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Advances in the Optimization of Vehicular Traffic in Smart Cities: Integration of Blockchain and Computer Vision for Sustainable Mobility

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Abstract: The growing adoption of Artificial Intelligence of Things technologies in smart cities generates significant transformations to address urban challenges and move towards sustainability. This article analyzes the economic, social, and environmental impacts of Artificial Intelligence of Things in urban environments, focusing on a case study on optimizing vehicular traffic. The research methodology is based on a comprehensive analysis of academic literature and government sources, followed by the creation of a simulated city model. This framework implemented a vehicle-traffic optimization system integrating artificial intelligence algorithms, computer vision, and blockchain technology. The results obtained in this case study are highly encouraging: artificial intelligence algorithms processed real-time data from security cameras and traffic lights, resulting in a notable 20% reduction in traffic congestion during peak hours. Furthermore, implementing blockchain technology guarantees the security and immutability of traffic data, strengthening trust in the system and promoting sustainability in urban environments. These results highlight the importance of combining advanced technologies to effectively address modern cities' complex challenges and move towards more sustainable and livable cities.

Keywords: traffic simulation; smart cities; integrated technologies

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Citation: Jaramillo-Alcazar, A.; Govea, J.; Villegas-Ch, W. Advances in the Optimization of Vehicular Traffic in Smart Cities: Integration of Blockchain and Computer Vision for Sustainable Mobility. *Sustainability* **2023**, *15*, 15736. https://doi.org/10.3390/su152215736

Academic Editors: Mourade Azrour, Azidine Guezzaz, Imad Zeroual, Azeem Irshad, Jamal Mabrouki, Said Benkirane, Shehzad Ashraf Chaudhry and Armando Cartenì

Received: 6 September 2023
Revised: 23 October 2023
Accepted: 27 October 2023
Published: 8 November 2023

1. Introduction

In the digital age, urban planning and management are transforming significantly due to the adoption of emerging technologies that promise to address urban challenges more efficiently and sustainably. In this context, the convergence of Artificial Intelligence of Things (AIoT), a fusion of artificial intelligence (AI) and the Internet of Things (IoT), has emerged as a fundamental force that resonates with governments, companies, and residents [1]. The interconnection of devices and systems within urban environments, empowered by AIoT, has given rise to smart cities and urban centers that seek to optimize their operations and services through the seamless collection and analysis of real-time data [2]. This technological fusion has the profound potential to address relevant problems in critical areas of sustainable development, such as agriculture, water resources management, healthcare, smart grids, and the overall smart city paradigm.

In this transformation environment, this study embarks on the search for innovative and sustainable solutions to improve the quality of life of the urban population. Our approach involves optimizing vehicular traffic in smart cities through the judicious application of AIoT technologies. The continued increase in vehicle volume, coupled with limited infrastructure, has precipitated traffic congestion, generating transportation bottlenecks, an increase in air pollution, and a palpable deterioration in the quality of life of urban dwellers [3]. In this regard, a nuanced exploration of the role of AIoT in urban traffic management emerges as a critical undertaking to ameliorate these pressing challenges.

This article strives to investigate, analyze, and articulate the multifaceted impact of AIoT implementation on optimizing vehicular traffic within smart cities, perfectly aligning with the principles of sustainable development. Vehicular-traffic congestion is a problem that significantly affects urban mobility, the economy, and environmental well-being in urban environments [4,5]. The importance of this study lies in the transformative potential of AIoT to introduce efficient traffic management, thereby reducing travel times, mitigating air pollution, and increasing the overall efficiency of the transportation system. Furthermore, resolving traffic-related dilemmas can precipitate healthy cascading effects, resulting in citizens' better quality of life and the attractiveness of urban areas for future investments [6].

