains LBTC and can also hold a stablecoin amount.

Users are free to pay Autostrade using either L-BTC or stablecoins, with the transaction fees incurred in L-BTC. This solution proves particularly advantageous for cross-border payments as it eliminates fees associated with exchanging foreign currencies. Foreign users are not obligated to convert their currency into the local highway currency. As noted by Bindseil et al. (2022), ”For too long, cross-border payments have faced four particular challenges: high costs, low speed, limited access, and insufficient transparency. Faster, cheaper, more transparent, and inclusive cross-border payments would have widespread benefits for supporting economic growth...” (cite: Bindseil and Pantelopoulos (2022)).

3.6.2 RSU

Once the user’s ID is verified and added to the blockchain, they can initiate transactions. The user’s card is inserted into the On-Board Unit (OBU). At the entrance, the blockchain stores the user’s public keys (i.e., the User’s ID). If the user forgets to recharge his or her wallet and the wallet is empty, a minimum amount of money is directly deducted and exchanged with the user’s bank account through a protocol or a smart contract. After a brief delay of 5-6 seconds, a timestamp is created, certifying the vehicle’s passage (recorded as a transaction on the blockchain). This timestamp includes the time of the certified passage. Other Roadside Units (RSUs) along the route can repeat the same procedure to certify the vehicle's passage.

Now, assuming the vehicle reaches the exit, the RSU exit records the user's information, including his or her public key. Based on the information collected by both the entrance and the exit, the exit sends the information about the payable amount in L-BTC or stable coin and its own public key address to the user (”tlq1qqwu4sqlfyx7mwssqd6m800empw25x6v5t4h huj24x h3gfetqa3ut2fatr6qvvlt5ap2k9nkj33h58ylh6e766tr3gh5hrr7hn”).

3.6.3 Highway travel

The users transfer the corresponding sums and tokens to the RSU exit. Let us assume that the customer has to pay 51.56 euro which is equivalent to 0,251 L-BTC and 50 units of highways stablecoin.

1. Code1: ”Approved (”tlq1qqwu4sqlfyx7mwssqd6m800empw25x6v5t4hhuj24xh3gfetqa 3ut2fatr6qvvlt5ap2k9nkj33h58ylh6e766tr3gh5hrr7hn” 50)”. This means that the underlying platform of the blockchain approves the transfer of the corresponding Lbtc toll (price=50) LBTC to the highway company address. If the highway line is made up of several links, managed by different companies, the message will contain the public keys of each of them. At the same time, loyalty tokens can be issued from the highway blockchain's wallet as a ” premium” when some kilometers threshold is reached.

2. The customers pays the toll. The blockchain executes Code 2: ”Transfer From (”tlq1qq0df7fd04dvcn9pl2pdn84g7x6t90jwjvf2ja3v9uk03r2wt4vddrrcv3vcf087hwvwqtr 4k70uuhvesgee82skn4cc93hfzv”, “tb1qqwu4sqlfyx7mwssqd6m800empw25x6v5t4hhuj24 xh3gfetqa3ut2fatr6qvvlt5ap2k9nkj33h58ylh6e766tr3gh5hrr7hn”, 50). “This means that the user account transfers the corresponding toll amount ($price = 50$) to the RSU account.

3. The highways company decides to give a ”premium” of 30 tokens to the customer. The blockchain executes Code 3: ”Transfer From (”tlq1qqwu4sqlfyx7mwssqd6m800empw

25x6v5t4hhuj24xh3gfetqa3ut2fatr6qvvlt5ap2k9nkj33h58ylh6e766tr3gh5hrr7hn", "tlq1qq0df7fd04dvcn9pl2pdn84g7x6t90jwjvf2ja3v9uk03r2wt4vddrrcv3vcf087hwvwqtr 4k70uuhvesgee82skn4cc93hfzv", 30TK". The loyalty token is transferred by the RSU wallet to the user's wallet. Then, the user leaves. After less than one minute a new timestamp is issued.

4. Let us assume that the network tries to execute Code 4 to allow the money transfer to the highway company's wallet but the user's wallet is empty. Code 4:"Approved ("tlq1qq0df7fd04dvcn9pl2pdn84g7x6t90jwjvf2ja3v9uk03r2wt4vddrrcv3vcf087hwvwqtr 4k70uuhvesgee82skn4cc93hfzv", 50)". If the user wallet is empty the amount of money needed to pay the toll is directly taken from its bank account, exchanged in L-BTC or in a stablecoin and deposited on the highway's wallet.

When the user recharges the IC card with a stablecoin (1000), the basic blockchain platform will execute the following code

1. Code 5 : "Approved ("tlq1qq0df7fd04dvcn9pl2pdn84g7x6t90jwjvf2ja3v9uk03r2wt4vdd rrcv3vcf087hwvwqtr4k70uuhvesgee82skn4cc93hfzv", 1000)." This means transferring the corresponding stable coin (amount=1000) to the user account. In this way, charging is completed.

3.6.4 Merchandise Company

The merchandise company opens its wallet too on the Liquid Blockchain and receives its own private and public keys. Let us assume that its public key is given by"tlq1qqwt9ewa5a n7vez5s3pgd62lcy3h3aepzsfzc7gk37dgjf2ae7tynp7nk0qz7w65q35qlw2pdqzc0n8lx5f9n5jh4uj v8h34hn". After receiving its public key, the merchandise company gets a payment of 30 LBTC from the customer and decides to transfer on his or her wallet some loyalty points (9 LT). These points are tokens that can be accumulated for a discount on toll payments or on future purchases at its store.

1. Operation 6: Approved (”tlq1qq0df7fd04dvcn9pl2pdn84g7x6t90jwjvf2ja3v9uk03r2wt4vddrrcv3vcf087hwvwqtr4k70uuhvesgee82skn4cc93hfzv”, 30). The user account transfers the corresponding L-BTC or stablecoin units (price=30) he spent to the merchandise company’s account.

2. Code 7 “Transfer From (”tlq1qqwt9ewa5an7vez5s3pgd62lcy3h3aepzsfzc7gk37dgjf2ae7tynp7nk0qz7w65q35qlw2pdqzc0n8lx5f9n5jh4ujv8h34hn”,”tlq1qq0df7fd04dvcn9pl2pdn84g7x6t90jwjvf2ja3v9uk03r2wt4vddrrcv3vcf087hwvwqtr4k70uuhvesgee82skn4cc93hfzv”, 9 LT). The merchandise company’s account transfers the corresponding tokens 9 LT to the customer’s account. These loyalty tokens can be accumulated on his or her wallet or tranformed in LBTC or stablecoin units to pay tolls at RSU exit or goods and services at the store.

The loyalty token is transferred by the Merchandise company wallet to the user’s wallet. He or she can decide to change them to L-BTC. Otherwise, the user can ask the merchandise company to use tokens to get some goods or services or get discounts, or participate in particular events. All these operations are done through protocols or smart contracts on the liquid blockchain. The user can decide to change tokens received in L-BTC or highways stablecoins. Otherwise, the user can ask the merchandise company to use tokens to get some goods or services or get discounts, or participate in particular events. All these operations are done through protocols or smart contracts on the liquid blockchain. The following short codes are relative to the possibility of receiving goods, gadgets, or services just by transferring some loyalty tokens (2 LT) from the user wallet to the Merchandise company wallet. It can be done by connecting the user’s wallet through its card or a QR code reader to the blockchain. This operation can be expressed as Code 8 “Transfer From (”tlq1qq0df7fd04dvcn9pl2pdn84g7x6t90jwjvf2ja3v9uk03r2wt4vddrrcv3vcf087hwvwqtr4k70uuhvesgee82skn4cc93hfzv”, ”tlq1qqwt9ewa5an7vez5s3pgd62lcy3h3aepzsfzc7gk37dgjf2ae7tynp7nk0qz7w65q35qlw2pdqzc0n8lx5f9n5jh4ujv8h34hn”, 2 LT”)”

3.6.5 Highways profits

In this operation, which concerns the banks of the highway company and the merchandise company, the underlying blockchain platform executes the following code.

1. Code 8: “Transfer (“tb1qqwu4sqlfyx7mwssqd6m800empw25x6v5t4hhuj24xh3gfetqa,”50).”

This means transferring the corresponding LBTC (profit=50) to the company wallet account. At this point, the extraction is completed. The highway will ask, through a protocol or a smart contract, to its bank for exchanging L-BTC or its stable coin with money at the end of the day. According to information managed by the highway company, the bank verifies the highway company’s revenue or executes the smart contract order to change the corresponding LBTC or stablecoins amounts in fiat money. The fiat money is credited to the company’s bank account. The bank will verify that the order of payment is done by the company and will approve it through the following code message registered on the blockchain: Code 9: ”Approved (”tlq1qqwu4sqlfyx7mwssqd6m800empw25x6v5t4hhuj24xh3 gfetqa3ut2fatr6qvvlt5ap2k9nkj33h58ylh6e766tr3gh5hrr7hn”, 500000)”. The blockchain records all the highway’s transaction and the bank will accredit the money to the highway company’s account only after that the blockchain approves them. The same procedure will be followed by the merchandising company.

3.7 Discussion

3.7.1 Strengh of Techincal Innovation

There are problems associated with traditional highway toll collection systems, particularly in the context of the Italian case. The payment process involves third-party companies, like banks or Telepass in Italy, and uses clearance and settlement systems that require time and high operational costs. All the payment mechanism is built around central ledgers vulnerable to hacking, operational costs, and risks for customers such as losing cards or freezing bank accounts.

The proposed blockchain payment system aims to address these challenges. Blockchain technology is presented as a secure and decentralized alternative that eliminates the need for intermediaries like banks or toll-pass companies. Unlike traditional systems, where central ledgers can be hacked, the blockchain ensures the security of transactions by distributing them across a network of nodes. This decentralized nature makes it difficult for hackers to compromise the entire system.

There are other specific risks associated with traditional toll collection systems, such as the vulnerability of the Electronic Toll Collection (ETC) system to swiping forged cards and fraudulent activities. The proposed blockchain system is positioned as a more secure solution that prevents such fraudulent activities and provides a transparent and traceable record of all transactions.

Furthermore, there are common issues faced by toll users, such as malfunctioning toll machines, incorrect ticket readings, and the risk of paying twice for a single journey. These issues can lead to financial losses, legal disputes, or inconvenience for users. The blockchain payment system is presented as a resilient solution that operates in real-time, ensuring that all payment transactions and vehicle passages are recorded and stored on the blockchain. This distributed storage across nodes in the network safeguards against data loss due to equipment damage or failures.

Implementing a blockchain-based payment system for highway tolls can enhance security, transparency, and efficiency while addressing the shortcomings of traditional toll collection methods.

3.7.2 Settlement Center Intrusion

There is an inherent vulnerability of traditional Electronic Toll Collection (ETC) systems, such as Italy's Telepass, due to their reliance on centralized servers. If a hacker gains control over the central server of an ETC system, they can manipulate revenue data, perform unauthorized transfers and withdrawals, and cover their tracks effectively. This centralized nature makes traditional systems susceptible to network attacks, potentially resulting in the loss of vast amounts of transaction data.

In contrast, the security advantages of a public blockchain help in mitigating such risks. In a public blockchain, every transaction is recorded on a distributed ledger that is accessible to anyone with an internet connection. This distributed and transparent ledger eliminates single points of failure. Even if a hacker attempts to tamper with data on certain nodes, the rest of the system will reject the altered data. The passage mentions that for a hacker to successfully manipulate data on a blockchain, they would need to control more than 50% of the nodes in the entire network, which is considered an impractical and exhaustive process.

The strength of blockchain technology lies particularly in terms of security and resistance to tampering. The decentralized and transparent nature of blockchain transactions provides a level of security that traditional centralized systems struggle to match. The irreversible nature of Bitcoin and LBTC transactions means that once a transaction is confirmed, it cannot be canceled or changed. This characteristic is quite opposite to the centralized systems where electronic transactions can be subject to alterations or cancellations if control is compromised or if sensitive information is leaked to hackers.

Another important feature is the absence of chargebacks for companies accepting payments via Bitcoin or LBTC. A charge-back is a demand by a credit card provider or a bank for a retailer to cover the loss on a disputed or fraudulent transaction. The non-reversibility of blockchain transactions adds a layer of security for businesses that accept payments in cryptocurrencies.

3.7.3 Scalability and Feasibility

”Scalability” refers to transactions per second (TPS), but on a more general level, it refers to the number of computations per second. The Liquid Network is a sidechain of Bitcoin that enables users to transfer Bitcoin and Liquid Bitcoin between Liquid and Bitcoin networks. Liquid’s block generation occurs less frequently than every minute, making its block generation more consistent than that of the Bitcoin blockchain. Bitcoin ledger, with a maximum transaction throughput of approximately 7 TPS, is currently rather slow and limited, compared to other blockchains.

Many traders and investors are turning to Liquid to exchange large sums of money, shortening block closure times not through Bitcoin on-chain transactions but through sidechains or off-chain networks that offer lower fees. Currently, Bitcoin fees stand at 1.20 euros. Low scalability leads to high network fees, network congestion, pending transactions, and consequently, long confirmation times. Thus, it is challenging to envision using Bitcoin (BTC) on a global scale. Liquid offers practically instant transfers with cheap fees (currently 0.0002 euros). While the BTC blockchain allows 3-6 transactions per second (assuming 6 blocks per hour), Liquid processes 7-10 transactions per second (assuming 60 blocks per hour). In addition to the extra capacity, Liquid's shorter block intervals allow for faster confirmation times. Liquid, being a permissioned federated blockchain, is ideal for high volumes and large transactions. Wüst and Gervais (2018) noted, ”In general, using an open or permissioned Blockchain only makes sense when multiple mutually mistrusting entities want to interact and change the state of a system and are not willing to agree on an online trusted third party.”

Even if Italian highway companies agreed upon a trusted central entity, ”Telepass”, its role in the redistribution of toll revenues requires time. Telepass is not responsible for data handling; another company, ”Movyon”, primarily manages any damage to the centralized database. ”Movyon” operates in the research, development, and integration of hardware and software systems in the field of Intelligent Transport Systems (ITS). A decentralized blockchain allows all companies to manage the same technology, preventing data damage and achieving transparency in payment data. Wüst and Gervais (2018) underscores that ”...There exists an inherent tradeoff between transparency and privacy...”

Liquid network increases scalability compared to Bitcoin by offering faster transactions on their sidechain while maintaining a high level of transparency and privacy. The Liquid two-way-peg is transparent because any user can detect and inspect the peg-in and peg-out transactions, allowing users to audit the federation's multisigs holdings and monitor blocking transfers. Although Liquid will never reach Bitcoin's level of decentralization, no single party, including the parent company, will control the network. Geographically diverse partners will form a ”consensus pool of participants” to ensure the highest possible level of decentralization. No participant will control more than one Liquid functionary server. On the Liquid network, amounts and types of asset transactions are hidden by default, safeguarding users' financial data. This reconciles anonymity and privacy with transaction transparency, even though the flow of funds can be traced.

Since a Liquid full node is freely accessible, anyone can trustlessly self-validate the Liquid sidechain. Users running a full node can independently perform a peg-in to the network, execute confidential transactions, and issue tokenized assets on Liquid. However, Liquid is decentralized but not fully permissionless. Only a few members, known as federation members, act as block signers, meaning transactions on the Liquid network can only be processed after their signature. Liquid's federated model requires blocks to be signed by at least two-thirds of all block signers. This mechanism allows for the easy expansion of nodes, but a certain level of computational power is necessary. Currently, it is not credible that single vehicles, without an onboard computer system, can run a full node later approved by the Federation.

Recent developments have shown that Tesla cars can be used to run Bitcoin nodes through their onboard computer devices in a project called ”Bcoin”. However, this project needs refinement. Running a Bitcoin node requires significant resources, including processing power. Tesla cars can mine Bitcoin using their internal battery, but it consumes a lot of energy and affects battery duration. Moreover, downloading and processing Bitcoin blockchain data for running a node could interfere with the user experience of the car's computer. The current state of blockchain technology allows only major stakeholders or individuals with the appropriate computational power to run nodes in Bitcoin and the Liquid Network. Nonetheless, electric vehicle maker Tesla Inc (TSLA.O), payments firm Block Inc (SQ. N), and Blockstream Corporation plan to collaborate on mining bitcoin using solar power in Texas to enhance and integrate their technologies.

3.8 Conclusion

This work proposes a blockchain toll payment system for Italian highway companies, aiming to enhance security, and trust, and reduce operational costs in toll collection. A properly designed blockchain can effectively improve the highway toll collection process. The use of Bitcoin, Liquid Bitcoin, or stablecoins for payments, offers advantages such as simplicity, user anonymity, no intermediary disruptions, and lower transaction fees compared to credit or debit card transactions, which entail higher fees and interest charges.

Blockchain technology can significantly benefit electronic toll collection by ensuring trust, immediate fraud-free payments, and eliminating intermediaries and third-party clearing systems. This results in a reduction of operational costs associated with money transactions. Additionally, when a highway route is segmented among different companies, adopting the same blockchain technology minimizes disputes and uncertainties related to payment delays, legal conflicts with vehicle owners, and inter-company disputes.

The proposed blockchain system focuses on utilizing Blockstream Liquid blockchain, developed by Blockstream, a global tech company specialized in Bitcoin and blockchain technology. The Liquid network, a layer-two application for scaling Bitcoin, enables the trading of various assets like Bitcoin, Euro, Swiss Franc, stablecoins, and other Liquid-based assets. The interoperability between Bitcoin's main chain and the Liquid sidechain extends Bitcoin's capabilities while maintaining its public and permissioned nature, as well as to scale to larger and more efficient operational scenarios.

The paper suggests a network model where highway concessionaries can establish a common platform for receiving immediate payments without the need for a clearinghouse or waiting for interbank settlements. The Liquid network's features allow the issuance of custom assets, such as stablecoins or loyalty tokens. In this work, the features of Liquid are used to exploit the possibility of creating trustworthy electronic toll payments that integrate the needs for transparency, trust and speed of payments between customers and highway companies, and among the companies themselves. The blockchain network proposed creates a unique payment system between companies and retail industry or between drivers, highway companies and merchandise stores that operate along the highway segments. Furthermore, it can promote the issuance of loyalty tokens to incentivize the use of highway routes through fidelity programs or the use of the same routes during certain hours or periods. This unique integrated payment system can foster transparent, trusted, and speedy electronic toll payments among customers, highway companies, and merchandise stores along the highway lanes.

The research demonstrates that decentralized technology is suitable for a road toll architecture, removing the need for a centralized system and streamlining operations among various companies' systems. The decentralized payment system reduces operational costs by minimizing the number of intermediate payment settlements, currently managed by third parties, and offers transparency for both highway companies and users.

The answer to the first research question “Is decentralized technology suitable for a road toll architecture?” is certainly positive.

The architecture of the proposed road toll system involves payments via an electronic wallet supporting BTC, L-BTC, or a stablecoin issued by highway companies managing segmented lanes. This payment mechanism ensures trusted direct payments to companies with short processing times and preserves user privacy by storing only transaction-related data in the blockchain, maintaining anonymity. Liquid transactions employ ”Confidential Transactions”, a cryptographic protocol designed to hide both the types of assets and the transaction amounts to any third parties monitoring the Liquid blockchain.

All these reasons give a positive answer to the question ”Is using blockchain technology in a road toll system justified?”.

Blockchain protocols, being open-source, enable stakeholders to adopt them freely for various purposes such as operational cost savings, direct payments, trusted cooperation, loyalty programs, and discount campaigns. These incentives can promote smart travel during specific periods or alleviate congestion.

Future studies could explore how this technological framework might facilitate safe communication about road conditions among interconnected vehicles. Additionally, forthcoming research could focus on developing blockchain protocols capable of providing 'proof of traffic' in specific segments of highway networks, aiding congestion management in connected lines.

Chapter 4

Potential Impacts of Blockchain and Highway Infrastructures on the EU-27 Economic Growth

Abstract:

This study examines the effects of highway extension and the adoption of Bitcoin blockchain for digital payments on the economic growth of the 27 EU member countries. Blockchain is recognized as a groundbreaking innovation in digital payments. Its impact on economic growth is compared with that of other traditional digital payment methods. A neoclassical growth model is constructed to systematically assess the empirical significance of Blockchain digital payments innovation on production. Using a robust random effects panel model, the study finds limited support for claims of a substantial increase in productivity resulting from increased infrastructure investments. Specifically, the analysis suggests that augmenting the rate of highway extension investment would have had a minimal or negligible impact on annual productivity growth from 2003 to 2021. Bitcoin blockchain, offering secure digital payments and serving as a hedge against inflation and currency depreciation, demonstrates a favorable influence on growth, as evidenced by its trade volumes. In contrast, other digital payment systems play a marginal and insignificant role. Nevertheless, fees associated with daily digital transactions can prevent economic growth. Debit card fees, similar to taxes on daily merchant revenue, have the potential to slow real GDP growth if excessively high.

4.1 Introduction

Cashless payments are pivotal in shaping digital economies, fueled by innovations driven by Information Technology (I.T.). The landscape of payments is transforming with the rise of digital instant payments, cryptocurrencies, stablecoins, and the development of digital fiat currencies by central banks. While cryptocurrencies have found applications across various industries, their volatility can lead to sudden job losses within the crypto sector and spillover effects to traditional financial companies exposed to the crypto market (White et al., 2022).