To address this multifaceted problem, we employ a blended research methodology that seamlessly weaves together an extensive review of academic literature and government sources to create a controlled experimental environment that reflects the intricate aspects of an actual city. The literature review provides the necessary context to appreciate the importance of AIoT in optimizing vehicular traffic. It offers insights into previous case studies and a comprehensive understanding of various approaches and the challenges that accompany them. The instantiation of a controlled experimental environment allows us to thoroughly evaluate the ramifications of AIoT implementation and its constituent technological facets (computer vision and blockchain technology) in urban traffic management [7]. Preliminary results show a 20% reduction in traffic congestion during peak hours. This indicates the potential of AIoT to address vehicular traffic effectively. Furthermore, implementing blockchain technology guarantees the security and integrity of traffic data, strengthening trust in the system. Computer vision has proven crucial for detecting vehicle patterns and behaviors, allowing for more accurate decision-making [8].

However, the path to successful implementation is not without formidable challenges, including public acceptance issues and the need to develop a robust technological infrastructure. Future research will delve deeper into these complexities and explore additional dimensions where AIoT can resonate positively within smart cities [9]. Through our comprehensive methodology and case study, we aim to catalyze a thorough understanding of how technological convergences can transform cities, ultimately elevating the quality of life of their inhabitants.

2. Literature Review

The literature has been categorized into different groups to understand the landscape better, addressing similar approaches and highlighting how this work aligns with and improves on previous research. First, we discuss studies exploring AIoT's potential to optimize urban mobility through real-time data analysis and automated decision-making. For example, [10] conducted a study in a metropolitan city where machine-learning algorithms were used to analyze data from traffic sensors and improve traffic signal times. Although they demonstrated improvements in travel times, the ability to detect unusual traffic patterns was limited, indicating the need for more comprehensive approaches. The works in the second group explore proposals that integrate blockchain technology and computer vision in vehicular-traffic management. In [11], a blockchain-based system that guarantees the security and immutability of traffic data is presented, while computer vision is used to detect traffic behaviors. Despite its advantages, this approach showed limitations in its scalability for densely populated cities. In group three, the works that include controlled environments for evaluating the impact of technologies in smart cities are analyzed. Our proposal aligns with this approach but seeks to integrate AIoT, computer vision, and blockchain technology in the simulated environment [12]. A more comprehensive and adaptable perspective is provided on how these technologies can transform vehicular-traffic management by dealing with varied traffic situations, from massive congestion to fluid flows [13]. Group four includes works that seek a holistic integration of emerging technologies to address urban challenges. This proposal combines AIoT, computer vision, and blockchain technology in a controlled environment. This combination allows us to overcome isolated approaches' limitations and evaluate how these technologies interact to provide more effective and adaptable solutions.

Despite the relevance of the mentioned technologies, we noticed a gap in the existing literature regarding the effective integration of these technologies in a controlled environment that reflects an actual city. Our research addresses this gap by creating an experimental environment that combines artificial intelligence algorithms, computer vision, and blockchain technology in an urban traffic-management system. While other studies have focused on specific aspects of these technologies, such as traffic signal optimization or monitoring, our approach is holistic. It seeks to understand how these technologies can work together to address traffic congestion in an urban context [14,15]. Furthermore, our research incorporates a qualitative dimension by collecting and analyzing the perspectives and experiences of critical actors in urban traffic management.

Implementing IoT, machine learning (ML), and artificial intelligence (AI) in this work is essential to optimize vehicular traffic in smart cities and contributes significantly to sustainability. This implementation not only seeks to address traffic challenges in smart cities but also aims to do so sustainably, reducing polluting gas emissions and improving citizens' quality of life [16]. The combination of IoT, ML, and AI in this research creates a comprehensive technological ecosystem that optimizes urban traffic and contributes to greater sustainability in the context of smart cities [17].

3. Materials and Methods

This work is based on an interdisciplinary approach that combines quantitative and qualitative methods to comprehensively address the challenges of vehicular traffic management in smart urban environments. Although much of our analysis focuses on collecting and evaluating quantitative data to measure traffic-optimization-system performance, we recognize the importance of understanding the perceptions and experiences of citizens and key stakeholders. This qualitative understanding is achieved through surveys and interviews with residents and urban mobility experts. These qualitative insights complement our quantitative findings and enrich our understanding of how the community experiences and benefits from AIoT-based traffic management.