Despite the high volatility of cryptocurrencies, their acceptance as legal tender could potentially reduce transaction fees due to the decentralized nature of blockchain technology. Blockchain enables direct electronic payments between parties, eliminating intermediaries such as banks and reducing transaction costs (Till et al., 2017; Yussof and Al-Harthy, 2018). The European Central Bank (ECB) notes a significant surge in cashless payments, particularly in online transactions, as reported in its 2020 European study titled 'SPACE' (Bank, 2020).

In 2022, the ECB SPACE survey revealed that 17% of day-to-day payments were made online, a notable increase from 6% in 2019. This shift is part of a broader trend, accelerated by the COVID-19 pandemic, which has driven the digitization of payments. Following the pandemic, consumers have shifted from physical cash to digital and contactless payment instruments at an unprecedented rate (Kosse and Szemere, 2021).

Card transactions surpassed cash transactions for the first time in 2022, accounting for 46% of point-of-sale (POS) transaction value compared to 42% for cash. However, the pace of this shift varies among countries and demographic segments. The 2000 ECB Space survey (Bank, 2020) and its 2022 version indicate that the Netherlands (34%), Finland (35%), and Estonia (48%) are the least cash-intensive countries, while Italy, Spain, Portugal, and Greece still rely heavily on cash transactions.

The primary cashless payment methods include credit and debit cards, with a noticeable shift towards mobile wallets and payment apps. Debit cards, surpassing credit cards in usage, offer cost-effectiveness for consumers and merchants. Unlike credit cards, debit cards immediately deduct funds from the buyer's account without additional charges, making them more favorable.

The article also delves into the evolution of monetary architecture towards fully digital currency through blockchain technology. Blockchain's ability to facilitate near-instant transactions at minimal cost promises economic growth. The study shifts its focus to the impact of highway infrastructure development on the economic growth of the EU-27 from 2003 to 2021, considering the presence of a digital blockchain payment system.

In exploring the economic growth contributions of both highway infrastructure and the digital payments economy, this study aims to provide a fresh perspective on the transport-led economic growth hypothesis. It distinguishes between traditional physical capital and digital capital, considering the diverse economic structures among EU-27 member countries.

The paper aims to highlight a possible relationship between highway infrastructure development, Bitcoin blockchain performance, and economic growth at a theoretical level. Adopting a Cobb–Douglas production function that includes digital payments it obtains an estimable linear equation. This theoretical approach implies that fees and digital payments could have an impact on growth together with transport infrastructure. Additionally, the paper seeks to develop an econometric model based on previous studies to evaluate the interference of highway infrastructure status and blockchain performance indicators (Bitcoin Volumes and Fees) with economic growth in the EU-27 from 2003 to 2021. The panel data estimates differentiate between credit, debit card, and Bitcoin blockchain payments. The paper's findings suggest that solely investing in highway extension does not influence growth. However, the method of payment and lower fees associated with digital cash may enhance economic growth within the EU-27 countries.

The article is structured into three main sections: a summary of existing studies providing theoretical background (Section 4.2), the econometric methodology is presented in Section 4.3, data description is presented in Section 4.4, and the results of the empirical study on the EU-27 over the period 2003–2021 are shown in Section 4.5. The paper concludes with insights drawn from the results and references.

4.2 Literature Review

Over the past few decades, macroeconomic modeling has been extensively used to evaluate the economic benefits of investing in transportation infrastructure (Lakshmanan, 2011). However, defining infrastructure varies across economic literature, often referring to specific capital assets crucial for essential services in sectors like transport, energy, water, and oil and gas production (Välilä, 2020). This study particularly focuses on highway infrastructure and its impact on economic growth within the European Union (EU-27).

Highway infrastructure, crucial for mobility, plays a pivotal role in economic development by improving market accessibility, expanding job opportunities, and facilitating just-in-time production strategies (Shantz et al., 2011). The study adopts a panel data approach to investigate the growth impact of highway infrastructure within the EU-27, considering variations between countries.

While some studies, such as (Cigu et al., 2018; Ignatov, 2024), highlight the positive contributions of new highway projects to annual income, divergent conclusions exist (Boarnet, 1999; Button, 1998). The effectiveness of transportation infrastructure, as emphasized by (Polyzos and Tsiotas, 2020), depends on meeting broader social needs and reducing intra-regional transportation costs.

It is important to note that not all highway infrastructure produces economic benefits uniformly. The final result hinges on the type of highway infrastructure in place. Some transportation systems cater solely to local needs, while others facilitate connections to national and international markets. The impact on economic growth is related to rapid access to markets through a better quality of highway capacity (Aschauer, 1989).

Moreover, the infrastructure investment alone is not enough to boost economic productivity. The increase in economic output is higher in countries that increase their overall spending for highways to facilitate personal travel and freight shipments throughout national and international networks (Boarnet, 1995; Kollias and Paleologou, 2013).

The world is moving towards financial assets digitalization and a cashless economy, Noman et al. (2023) find that cards and e-money payments have a strong positive relationship with the real GDP of G7 countries. Wong et al. (2020) analyzing annual data from 2007 to 2016, shows that cashless payments stimulate economic growth in OECD countries, especially through debit cards, while credit cards, e-money, and cheque payments have no impact. Patra and Sethi (2023) examines the direct and interactive impact of digital payments on economic growth, considering factors such as institutional quality, consumption expenditure, and bank credit across 25-member countries of the Committee on Payments and Market Infrastructures (CPMI) from 2012 to 2020. Employing a Fixed Effect Model with Driscoll-Kraay Panel Corrected Estimators, their study reveals a positive association between increased digital payments and economic growth through consumption expenditure. Zandi et al. (2013) wrote that, ”Moody’s Analytics set out to test whether the long-term shift to credit and debit cards stimulates economic growth, and found that electronic card payments continue to have a meaningful impact on the world economy.” According to their estimates, between 2011 and 2015, the increase in card usage produced an increase of 0.1% per annum in European average GDP growth.

Moving beyond traditional digital payment infrastructure, the study delves into the influence of cryptocurrency, particularly Bitcoin, on economic growth. Various studies, such as (Bojaj et al., 2022; Masharsky and Skvortsov, 2021; Utomo, 2018), have explored the relationship between Bitcoin transactions and nominal GDP growth. Results vary, with some studies indicating a negative impact on economic growth (Utomo, 2018).

Studies like (Chiu and Koeppl, 2019) reveal that, from a social welfare standpoint, utilizing Bitcoin can be significantly more expensive than traditional currency. While (Bojaj et al., 2022) suggests potential benefits from stablecoins and Bitcoin adoption, concerns about government regulation and the risk of money laundering underscore the need for robust financial market oversight (Masharsky and Skvortsov, 2021).

Research on the economic role of Bitcoin is relatively limited, and findings are not always consistent. As this study focuses on Bitcoin as a proxy for digital infrastructure's capacity to generate aggregate income or production benefits, it aims to contribute to the understanding of the broader economic implications, emphasizing the role of fees and neglecting financial stability issues. Boarnet (1997) highlights the necessity for decentralized, project-oriented highway finance to integrate efficient pricing mechanisms. Taking into consideration his conclusion, this paper studies the effects of a Bitcoin-based decentralized payment system capable of achieving future decentralized financial objectives by managing funds with minimal fees.

4.3 Model and methodology

4.3.1 The Aggregate Output

Growth accounting research, exemplified by the work of Hulten and Schwab (1984, 1991), typically starts with a production function that links tangible inputs to actual output. The underlying assumption is that compensation for factors equals their marginal contribution to production, known as marginal productivity. To examine the role of a transport infrastructure stock on economic performance, this paper employs a variant of the Cobb–Douglas production function, inspired by Banerjee et al. (2020), which includes capital, labor force, physical, and IT infrastructure.

$$\$Y_t = P(1-f)AK_t^{\alpha}L_t^{1-\alpha}I_t^{\gamma}D_t^{\tau} \tag{4.1}$$

Here, K, L, I, and D represent the stock of physical capital, labor force, physical infrastructure, and payment infrastructure endowment, respectively. $\$Y$ represents the Nominal Gross Domestic Product (GDP) in purchasing power standard, K is the physical capital estimated using the perpetual inventory method, L represents the national labor force, and D stands for the 'payment infrastructure' allowing cash or electronic money payments. The constant A describes total factor productivity. Assuming $A = A_0e^{\epsilon_t}$, where A_0 is a non-negative constant and ϵ is a stochastic shock. P is the general level of prices, and $0 \leq f \leq 1$ is a fee paid to the financial sector for each unit of product sold in the market. Y is the Nominal Gross Domestic Product Value net of the fees paid to the financial sector. In this work, there is no distinction between public and private capital. Dividing both sides of Equation (4.1) by P allows us to express it in real terms. By taking the natural logarithm of Equation (4.1), we can write:

$$\begin{aligned} \ln\left(\frac{\$Y_t}{P_t}\right) &= \ln(1-f_t) + \ln(A_0) + \alpha\ln(K_t) + (1-\alpha)\ln(L_t) \\ &\quad + \gamma\ln(I_t) + \tau\ln(D_t) + \epsilon_t \end{aligned} \tag{4.2}$$

Taking the first difference of both sides of Equation (4.2), we obtain:

$$\begin{aligned} \Delta\ln(Y_t) &= \Delta\ln(1-f_t) + \Delta\ln(A) + \alpha\Delta\ln(K_t) \\ &\quad + (1-\alpha)\Delta\ln(L_t) + \gamma\Delta\ln(I_t) + \tau\Delta\ln(D_t) + \eta_t \end{aligned} \tag{4.3}$$

Here, Δ indicates the first difference of the logarithm of the variable between two subsequent time instants. Y is the real aggregate supply, and η_t is a stochastic shock or error. The aggregate supply is conceptualized as the sum of the total real output of all individual firms. Given $0 \leq f \leq 1$, the function $\ln(1-f_t)$ can be approximated at the first order by a Taylor series around $t = 0$, such that $\ln(1-f_t) \approx -f_t$. In this case, Equation 4.3 can be rewritten and estimated as:

$$\begin{aligned} \Delta\ln(Y_t) &= \Delta\ln(A) + \alpha\Delta\ln(K_t) + (1-\alpha)\Delta\ln(L_t) \\ &\quad + \gamma\Delta\ln(I_t) + \tau\Delta\ln(D_t) - \Delta f_t + \eta_t \end{aligned} \tag{4.4}$$

4.3.2 Econometric Analysis

In this study, a panel data approach is employed, leveraging the combined features of cross-sectional and time series data. Panel data, amalgamating both dimensions, proves advantageous in identifying and measuring effects that may go unnoticed in either pure cross-sectional or pure time series data (Baltagi and Baltagi, 2008).