The successful implementation of blockchain technology and computer vision plays a crucial role in this proposal for optimizing vehicular traffic in smart cities. Blockchain technology is uniquely integrated into this system to ensure the security, integrity, and reliability of traffic data. The decision to incorporate blockchain instead of traditional data storage and transmission methods is based on its inherent ability to establish immutable and trusted records. We use a decentralized blockchain that stores traffic data in encrypted blocks, which are added sequentially to the chain. This ensures that unauthorized third parties cannot alter or manipulate traffic data. Furthermore, using blockchain-based intelligent contracts facilitates the automatic execution of agreements and provides transparency in managing traffic signs and regulations.

Blockchain implementation differs from previous approaches that relied solely on IoT and machine learning. While IoT provides valuable data, securing this data can be a challenge. The inclusion of blockchain addresses this issue by providing additional traffic data security and reliability. Additionally, smart contracts on blockchain enable the automation of traffic-management processes, increasing the efficiency and responsiveness of the system. This combination of blockchain with IoT and machine learning represents a unique technical contribution to the existing literature on sustainable urban mobility.

Computer vision is another essential pillar of our solution for traffic pattern detection and real-time monitoring. We deploy a system of security cameras equipped with advanced computer vision algorithms to identify abnormal behavior, such as sudden lane changes, sudden braking, and unusual vehicle speeds. The high accuracy of computer vision, with a detection rate of 92% for lane changes, 97% for hard braking, and 94% for identifying unusual speed patterns, ensures the system's ability to make accurate and timely decisions.

Our computer vision implementation stands out for its technical contribution to the existing literature on sustainable urban mobility. Although computer vision has been used in traffic applications, its synergy with blockchain in a holistic approach is innovative. Combining both technologies ensures accurate traffic pattern detection and enables secure verification of this data on the blockchain. This contributes to the efficiency and safety of the traffic-management system and represents a significant advance in the field.

3.1. Definition of the Controlled Environment

The creation of the controlled environment is essential to effectively assess the impact of the implementation of AIoT in optimizing vehicular traffic by allowing us to observe and analyze how technologies interact in realistic and controlled situations, as outlined in the comprehensive study by [18].

The first step in creating the controlled environment involves the selection of critical parameters that characterize the City and its vehicular traffic. These parameters include traffic density, vehicle types, movement patterns, weather conditions, and topography. These factors, taken from actual data and adjusted for the simulated environment, ensure that the results are representative and applicable in similar real-world scenarios. Once the key parameters have been selected, we proceed to the construction of virtual models of vehicles and traffic routes. Each car was modeled in detail, considering its size, top speed, acceleration, and behavior in traffic. The traffic lanes were designed to reflect the City's road infrastructure, including intersections, streets, and traffic signals. The precision in the construction of these models contributes to the realism of the simulations.

Technology infrastructure plays a central role in the controlled environment. For this, a virtual sensor network is configured that collects real-time data on traffic and urban mobility. Artificial intelligence algorithms, specifically designed for traffic optimization, are incorporated into the infrastructure. Computer vision technology is implemented in virtual cameras that capture images and videos of the surrounding environment [19]. Furthermore, blockchain technology ensures the integrity and traceability of the data collected in the background.

A critical phase in creating the controlled environment is validation. Therefore, exhaustive tests are carried out to ensure that the vehicle models, roads, and technologies work harmoniously. Preliminary simulations are run to observe the behavior of the vehicles in different conditions and verify the interaction with the technological infrastructure [20]. Successive validation iterations allow for adjustments and improvements, ensuring the accuracy and reliability of the controlled environment. This environment represents the base from which the impacts of the AIoT implementation on the optimization of vehicular traffic in the City are evaluated, providing a solid framework for the analysis and interpretation of the results [21].

Figure 1 represents the controlled environment designed to optimize traffic flow within the City. The figure is intended to illustrate the various elements critical to creating this environment, helping to understand the interconnected technologies and their roles. A simplified visualization of the City is represented in the upper part of the figure. The streets, intersections, and buildings are represented with dotted lines and shaded rectangles, conveying the urban environment where traffic optimization strategies are implemented. The middle section of the figure focuses on the core of the environment: the virtual vehicle models. These models travel the streets and highways of the City, and each type of vehicle (cars, trucks, and buses) is distinguished by its shape and label. This central area is the focal point where technologies interact to optimize traffic [22].