The general aim of utilizing panel data is to explore unobserved factors influencing output, categorized into those that remain constant and those that vary over time. In a general linear model representation for panel data, both intercept and slope coefficients can exhibit variations (Trivedi, 2005). Let i represent the location and t represent the time. According to Trivedi (2005), the mathematical formula for a general panel data model is as follows:

$$y_{it} = \alpha_{it} + x'_{it}\beta it + u_{it}, \quad i = 1, ..., N, \quad t = 1, ..., T \tag{4.5}$$

Here, y_i is a scalar dependent variable, x_{it} is a $K \times 1$ vector of dependent variables, u_{it} is a scalar disturbance term, i indexes individuals (European countries in this paper) in a cross-section, and t indexes time. The first equation estimated is a pooled model that specifies constant coefficients $\alpha_{it} = \alpha$ and assumes no dependence within individual groups (countries) ((Trivedi, 2005)):

$$y_{it} = \alpha + x'_{it}\beta it + u_{it}, \quad i = 1, ..., N, \quad t = 1, ..., T \tag{4.6}$$

In the specific context of this work, the pooled model is represented as:

$$\Delta \ln(Y_t) = \alpha + \beta_1 \Delta \ln(K_t) + \beta_2 \Delta \ln(L_t) + \beta_3 \Delta \ln(I_t) + \beta_4 \Delta \ln(D_t) + \beta_5 \Delta f_t + \eta_t \tag{4.7}$$

Here, $\Delta \ln(Y_t)$ represents the change in the logarithm of real GDP at time t (percentage growth rate when multiplied by 100), while $\alpha, \beta_1, \beta_2, \beta_4, \beta_5$ denote the coefficients associated with different variables. $\Delta \ln(K_t)$, $\Delta \ln(L_t)$, $\Delta \ln(I_t)$, and $\Delta \ln(D_t)$ stand for the natural logarithm of capital, change in the logarithm of labor, change in the logarithm of investment, and change in the logarithm of the digital infrastructure variable D at time t, respectively. All these changes in logarithms represent percentage growth rates when multiplied by 100. Δf_t represents the change in fees on payments at time t, and η_t is the error term. In panel data analysis, a fixed-effects model can be applied to account for unobserved factors over time. Following Trivedi (2005) the general formula for a fixed is

$$y_{it} = \alpha_i + x_{it}'\beta_i + u_{it} \qquad i = 1, \ldots, N \qquad t = 1, \ldots, T \tag{4.8}$$

where, differently than before α_i are entity (country in this context) specific fixed effects. This work estimates the following one-way fixed effects:

$$\Delta \ln(Y_t) = c_i + \beta_1 \Delta \ln(K_t) + \beta_2 \Delta \ln(L_t) + \beta_3 \Delta \ln(I_t) + \beta_4 \Delta \ln(D_t) + \beta_5 \Delta f_t + \eta_t \tag{4.9}$$

In this specific case we set $\alpha_i = c_i + \gamma_t$. Finally, a random effect model is estimated. The unobservable individual effects are treated as random variables that are distributed independently of the regressors. As suggested by Trivedi (2005) the random effects regression can be written as:

$$y_{it} = \alpha_i + x_{it}'\beta_{it} + u_{it} \qquad i = 1, \ldots, N \qquad t = 1, \ldots, T \tag{4.10}$$

In this model, the additional assumption is :

$$\begin{aligned} &\alpha_i \sim F_1(\alpha, \sigma_\alpha^2) \\ &u_{it} \sim F_2(0, \sigma_u^2) \qquad i = 1, \ldots, N \qquad t = 1, \ldots, T \end{aligned} \tag{4.11}$$

Both the random effects and the error term in this model are assumed to be independently and identically distributed. F_1 and F_2 are generic distributions. Accordingly, the real GDP growth regression is :

$$\Delta \ln(Y_t) = \alpha_i + \beta_1 \Delta \ln(K_t) + \beta_2 \Delta \ln(L_t) + \beta_3 \Delta \ln(I_t) + \beta_4 \Delta \ln(D_t) + \beta_5 \Delta f_t + \eta_{it} \tag{4.12}$$

4.4 Data description

This section provides a concise overview of the data employed in the empirical analysis. Data are on annual frequency from 2000 to 2021. The paper studies the economies of the 27 countries that are currently part of the European Union: Austria (AUT), Belgium (BEL), Bulgaria (BGR), Croatia (HRV), Republic of Cyprus (CYP), Czech Republic (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), France (FRA), Germany (DEU), Greece (GRC), Hungary (HUN), Ireland (IRL), Italy (ITA), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Malta,(MLT) Netherlands (NLD), Poland (POL), Portugal (PRT), Romania (ROU), Slovakia (SVK), Slovenia (SVN), Spain (ESP) and Sweden (SWE).

Four categories of variables are considered: Macroeconomic Indicators, Highways Infrastructure Indicators, Digital Payments Indicators, and Blockchain Performance Indicators The macroeconomic indicators are the real Gross Domestic Product Growth (GDP) Rate, the Employment Rate, the Investment Rate, and the Real Interest Rate. The Employment Rate is the annual growth rate of the Labour Force, The Investment rate is obtained as the growth rate of the Gross Fixed Capital Formation. The Real Interest Rate is the prime lending rate deflated using the GDP deflator. All the data used in the investigation were collected from available sources: the European Commission[1] [2], the European Central Bank[3] and Blockchain [4].

Digital payments are quantified by the number of transactions made using debit and credit cards, as well as the associated fees per transaction. Furthermore, Blockchain Performance Indicators are delineated by the average annual trading volumes of Bitcoin (BTC) and the corresponding annual average fees per Bitcoin transaction. These metrics are sourced from ”blockchain.com”. The annual average trading volume of Bitcoin, along with the relative average fees, is derived from data obtained from ”blockchain.com”. The trading volume of Bitcoin encompasses the cumulative value of all buy-sell transactions occurring

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[1] https://ec.europa.eu/eurostat/web/main/data/database(Accessed on 2024-02-28)

[2] https://ec.europa.eu/eurostat/web/transport/data(Accessed on 2024-02-28)

[3] https://www.ecb.europa.eu/stats/all-key-statistics(Accessed on 2024-02-28)

[4] https://www.blockchain.com/(Accessed on 2024-02-28)

Variable	**Measure**	**Source of Raw Data**
Macroeconomic Indicators		
Real National Product (RGDP)	National Real Gross Domestic Product (RGDP), Seasonally Adjusted at constant prices(2010), Euro.	Eurostat Statistics
Gross Domestic Product Deflator	Harmonized Index of Consumer Prices	Eurostat Statistics
National Nominal Gross Domestic Product	National Gross Domestic Product, Total at Market Prices (ESA 2010), Seasonally Adjusted, Millions Euro	Eurostat Statistics
Labour Force	Employed Population, Aged 15-74, All Persons (Ages 15-74), SA	Main Economic Indicators, OECD
Investment	Gross Fixed Capital Formation (ESA 2010) Constant Prices, Data adjusted by working day (WDA), SA	Eurostat Statistics
Nominal Interest Rate	Prime Lending Rate (percentage)	Historical Data, The World Bank
Digital Payment Indicators		
Credit Card Transactions	Total Number of Credit Card Transactions in billions	European Central Bank Statistics
Debit Card Transactions	Total Number of Debit Card Transactions in billions	European Central Bank Statistics
Blockchain Performance Indicators		
Bitcoin Trading Volumes	The total Euro value of trading volume on major bitcoin exchanges, Volumes are measured over 24 hours in Euro applying the historical exchange rates Euro (EUR) to U.S. Dollar (USD)	Historical Data, blockchain.com
Bitcoin Fees	The total BTC value of all transaction fees paid to miners	Historical Data, Blockchain.com
Highways Infrastructure		
Length of motorways and e-roads	The total extension in Kilometres of motorways and e-roads	Historical Annual Data, Eurostat Transport Statistics

Table 4.1: Description and Source of the Data

daily. It reflects the exchange of Bitcoins for goods or services and excludes transactions with Bitcoin exchanges. The Bitcoin Average Transaction Fee denotes the average fee charged in dollars for processing a Bitcoin transaction by a miner and confirming it. Table 4.1 presents a description and source of the data, considered on an annual basis.

4.4.1 Real GDP Trends and Growth Patterns

Between 2000 and 2007, the European economy displayed an annual growth rate ranging from +1% to +4%, with most countries exhibiting an upward trend (see Figure 4.1 and Figure 4.2). Notable exceptions with a downward trend in real GDP during this period include Austria (AUT), Belgium (BEL), Italy (ITA), Greece (GRC), Malta (MLT), Netherlands (NLD), Portugal(PRT), Romania (ROU), and Slovakia (SVK).

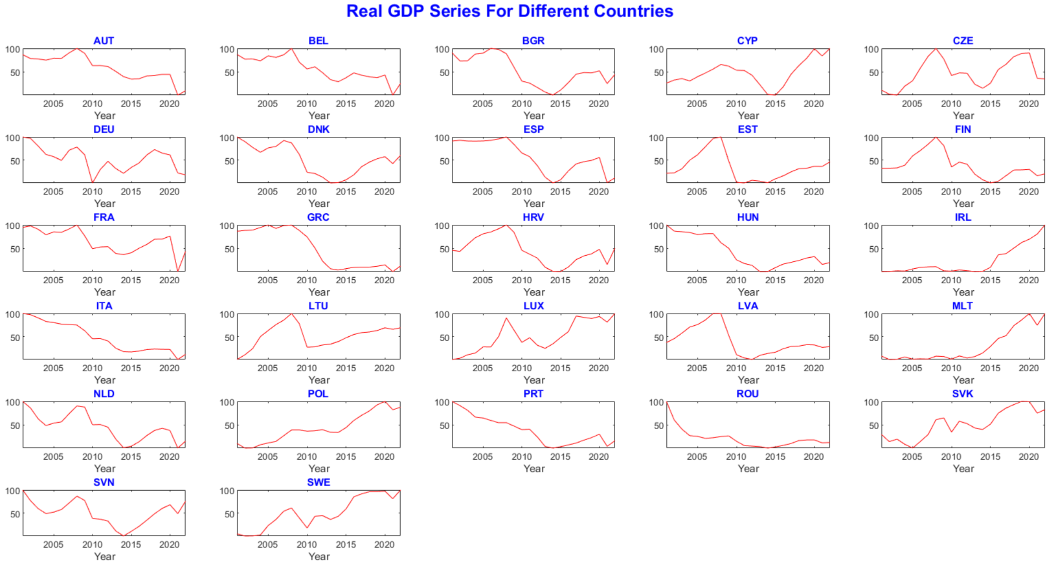


Figure 4.1: Real GDP Trends in European economies from 2000–2021

The aftermath of the 2008 financial crisis saw the European economy experiencing a significant decline in GDP, surpassing 4% in 2009, followed by a slight dip in 2012. Various countries endured recession, with Sweden (SWE), Germany (DEU), and Czech Republic (CZE) experiencing general growth and Luxembourg (LUX) showcasing a swifter recovery. From 2014 to 2019, European economies gradually recovered, achieving annual growth rates of around 2%. However, the year 2020 witnessed a widespread economic contraction due to the COVID-19 outbreak, leading to nearly a 6% drop in the Euro Zone.