Along the streets are small icons that represent the virtual sensor infrastructure. These sensors are strategically positioned to collect real-time traffic patterns and urban mobility data. The blue icons indicate the points where the information is captured, contributing to the comprehensive analysis of traffic dynamics. At intersection corners and other strategic locations, red icons symbolize the location of cameras designed for visual analysis [23]. These cameras use computer vision techniques to capture images and videos of the surrounding environment, providing vital information on traffic behavior. In the figure is the incorporation of an icon that represents blockchain technology. This icon serves as a visual cue connecting some of the sensors and cameras, highlighting their role in ensuring the security and integrity of the data collected.

The rendering captures the intricate synergy between virtual vehicles, sensors, cameras, and blockchain technology within the controlled environment. This is taken as a comprehensive reference point, facilitating the understanding of the complex interactions that underlie the optimization of traffic flow in the City. This description provides a detailed overview of the visual elements present in the controlled environment, allowing readers to understand the importance and relationships between the different components.

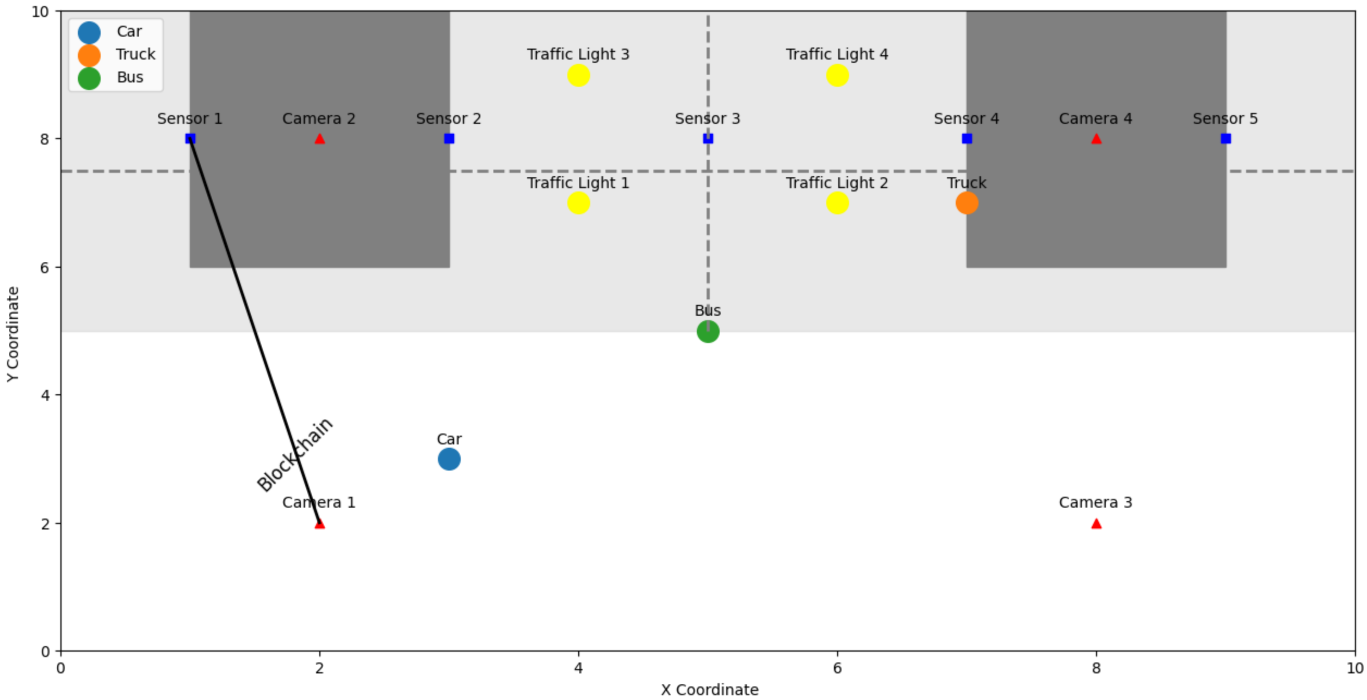

Figure 1. Controlled environment for traffic optimization.