Figure 4.2 shows the Real GDP Growth Rate of the European economies between 2000 – 2021. The figure shows that while all countries experienced recovery, some, notably Austria, Romania, Italy, Greece, and Portugal, Finland (FN), faced a sluggish resurgence, having endured substantial declines in real GDP since 2003. However, in 2021, the EU economy rebounded, registering an annual GDP increase of over 5%.

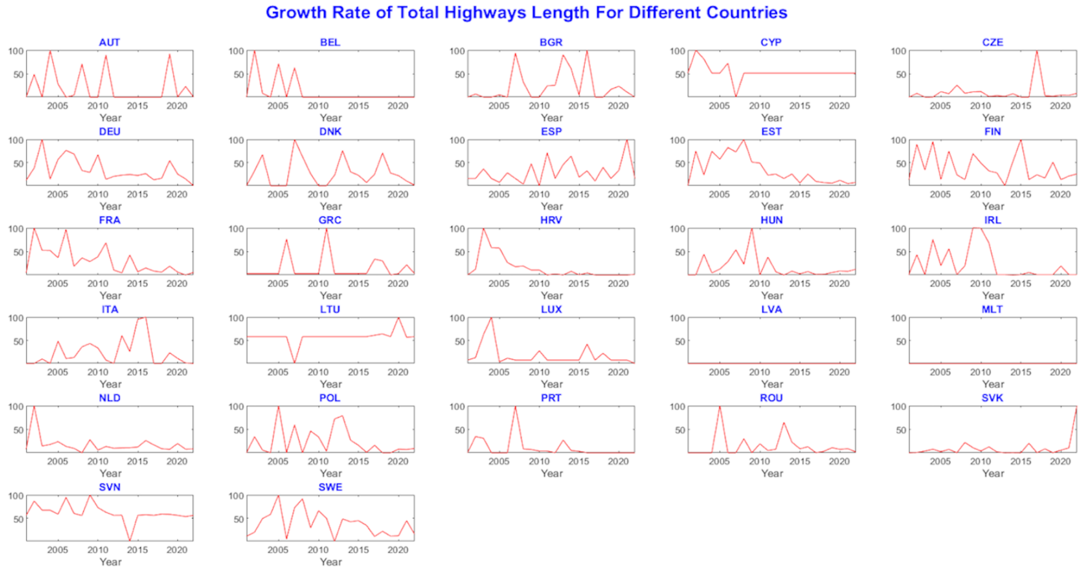


Figure 4.2: Real GDP Growth Rate in European Economies from 2000–2021

4.4.2 Highway Extensions: Trends and Growth

The impact of highway infrastructure on regional economic performance is captured by regional kilometers (km) of highways (Canning and Pedroni, 2004). The infrastructure data are from ”Eurostat”, the International Road Federation, national statistics, and estimates. The emphasis on highways is driven by two primary factors. Firstly, motorways exert a more direct and significant impact on the (re)location of economic activity compared to other modes of transportation. This influence is primarily attributed to their extensive role in transporting both intermediate and final goods, as highlighted in studies by (Button, 1998; Puga, 2002). Secondly, motorways have been the recipients of long-term policy support from the European Union that considered them an engine of development (Crescenzi and Rodríguez-Pose, 2012).

The length of motorways, especially when the model is specified in terms of differences, effectively measures the direct influence of changing regional accessibility to markets uniformly across regions and countries.Button (1998). Between 2003 and 2021 the EU-27 member states have been investing in the construction and expansion of highways to accommodate increasing traffic volumes, improve safety standards, and enhance overall transportation efficiency.

Spain has the longest motorway network in Europe, with a continuously growing trend, followed by Germany and France. As shown in Figure 4.3, an upward trend is also evident in Austria, Bulgaria, Germany, Denmark, Estonia, Finland, France, Greece, Croatia, Hungary, Italy, Ireland, Luxembourg, Netherlands, Portugal, Poland, Romania, Czech Republic, Slovenia, and Sweden. Data for Malta and Latvia are not available. Latvia has no highways but only high-speed roads. Similarly, Malta lacks highways and instead has a poor-quality road network, which urgently needs upgrading to accommodate heavier vehicles. However, this general growth happened in a heterogeneous way.

Slovenia and Slovakia experienced very low growth in their highway extension, with no growth in highway extension in Slovenia since 2015. Similarly, Cyprus has seen no growth since 2006. Lithuania experienced slow growth of its highway kilometers, with a period of no growth from 2006 to 2015. Luxembourg maintained a constant level of highway construction from 2003 to 2014, while Belgium showed the same pattern from 2006, and Austria from 2010 to 2017.

In the south of Europe, Spain, Italy, Greece, and Portugal show a general increase in their highway network, but with different speeds and periods of no growth. Portugal saw no growth from 2013, Italy from 2015 to 2017, and Greece from 2010 to 2015.

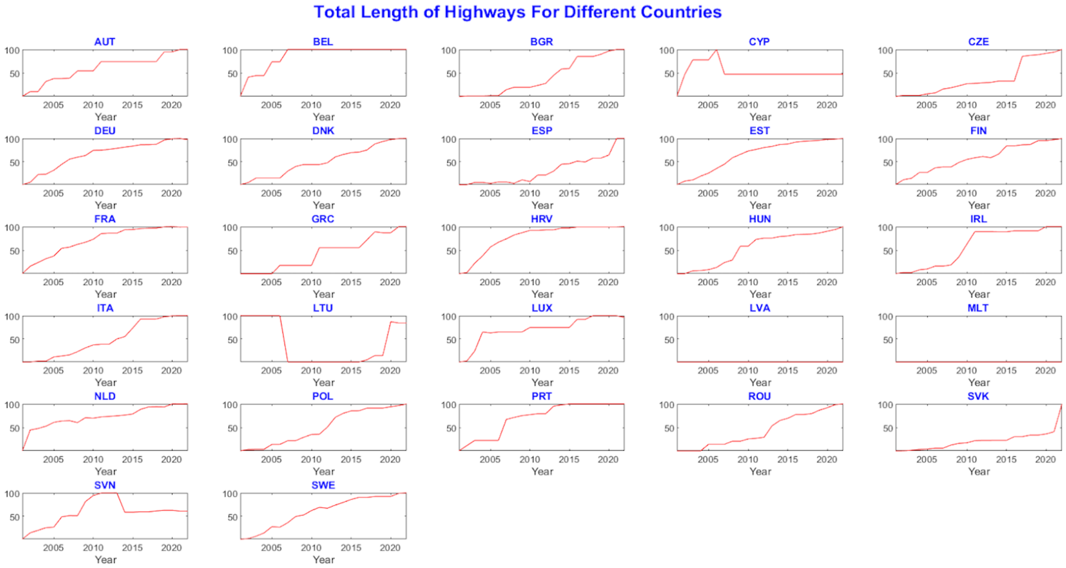


Figure 4.3: Total Length of Highways for Different Countries from 2001–2021

4.4.3 Physical Capital Stock

The non-residential capital stock, a crucial element in economic growth, represents the accumulation of capital goods such as machinery, equipment, and technology essential for production. While not directly measurable, it can be approximated for analysis purposes. Figure 4.4 shows the investment in physical capital stock in the Euro economies from 2001–2021, measured in euro at constant price. Investment is represented by Gross Fixed Capital Formation (GFCF) data taken from the ”Eurostat Statistics”. Gross Fixed Capital Formation is defined as the acquisition of production means like machinery and equipment. It includes both new and second-hand assets, as well as assets produced by producers for their use, with disposals subtracted. These assets are intended for use in the production of other goods and services over a period exceeding one year. The term ”produced assets” specifically refers to assets originating from a production process, excluding purchases of land and natural resources. All the countries experienced a drop in physical capital accumulation during the 2008 and COVID-19 crisis. The higher reductions were suffered by Spain, Greece, Portugal, and Italy, together with those of Romania, Bulgaria, Czech

Republic, Slovakia, Croatia, Cyprus, Estonia, and Lithuania.

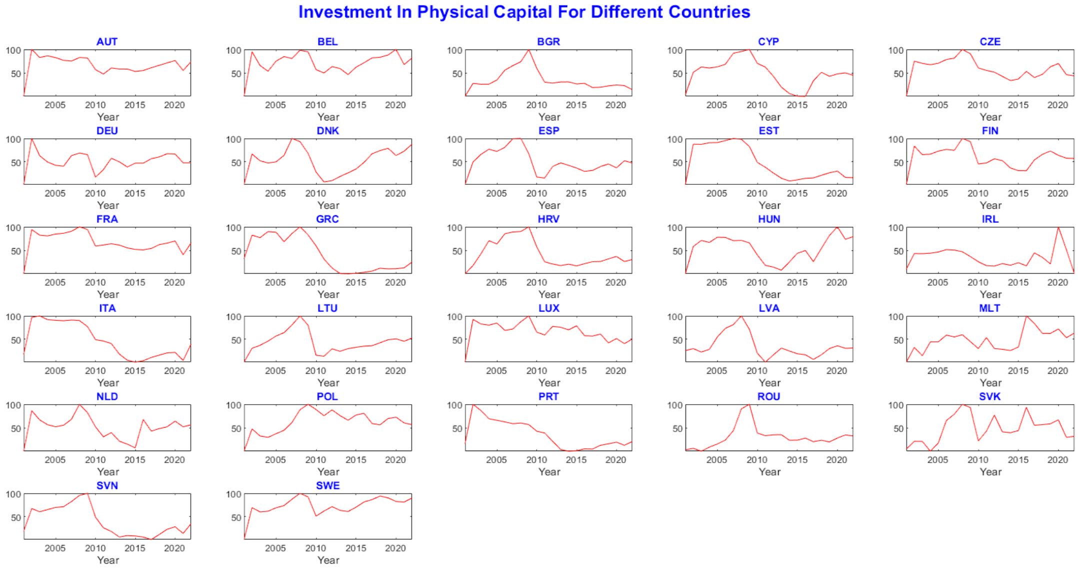


Figure 4.4: Investment in Physical Capital Stock in the 27 EU countries

4.4.4 Bitcoin Transaction Data Analysis

This analysis relies on global Bitcoin transaction data for each country. Obtaining Bitcoin data on a per-country basis poses challenges due to the cryptocurrency's privacy and security features, which make individual transactions untraceable. Figures 4.5 and 4.6 depicts the volume and fees of Bitcoin i The Bitcoin volumes and fees time series exhibits a noticeable trend over time. The cumulative value of all bitcoins has currently risen above $80bn$ of U.S dollar, while in 2021 it was above $5bn$, with the number of transactions on the Bitcoin blockchain rising exponentially from around 1,000 per day in 2011 to more than $49,000$ per day at the moment of writing. The transaction fee was 1.5 U.S. dollars in 2011, and 29.01 in 2021, while the fee per transaction is currently over 7 U.S. dollars.