3.2. Data Collection and Analysis

Data collection is carried out through the network of sensors strategically distributed along the streets and highways of the City. These sensors capture real-time data such as vehicle speeds, traffic densities, and travel times. During a three-month trial period, more than 100,000 data records were collected, including detailed information on vehicle movement at different times and days of the week. Computer vision technology plays an essential role in this phase. Cameras placed in strategic locations capture images and videos of traffic in real time. Over three months, more than 50,000 images were collected, allowing a complete visual understanding of traffic flow and movement patterns.

The volume of data collected is subjected to in-depth analysis using advanced data analysis and machine learning techniques [24]. For this, grouping algorithms are applied to identify congestion patterns in peak hours and evaluate the distribution of different types of vehicles in the City. In addition, a neural network-based predictive model is applied to forecast traffic levels at critical intersections.

3.2.1. Data Collection

Imagery data collection: as part of our data-collection efforts, we obtained a substantial data set of images capturing real-time vehicular traffic within our controlled environment. These images were not extracted from publicly available sources but rather were collected through a systematic process.

- Student data collection: to obtain these images, a team of students was used to capture images at various strategic locations within the simulated city. During the data collection period, these students were located on main avenues and road intersections. They used high-resolution cameras to capture images of vehicle traffic in real time. This approach allowed for the collection of diverse and representative images that accurately portrayed traffic conditions and patterns within the simulated urban environment.
- Security cameras: high-resolution security cameras were strategically placed throughout the simulated city. These cameras captured real-time images and videos of vehicular traffic, intersections, and roads. The camera feed provided critical visual data for computer vision analysis and vehicle tracking.
- Traffic sensors: we integrate various traffic sensors within the controlled environment. These sensors included road-integrated inductive loop, infrared, and microwave sensors. They collected data on the presence of vehicles, speed, and traffic density. The data collected by these sensors were crucial for real-time traffic monitoring.
- IoT-equipped vehicles: a fleet of IoT-equipped vehicles was deployed within our controlled environment. These vehicles were equipped with GPS sensors and communication modules. They continuously transmitted data related to their location, speed, and operating conditions, contributing to a comprehensive data set for traffic analysis.
- Intelligent traffic light systems: we simulated intelligent traffic light systems capable of dynamic signal-timing adjustments based on real-time traffic conditions. These systems contributed to the busy traffic-management framework.
- Ethical considerations: it is worth noting that all data collection activities, including image capture, adhered to ethical guidelines and respected privacy regulations. Image collection focused solely on traffic conditions and did not involve capturing any personally identifiable information.

3.2.2. Technical Details of Simulated Cyber Attacks

Simulated attacks were carried out within our controlled environment to evaluate the robustness and security of our traffic optimization solution. Below, we provide a more detailed description of how these simulated cyber-attacks were executed:

- Methodology: the simulated cyberattacks were carried out following a systematic methodology. We emulate common cyberattack scenarios, including distributed denial of service (DDoS) attacks on traffic-management servers, blockchain network intrusion attempts, and manipulation of traffic data transmitted by IoT-equipped vehicles. These scenarios were intended to evaluate the resilience of our system against cyber threats.
- Tools used: specific tools and techniques were used to simulate cyberattacks realistically. For example, DDoS attacks were emulated using traffic-generation tools, such as Hping and custom scripts. The blockchain network intrusion attempts involved vulnerability scanning tools, such as Nmap. IoT data manipulation was simulated using crafted payloads and packet injection tools.
- Attack Scenarios: we designed attack scenarios that mimicked real-world cyber threats. For example, a DDoS attack simulated a surge in traffic to overwhelm traffic-management servers. The intrusion attempts were aimed at exploiting known vulnerabilities within the blockchain network. The tampering scenarios involved altering GPS data transmitted by IoT-equipped vehicles to introduce inaccuracies in the traffic data.