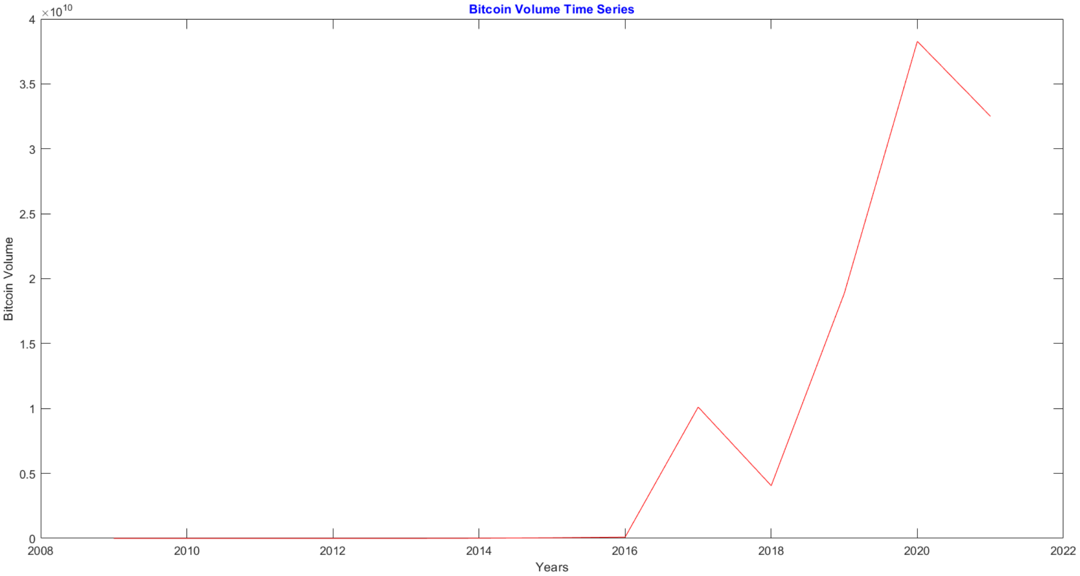


Figure 4.5: Volume of Bitcoin in European economies from 2008–2021

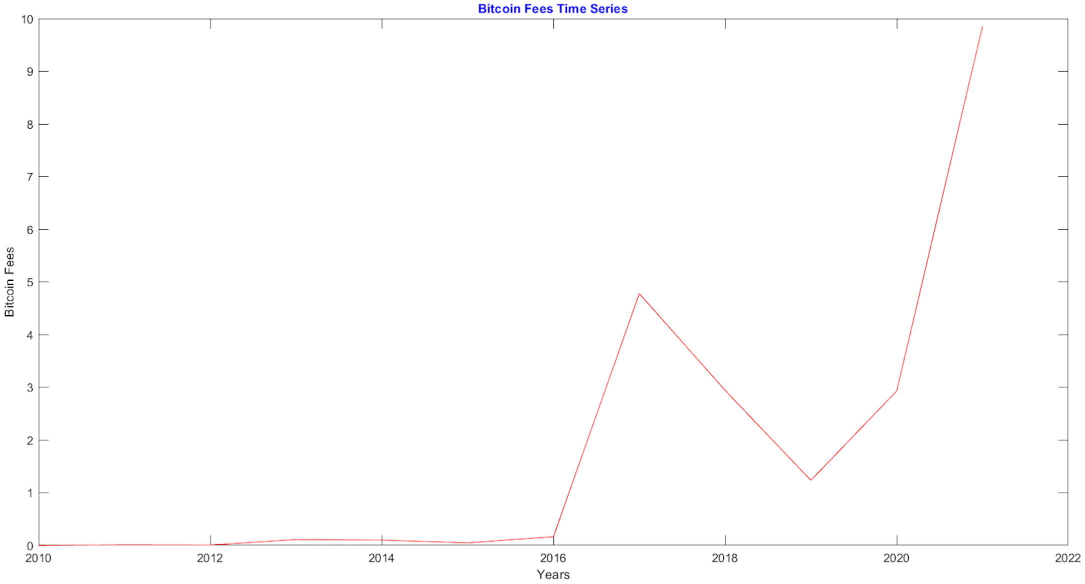


Figure 4.6: Bitcoin Fees in European economies from 2010–2021

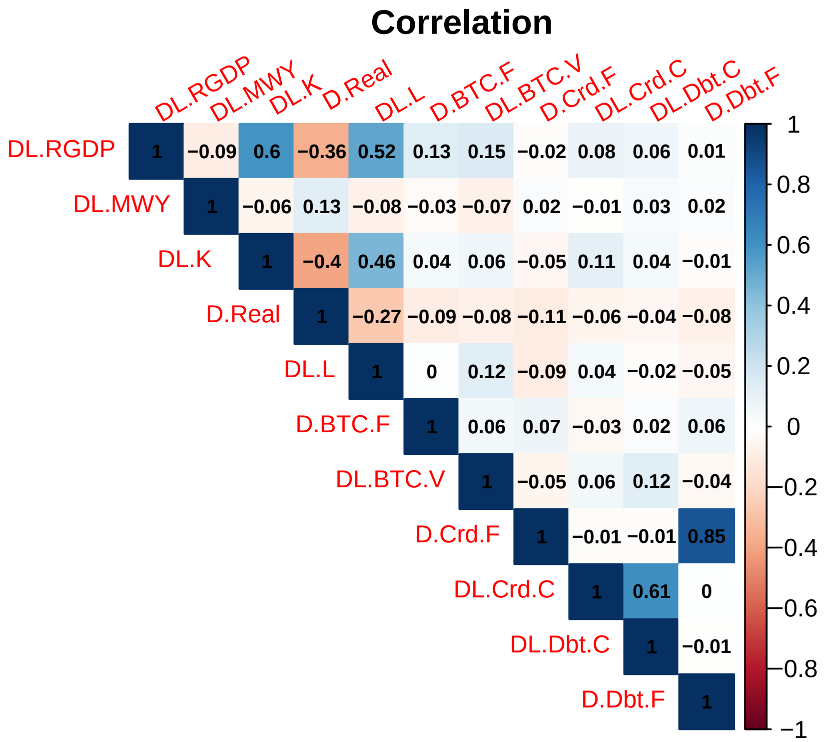
4.5 Empirical analysis and results

The dependent variable of our empirical analysis is the Real GDP which measures the growth rate of the Real National Product (RGDP) obtained by dividing the National Nominal GDP by the GDP Deflator. Most of the variables enter the models in log differences and the rest in first differences. The complete list of all variables and transformations is provided in Table 4.2.

No	Variable	Transformation	Code
1	Real GDP	$\Delta \log(x_t)$	DL.RGDP
2	Gross Fixed Capital	$\Delta \log(x_t)$	DL.K
3	Labour Force	$\Delta \log(x_t)$	DL.L
4	Real Interest Rate	Δx_t	D.Real
5	Credit Card Fees	Δx_t	D.Crd.F
6	Credit Card Transactions	$\Delta \log(x_t)$	DL.Crd.C
7	Debit Card Fees	Δx_t	D.Dbt.F
8	Debit Card Transactions	$\Delta \log(x_t)$	DL.Dbt.C
9	Bitcoin Fee	Δx_t	D.BTC.F
10	Bitcoin Trade Volumes	$\Delta \log(x_t)$	DL.BTC.V
11	Motorway Extension	$\Delta \log(x_t)$	DL.MWY

Table 4.2: Model variables and transformation.

A balanced panel model has been estimated using pooled, fixed effects, and random effects models. Regression analyses are conducted using an empirical model that incorporates the real lending rate, as this paper considers the financial aspect of economic growth. The independent variable is the Real GDP growth rate. The figures 4.7 and 4.3 show pairwise correlation coefficients and ”variance inflation factors (VIF)” statistics from the fixed effect model. The results reveal the absence of pairwise correlation and collinearity between regressors. It is possible to see from Figure 4.7 that all the pairwise correlation coefficients are far below 0.50, except the correlation coefficient between real GDP and the employment growth rate, which is 0.52. Figure 4.3 displays all variance inflation factors below 5. The explorative analysis concludes that there is not a correlation or multicollinearity problem between independent variables.



	DL.RGDP	DL.MWY	DL.K	D.Real	DL.L	D.BTC.F	DL.BTC.V	D.Crd.F	DL.Crd.C	DL.Dbt.C	D.Dbt.F
DL.RGDP	1	−0.09	0.6	−0.36	0.52	0.13	0.15	−0.02	0.08	0.06	0.01
DL.MWY		1	−0.06	0.13	−0.08	−0.03	−0.07	0.02	−0.01	0.03	0.02
DL.K			1	−0.4	0.46	0.04	0.06	−0.05	0.11	0.04	−0.01
D.Real				1	−0.27	−0.09	−0.08	−0.11	−0.06	−0.04	−0.08
DL.L					1	0	0.12	−0.09	0.04	−0.02	−0.05
D.BTC.F						1	0.06	0.07	−0.03	0.02	0.06
DL.BTC.V							1	−0.05	0.06	0.12	−0.04
D.Crd.F								1	−0.01	−0.01	0.85
DL.Crd.C									1	0.61	0
DL.Dbt.C										1	−0.01
D.Dbt.F											1

Figure 4.7: Pairwise Correlations

Variable	GVIF	$GVIF^{\left(\frac{1}{2\cdot Df}\right)}$
factor(Country)	1.524174	1.008138
DL.K	1.107780	1.052511
DL.L	1.345891	1.160125
D.Real	1.138013	1.066777
D.Crd.F	3.754718	1.937710
DL.Crd.C	2.162231	1.470453
D.Dbt.F	3.711146	1.926433
DL.Dbt.C	2.158478	1.469176
D.BTC.F	1.023308	1.011587
DL.BTC.V	1.040852	1.020222
DL.MWY	1.177107	1.084946

Table 4.3: Variance Inflation Factors. Note: This is estimated from the Fixed effect model.

The theoretical models adopted in these estimations presuppose homoskedasticity of regression disturbances, implying a consistent variance across both time and individuals.

However, this assumption may be overly restrictive for panel datasets.

To address potential heteroskedasticity, which can bias the standard errors of estimates, robust standard errors are computed. Specifically, White cross-section robust standard errors are employed to mitigate the impact of heteroskedasticity on Ordinary Least Squares Regression (OLS). Heteroskedasticity is assessed using various diagnostic tests, including the Breusch-Pagan test, the White test, the Breusch-Goffery test, and the Wooldridge score test. These tests aim to detect evidence of heteroskedasticity in the data. Robust standard errors are then utilized to ensure the reliability of regression results in cases where significant heteroskedasticity is detected.