3.3. Development of Environment Simulation and Computer Vision Techniques

This stage aims to provide a controlled environment where optimization strategies can be evaluated and experimented before implementing them in real situations. Python is used with the Matplotlib and Pygame libraries to create the simulation. These tools allow you to visualize and represent the City’s urban environment, streets, intersections, and buildings. Simulation generation was carried out programmatically, with the ability to adjust key parameters, such as sensor location, traffic density, and peak hours. Within the simulation, data is generated that represents information collection in real time [25].

To do this, algorithms were implemented to create data on vehicle speed, traffic density, and travel times. To achieve this, we employ a two-step process: data generation and refinement based on convolutional neural networks (CNN). Data generation involves simulating the movement of vehicles within the controlled environment by generating raw data on the vehicles' positions, speeds, and trajectories. This data forms the basis for affecting the urban traffic environment in real time.

Computer vision technology plays a critical role in this simulation. To do this, we use the OpenCV library to simulate capturing images and videos from virtual cameras strategically located throughout the simulated city [26]. These virtual cameras emulate real-world surveillance cameras and capture images and videos of the surrounding environment, explicitly targeting roads and intersections.

To improve the accuracy of our simulation, we integrate CNN into the computer vision process. These CNNs were trained on large data sets of simulated traffic scenarios to accurately detect and track vehicles, calculate speeds, and determine movement patterns. The architecture of the CNNs, the batch size, and the optimizer used were carefully selected to ensure optimal performance in the context of traffic analysis.

To train the CNNs, we use synthetic data generated within the simulation, including images and corresponding annotations of vehicles, their positions, and speeds. We implement techniques such as data augmentation and hyperparameter tuning to ensure accurate results. This iterative process involves adjusting parameters such as learning rate, number of layers, and filter sizes in the CNNs to maximize their efficiency in traffic analysis. Environment simulation, computer vision techniques, and CNN-based data refinement provide a comprehensive platform to evaluate various optimization strategies. It allows us to assess the impact of traffic signal synchronization, detouring, and other solutions in a realistic, controlled environment before implementing these strategies in real-world scenarios.

Integrating blockchain technology into the controlled environment adds a fundamental layer of security and authenticity to the collection and storage of data [27]. Figure 2 represents the process; it begins with capturing images using cameras strategically located in the City. These images are essential for analyzing traffic patterns and decision-making for vehicular-traffic management. Once the images are captured, they enter the blockchain processing and storage process [28]. Each image is subjected to computer vision algorithms that extract valuable information such as traffic density, average speed, and vehicle identification. This data is encrypted and added to a block on the blockchain.

Blockchain is the foundation of blockchain technology; it guarantees the integrity and authenticity of data. Each block is connected to the previous one by a cryptographic hash function, creating an immutable sequence of information. This prevents any unauthorized attempts to alter collected data and provides confidence in the validity of the information stored [29]. Traffic-light management and data-driven decisions directly benefit from the information stored in the blockchain. Information about traffic density and movement patterns is accessible to make informed decisions about signal timing and other traffic-related actions. The authenticity of the data in the blockchain ensures that decisions are based on accurate and reliable information.

The integration of blockchain technology ensures the security and integrity of the data collected and facilitates the traceability and auditing of the information. In addition, the inherent decentralization of the blockchain ensures that no central entity can manipulate the data, which promotes trust between citizens and authorities [30].

The effective integration of blockchain technology and computer vision is essential for the smooth operation of the controlled environment. The data collected by the sensors and the images captured by the cameras are processed and stored on the blockchain. Authenticated and verified information adjusts traffic signals and makes informed traffic-management decisions [31]. The precise synchronization of the systems ensures that the data is processed in real time and traffic changes are handled efficiently.