The heteroskedasticity test results are presented in Tables A.1. In the pooled model, the Breusch-Pagan test statistic is 19.39, yielding a p-value of 0.0487, slightly below the conventional significance threshold of 0.05. While this suggests potential heteroskedasticity, caution is warranted in interpretation. The White test suggests heteroskedasticity with a p-value of $2.707e^{-9}$. The Goldfeld-Quandt test rejects the null hypothesis of heteroskedasticity with a p-value of 5.978e-06. The Breusch-Goffery test rejects the null hypothesis, suggesting no significant evidence of autocorrelation. The Wooldridge test generates a p-value of 0.0002, indicating the presence of autocorrelation in the model residuals. Similar results are obtained for the second model

It is possible to conclude that there is evidence of heteroskedasticity in the pooled models which would cause the standard errors to be biased and the estimates to be less efficient.

Evidence of heteroskedasticity in the pooled model suggests potential bias in standard errors and reduced efficiency in parameter estimates. Biased standard error estimates can invalidate statistical inferences based on them. Fortunately, Newey and West (1987, 1994) introduced heteroscedasticity and autocorrelation consistent (HAC) covariance matrix estimators, which produce consistent standard errors robust to various forms of spatial and temporal dependence.

We can draw similar conclusions by applying the same tests to both the fixed-effect and random-effect models (tables A.2).

Heteroskedasticity-Autocorrelation Consistent (HAC) estimators, such as HC3, are particularly valuable when dealing with data exhibiting heteroskedasticity, even in the absence of within-cluster correlation. The Heteroskedasticity-Consistent Covariance Matrix Estimator 3 (HC3) is a member of this family of estimators. HC3 is preferred in scenarios characterized by relatively small sample sizes or a limited number of clusters (Cameron et al., 2008).

This paper adopts Arellano's HC3 estimator to correct standard errors by accounting for both heteroskedasticity and series and crossectional correlation. The HAC estimator of Arellano (1987) (clustered by panel unit) is a particular version of White (1980) HAC estimator in the panel setting. This estimator is appropriate for both large and short panels. Moreover, it is robust against cross-sectional heteroskedasticity and also against the serial correlation of arbitrary form (Millo, 2017).

A possible alternative to Arellano's HC3, the Driscoll-Kraay (DK) Standard Errors, which are heteroscedasticity and autocorrelation consistent (HAC) standard errors, were used as a preliminary analysis. Since the nature of the autocorrelation of residuals is unknown, both methods were employed. Arellano's HC3 estimator and DK standard errors yielded the same standard error results. However, while DK standard errors specifically target autocorrelation, HC3 standard errors primarily focus on heteroscedasticity. The identical results may suggest that one or both components are not significantly affecting the standard errors. Given the short time considered, the two methods can be considered equivalent. However, because Arellano's HC3 estimators address issues of heteroscedasticity and autocorrelation in the residuals for both short and long-panel data, this method was preferred.

4.5.1 Empirical Results

The theoretical model derived from the Cobb-Douglass production function was estimated without and including the real interest rate. Because the adjusted R squared was higher for the second one and validates the results of the first one, this paper reports estimates for the log linearized model where the real interest rate is added. All the estimates employ robust standard errors according to White and Arellano's HC3 approach.

This section discusses the estimation results of the three types of panel analytic models: (1) the pooled regression model, (2) the fixed-effects model, and (3) the random-effects model. All the regressions were performed using "R Studio". In Appendix A.2 Table A.4, Table A.5, Table A.6 provide the results of regression analysis with all the relevant statistics and p-values. From the p-values of the explanatory variables ($^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$), it is clear that only the variables investment rate, employment rate, real interest rate, BTC volumes rate and BTC fees rate, are significant. The credit and debit card number of transactions rate and relative fees rates are not significant.

Variable	**Pooled**	**Fixed-Effect**	**Random-Effect**
Constant	−0.0086***		−0.0073***
DL.K	0.3479***	0.1184***	0.1155***
DL.L	0.4909***	0.6469***	0.6686***
D.Real	−0.0014*	−0.0020***	−0.0020***
D.Crd.F	−0.288	−0.2592	0.2763
DL.Crd.C	−0.0020	0.0024	−0.0007
D.Dbt.F	0.0872	0.5399	0.5446
DL.Dbt.C	0.0044	0.0001	0.0008
D.BTC.F	0.0020**	0.0023**	0.0022**
DL.BTC.V	0.0008***	0.0009*	0.0009*
DL.MWY	−0.0141	−0.0218	−0.0180
Observations	594	594	513
R2	0.4653	0.3533	0.465
Adjusted R2	0.3434	0.3115	0.454
F Statistic	32.0138***	30.4349***	435.805***

Table 4.4: Regression Results

In all the estimated models, there is no evidence of a positive effect of traditional digital payments on growth. The extension of highways alone does not seem to contribute significantly to the growth rate of real GDP. However, traditional macroeconomic variables such as employment and investment rates exhibit a positive effect, while, as expected, the real lending rate shows a negative impact. While the effects of traditional digital payment tools and a potential increase in highways are consistent with the controversial literature, the behavior of macroeconomic variables aligns with expectations. The novelty lies in the role played by blockchain technology. In all the models it has a positive effect. As shown in Table 4.5, the Hausman statistic of 98.658 indicates that the fixed-effect model is preferred to the random one, while the Wald F statistic of 1.94 indicates that the fixed model is also preferable to the pooled one.

Test	**Statistics**	**df**	**p-value**
Hausman Test	chisq = 98.658	10	$< 2.2 \times 10^{-16}$
F-test	$F = 1.9436$	df1 = 26, df2 = 557	0.003704

Table 4.5: Hausman and F-tests for Fixed, Random, and Pooled Models

Finally, we reestimated the fixed effect model from 2009 corresponding to the year when there was the first monetary transaction that assigned a monetary value of $0.0009 US dollars to each bitcoin. The results of the previous analysis are confirmed as in Table 4.6 is shown.

Variable	**Estimate**	**Std. Error**	**T-Value**	**Pr(> |t|)**
DL.K	0.2827^{***}	0.0372	7.6078	0.0000
DL.L	0.5601^{***}	0.0761	7.3563	0.0000
D.Real	-0.0020^{**}	0.0006	−3.2285	0.0014
D.Crd.F	−0.2728	1.0663	−0.2558	0.7983
DL.Crd.C	0.0116	0.0090	1.2883	0.1986
D.Dbt.F	0.6231	0.9910	0.6288	0.5299
DL.Dbt.C	−0.0036	0.0054	−0.6589	0.5104
D.BTC.F	0.0019^{**}	0.0007	2.8596	0.0045
DL.BTC.V	0.0007^{*}	0.0004	1.7956	0.0735
DL.MWY	−0.0201	0.0249	−0.8057	0.4210

Significance levels: $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$
Standard Error of regression: 0.0279
Total Sum of Squares: 0.58435, Residual Sum of Squares: 0.26733
R-Squared: 0.54252, Adj. R-Squared: 0.49007
F-statistic: 37.2363 on 10 and 314 DF, p-Value: $< 2.22 \times 10^{-16}$

Table 4.6: Robust Fixed Effect Model from 2009 to 2021

4.6 Discussion and conclusions

This article delves into the positive impact of the diffusion of Bitcoin blockchain technology and its associated cryptocurrency on the economic growth of EU-27 countries from 2003 to 2021.

The study challenges the conventional belief that economic growth is primarily driven by traditional transport infrastructure development, such as highways and toll road extensions, by exploring the potential influence of digital technologies facilitating cross-border payments.

The total length of motorways, measured in kilometers (km), provides limited insight into variations in road quality and condition, such as the number of lanes and level of congestion. Moreover, it fails to account for differences in construction and maintenance costs. Therefore, a more comprehensive analysis should consider the quality attributes of motorways.

The length of motorways does not account for the varied efforts and expenditure levels required to achieve similar levels of transport infrastructure across different geographical and institutional contexts. This is why a further study should take into the effects on countries groups, like countries of Southern, North, and Eastern Europe.

Examining a panel dataset spanning countries and time, this study delves into the influence of highway infrastructure on economic growth. However, the work not only investigates the implications of highway infrastructure on economic growth but also explores the potential role of a blockchain-based digital payment system for the EU-27 members over the period from 2003 to 2021. All the models estimated find a positive impact of Bitcoin blockchain volumes and Bitcoin fees on growth. The Bitcoin network of instantaneous payments provides secure and international transactions with fees, that during the decades, were lower than those of the banking sector and free from any additional exchange rate commissions.

Bitcoin transactions operate similarly to cash exchanges, with payments moving directly between parties without the need for intermediaries. These transactions are processed through a decentralized network of computers, and each transaction is securely recorded on a public blockchain ledger. A notable feature is the anonymity afforded to customers opting for Bitcoin payments, while merchants benefit from being shielded from automatic chargebacks commonly associated with credit card transactions. Chargebacks occur when customers dispute or report fraudulent charges, leading to financial losses for retailers who are typically obligated to absorb the associated costs of fraud, as mandated by credit card providers.

Utilizing data on bitcoin exchange volumes, network volume, Wikipedia bitcoin searches, GARCH model analysis, and reports on both positive and negative news on bitcoin, Katsiampa (2017) try to ascertain whether Bitcoin is predominantly perceived and used as a currency or an asset. Their findings suggest that Bitcoin exhibits characteristics more similar to an asset, offering financial returns to investors. Dyhrberg (2016) suggests that Bitcoin behaves similarly to gold or the dollar, reacting to the same financial news. Pagano and Sedunov (2020) state that Bitcoin is used as a speculative asset, but they also provide strong and consistent evidence that Bitcoin is used as a transactional currency. However, the debate over whether Bitcoin should be classified as an asset or digital currency remains unresolved. The use of Bitcoin for payments has been increasing over the past few years, and it is currently accepted as a payment method by several merchants.

Whatever people think about Bitcoin, this study concludes that the exchange of digital currencies like bitcoin contributed to economic growth from 2009 to 2021. The inherent features of blockchain, including decentralization, minimal transaction costs, data anonymity, and robust resistance to cyber attacks, render it a more secure and cost-effective payment method compared to traditional credit and debit card technologies.

A limitation of the current study ensues from the fact that solely considering highway extension as a development factor could be misleading. As Ignatov (2024) underlines it could be useful to consider not just the highway extension as a proxy of highways' infrastructure but also a measure of transportation performance. A possible measure is market accessibility which is the highway's capacity to reach important market nodes with low congestion costs.