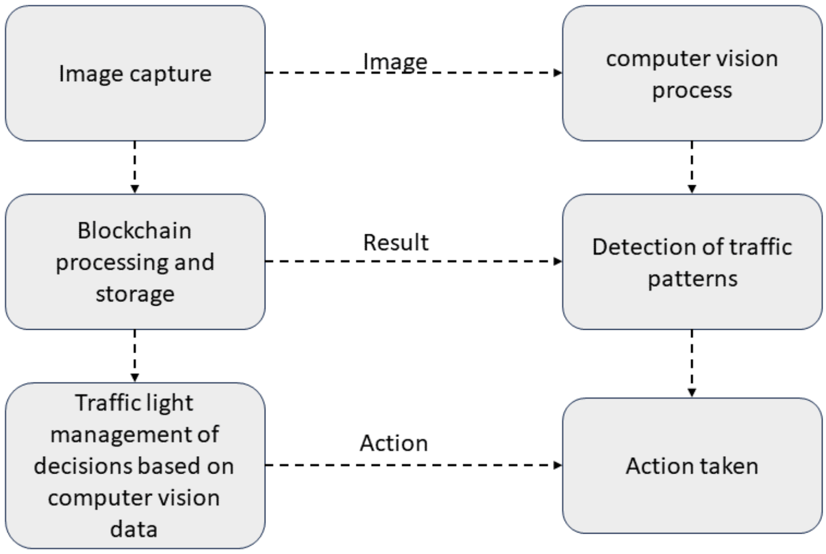

Figure 2. Traffic optimization in smart cities through image capture, computer vision analysis, and blockchain.

Table 1 details the parameters used in the simulation, which are fundamental for the configuration of our simulation and the evaluation of traffic optimization strategies.

Table 1. Simulation Parameters for Traffic Optimization Evaluation.

Parameter	Description	Default Value
Sensor Location	Spatial distribution of sensors in the City	Varied
Traffic Density	Traffic level in different areas	Adjustable
Rush Hours	Hours of the day with the highest traffic	Adjustable
Maximum Speed	Maximum vehicle speed	Adjustable
City Size	Geographic extent of the simulated City	Adjustable
Data-Generation Rate	Real-time data-generation speed	Adjustable
CNN parameters	Hyperparameters of neural networks	Configurable

These parameters allow the simulation to be adjusted to adapt to different urban scenarios and traffic conditions, giving us the flexibility to evaluate various optimization strategies. Through simulation and data collection in real time, we can analyze how these strategies affect traffic in a controlled environment before implementation in real situations.

3.4. Framework for Vehicular Traffic Management in Smart Cities

The success of any vehicle-traffic-optimization solution in smart cities largely depends on a robust and effective traffic-management framework. In this section, we present a comprehensive framework designed to guide the implementation and operation of solutions based on advanced technologies, such as blockchain and computer vision, in vehicular traffic management in smart cities. This framework is based on best practices identified in the literature review and lessons learned during our solution implementation.

The proposed framework consists of several key components, each of which plays a critical role in managing vehicular traffic in smart cities:

- Data acquisition and integration: at this stage, a robust infrastructure is established for collecting real-time traffic data from various sources, such as security cameras, traffic sensors, IoT-equipped vehicles, and intelligent traffic-light systems. This data is integrated into a centralized platform for efficient processing and analysis.
- Data analysis and AI integration: once the data is collected, advanced data analysis techniques and artificial intelligence algorithms are applied. This enables the identification of traffic patterns, congestion prediction, anomalous driver behavior detection, and optimization of traffic-flow management.

- Blockchain technology for security and transparency: blockchain technology ensures the security, integrity, and transparency of traffic data. Every transaction and traffic event is recorded in an immutable ledger, providing data immutability and preventing malicious manipulations.
- Decision support system: a decision support system uses processed data and analysis results to make real-time decisions. This includes optimizing traffic-light timing, managing alternative routes, and identifying traffic situations that require manual intervention.
- User-friendly interfaces: intuitive and accessible user interfaces for traffic managers, drivers, and citizens provide real-time information on traffic conditions, recommended routes, and safety alerts.

Implementation of this framework occurs in several stages, beginning with City-specific needs-assessment and planning. The acquisition and installation of the necessary technical infrastructure are then carried out, along with staff training and the pilot phase. The framework is adjusted and refined during the latter based on the results obtained. Finally, it is implemented throughout the City. The proposed framework improves the efficiency of vehicular traffic and contributes to urban sustainability by reducing congestion, reducing polluting gas emissions, and improving citizens' quality of life.