For future research, the results of this work should be expanded to include various payment methods, such as stablecoins, which offer flat low fees without the volatility associated with Bitcoin. Additionally, the forthcoming introduction of the digital euro and central banks' digital currencies (CBDCs) needs further exploration. The utilization of smart contracts and peer-to-peer payments, enabled by permissioned blockchain technology, is highlighted as a characteristic of the digital euro. Instead, the advantages of a permissionless blockchain payment system, like that of Bitcoin blockchain, include the elimination of intermediaries and of operational costs, as well as enhanced security through a decentralized ledger technology (DLT)

CBDCs are described as centralized money provided by the government, while Bitcoin represents a decentralized form of money provided by the market. It is reasonable to expect different impacts from these two payment methods on the economic landscape. It would be interesting to study the effects of changes in payment technologies on transportation costs and economic growth, considering both direct and indirect causal relationships through a network approach.

Chapter 5

Conclusion

5.1 Summary

This thesis is driven by the growing emphasis on and advancement of blockchain solutions in the transportation sector, particularly within the logistics and automotive supply chain realms. Notably, several automakers, including Toyota, Porsche, Jaguar, and Alfa Romeo Tonale, are actively delving into the potential of blockchain technology. They are integrating blockchain capabilities into their vehicles to securely store vehicle data. For instance, Tesla is exploring the possibility of enabling its vehicles to conduct Bitcoin payments, while BMW and Ford are investigating blockchain for vehicle identification and historical tracking.

These technological innovations present promising opportunities for various applications such as usage-based insurance, autonomous driving, and car-sharing. Volvo and its collaborators are exploring blockchain solutions to facilitate peer-to-peer payments for electric vehicle (EV) charging, while Mercedes-Benz is examining blockchain technology to streamline automated payments at fueling stations and EV charging points.

Additionally, Toyota is deeply involved in integrating autonomous driving vehicles into smart city environments. They are testing blockchain software for autonomous vehicle data sharing and payments. Given the imminent diffusion of blockchain technology, this work aims to investigate its current impact on the transportation industry and the broader economy. It also explores how blockchain could revolutionize payment systems within this emerging technological ecosystem, alongside the challenges it confronts.

In Chapter 2, an extensive literature review is undertaken, emphasizing the advantages and challenges associated with incorporating blockchain technology into the transportation sector. This segment explores the adoption of blockchain technology in diverse transportation fields, leveraging insights from scholarly literature as a credible basis. The examination emphasizes the potentially transformative impacts of blockchain on industries such as agri-food, pharmaceutical supply chains, retail supply chains, logistics, smart cities, and traffic management. Key features highlighted in the literature include peer-to-peer communication without central authority, transparent transaction processing, decentralized transaction records, and data immutability.

In Chapter 3, we outline a proposal for the implementation of a blockchain-driven toll payment system for Italian highway companies, aimed at bolstering security, trust, and operational efficiency. The suggestion advocates for leveraging Bitcoin, Liquid Bitcoin, or stablecoins for payments, citing their advantages over conventional methods. Blockchain technology is highlighted for its capacity to ensure trust, enable instant payments, and eliminate intermediaries, thereby driving down operational expenses. The proposed system harnesses the Blockstream Liquid blockchain, enabling transparent and swift toll payments among stakeholders. It underscores the decentralized nature of blockchain, which simplifies operations and minimizes reliance on intermediaries. Payments are envisioned to be conducted via electronic wallets supporting cryptocurrencies, ensuring direct transactions with user privacy. The adoption of blockchain is justified based on its cost-saving potential, immediate payment capabilities, and ability to potentially incentivize travel behavior. Subsequent research endeavors could delve into its role in facilitating communication among interconnected vehicles regarding road conditions.

In Chapter 4, We investigate the impacts of both highway expansion and the integration of the Bitcoin blockchain for digital payments on the economic growth of the 27 EU member countries. Recognizing blockchain as a pioneering innovation in digital payments, we compare its influence on economic growth with that of conventional digital payment methods. To systematically evaluate the empirical importance of blockchain digital payment innovation on production, we construct a neoclassical growth model. Employing a robust random effects panel model, our study reveals limited evidence supporting claims of a significant productivity boost stemming from highway infrastructure investments. However, we find that both Bitcoin blockchain and credit card transactions demonstrate a positive effect on economic growth.

5.2 Extensions and Further Research

In Chapter 2, we highlight that future research could explore the unaddressed challenges, including scalability, integration complexities, and lack of standardization, to provide a comprehensive understanding of blockchain adoption in transportation. Further investigations into the formation and expansion of Blockchain Consortia could shed light on collaborative approaches to overcome challenges and promote interoperability. Addressing the ethical and regulatory aspects of data privacy within blockchain networks could be a crucial area for future studies.

In Chapter 3, we pointed out that future studies could explore how this technological framework might facilitate safe communication about road conditions among interconnected vehicles and ensure interoperability. Additionally, the presented model could be generalized to enable a single onboard unit to communicate with other nearby OBUs in different vehicles. Finally, it is desirable to implement specific codes and perform robustness and performance tests of the proposed blockchain

In Chapter 4, We found strong evidence of a positive impact of blockchain technology on the real GDP growth rate. However, it appears that the simple increase of highway extension alone is not sufficient to stimulate development.

A constraint of the current investigation arises from the limited focus on highway expansion as a sole measure of development, potentially leading to skewed conclusions. As highlighted by Ignatov (2024), it could be beneficial to broaden the scope beyond merely extending highways, considering factors such as transportation efficiency. An alternative metric to explore is market accessibility, reflecting highways' ability to connect to vital market hubs with minimal congestion. A broad approach that considers congestion costs and the role of highways within a broader network of regional roads and ferries could give new insight into the role of highway infrastructure in the development of EU-27 countries.

Future studies could expand upon this research by examining alternative cryptocurrency payment methods, such as stablecoins, which offer fixed, low fees without exposing customers to Bitcoin's price volatility. The imminent introduction of digital euro and other central bank digital currencies (CBDCs) presents new opportunities. The utilization of smart contracts and peer-to-peer transactions, facilitated by permissioned blockchain technology, is touted as a hallmark of the digital euro. The touted benefits include streamlined payment systems, elimination of intermediaries, reduction of payment transaction costs, and heightened security through decentralized ledger technology (DLT). The primary concern remains the level of privacy associated with a potential blockchain adoption.

Nonetheless, CBDCs will be government-provided centralized currencies, contrasting with Bitcoin's decentralized nature and its market-driven volatility. These two payment methods, together with stablecoins, will coexist in an increasingly diversified payment system. It is reasonable to anticipate divergent impacts from these two or other different blockchain payment methods, which implies completely different levels of privacy, on the economic landscape. Investigating the repercussions of changes in payment technology infrastructures on transportation expenses and economic expansion in general, while considering both direct and indirect causal links through a network-based approach, would be an intriguing avenue for further exploration.

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Appendix A

Statistical Tests

Test	**Statistic**	**Df**	**P-value**
Breusch-Pagan	18.39	10	0.0487
White	60.669	10	2.707e-09
Goldfeld-Quandt	1.7656	246; 245	4.959e-06
Breusch-Godfrey	2.318	2	0.3138
Wooldridge	49.309	19	0.0002

Table A.1: Pooed Model: Tests

Test	**Statistic**	**Df**	**P-value**
Breusch-Pagan	43.266	10	4.457e-06
White	206.34	10	¡ 2.2e-16
Goldfeld-Quandt	1.7549	286; 286	1.176e-06
Breusch-Godfrey	16.359	2	0.0003
Wooldridge	103.04	22	6.433e-12

Table A.2: Fixed Effect Model: Tests

Test	**Statistic**	**Df**	**P-value**
Breusch-Pagan	59.909	9	1.396e-09
White	275.34	9	< 2.2e-16
Goldfeld-Quandt	1.6824	287; 287	5.978e-06
Breusch-Godfrey	21.705	2	1.935e-05
Wooldridge	100.01	22	6.433e-12

Table A.3: Random Effect Model: Tests

Variable	**Estimate**	**Std. Error**	**t value**	**Pr**$(>\lvert\mathbf{t}\rvert)$
Constant	-0.0086^{***}	0.0018	-4.8608	0.0000
DL.K	0.3479^{***}	0.0785	4.4280	0.0000
DL.L	0.4909^{***}	0.0779	6.3005	0.0000
D.Real	-0.0014^{*}	0.0010	-1.6492	0.0997
DL.Crd.F	0.0872	2.2418	0.0389	0.9690
DL.Crd.C	-0.0020	0.0048	-0.4214	0.6736
DL.Dbt.F	0.2759	2.3954	0.1152	0.9083
DL.Dbt.C	0.0044	0.0052	0.8539	0.3937
D.BTC.F	0.0020^{**}	0.0009	2.1349	0.0332
D.BTC.V	0.0008^{***}	0.0002	4.5615	0.0000
DL.MWY	-0.0141	0.0153	-0.9168	0.3597

R-Squared: 0.4653, Adj. R-Squared: 0.3434

Table A.4: Robust Pooled Least Squares

Variable	**Estimate**	**Std. Error**	**t value**	**Pr**$(>\lvert\mathbf{t}\rvert)$
DL.K	0.1184^{***}	0.0179	6.5854	0.0000
DL.L	0.6469^{***}	0.0619	10.4484	0.0000
D.Real	-0.0020^{***}	0.0005	-3.9659	0.0000
D.Crd.F	-0.2592	1.1631	-0.2229	0.8237
DL.Crd.C	0.0024	0.0044	0.5311	0.5955
D.Dbt.F	0.5399	1.0873	0.4965	0.6197
DL.Dbt.C	0.0000	0.0036	0.0042	0.9966
D.BTC.F	0.0023^{**}	0.0007	3.0900	0.0021
DL.BTC.V	0.0009^{*}	0.0004	2.2492	0.0249
DL.MWY	-0.0218	0.0184	-1.1862	0.2361

R-Squared: 0.3033, Adj. R-Squared: 0.3115

Table A.5: Robust Fixed Effect Model

Variable	**Estimate**	**Std. Error**	**t value**	**Pr**$(>\lvert\mathbf{t}\rvert)$
Constant	-0.0073^{***}	0.0019	-3.8070	0.0001
DL.K	0.1155^{***}	0.0179	6.4695	0.0000
DL.L	0.6686^{***}	0.0595	11.2314	0.0000
D.Real	-0.0020^{***}	0.0005	-3.9765	0.0000
D.Crd.F	-0.2763	1.1646	-0.2373	0.8125
DL.Crd.C	0.0007	0.0044	0.1638	0.8698
D.Dbt.F	0.5446	1.0871	0.5009	0.6164
DL.Dbt.C	0.0008	0.0036	0.2231	0.8234
D.BTC.F	0.0023^{**}	0.0007	3.0641	0.0022
DL.BTC.V	0.0009^{*}	0.0004	2.2019	0.0277
DL.MWY	-0.0180	0.0176	-1.0194	0.3080

R-Squared: 0.3539, Adj. R-Squared: 0.3428

Table A.6: Robust Random Effect Model