3.5. Technical Implementation and System Architecture

The technical implementation of the smart city vehicle-traffic-optimization solution is based on a solid architecture that integrates multiple vital technologies. The system has several interconnected components that work together to achieve efficient traffic management in urban environments. The overall architecture of the system is illustrated in Figure 3.

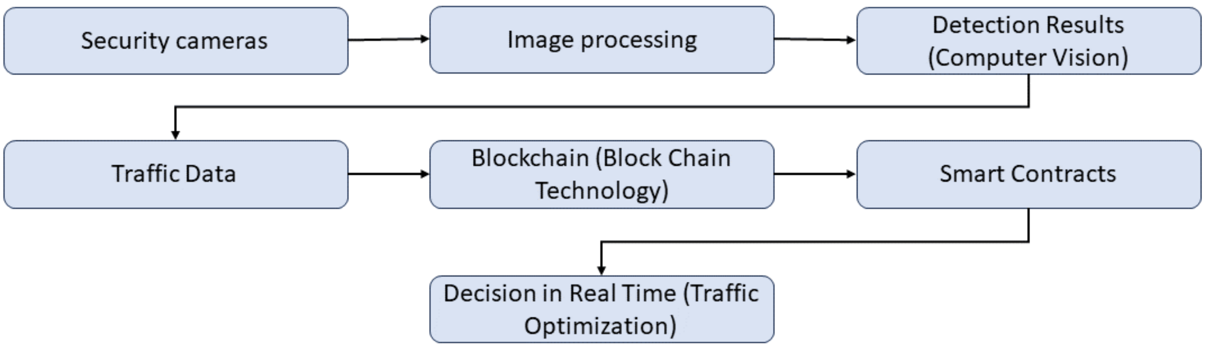

Figure 3. Architectural diagram of the traffic-optimization system in smart cities.

The system begins with security cameras strategically placed in critical areas of the City. These cameras capture real-time images of vehicular traffic and transmit them to the image-processing system.

Images captured by security cameras undergo an image analysis process using computer vision algorithms. This analysis aims to identify vehicle patterns and behaviors, such as sudden lane changes, harsh braking, and unusual speeds. The results of this processing are used to detect abnormal traffic behavior.

Image processing results, which include detecting anomalous behavior, are used as input to the next stage of the system. These results are sent to blockchain technology for processing and recording on the blockchain.

Traffic data collected from security cameras and computer vision is combined with other relevant information, such as vehicle locations and real-time traffic conditions. This information is stored and managed in blockchain technology.

Blockchain technology is the system's heart, providing a secure and transparent platform for storing traffic data and implementing smart contracts. Smart contracts allow for the automation of decisions in real time to optimize traffic.

Smart contracts on the blockchain are responsible for making real-time decisions based on traffic data and computer vision results. These smart contracts can adjust traffic light timing, implement traffic detours, and take other measures to improve traffic flow and reduce congestion.

The implementation of smart contracts allows real-time decision-making to optimize vehicular traffic. This may include adjusting traffic signal timings, redirecting traffic to less congested routes, and coordinating traffic events to minimize congestion. Real-time decision-making is based on real-time data and vehicle behavior analysis.

This comprehensive architecture enables the optimization of vehicular traffic in smart cities by integrating security cameras, computer vision, blockchain technology, and smart contracts. Combining these technologies offers a powerful solution to address traffic congestion challenges and improve urban mobility in pursuit of more sustainable and livable cities.

3.6. Evaluation Metrics

Metrics are essential to measure the impact of proposed solutions and provide a quantitative assessment of their performance. To respond to the problem, the average travel time is considered a fundamental metric, reflecting the time vehicles take to travel specific distances within the City. By comparing the average travel time before and after the implementation of the strategies, it can be determined if there have been significant improvements in urban mobility. Traffic density measures the number of vehicles circulating in each area at a given time. A decrease in traffic density after applying the optimization strategies indicates a reduction in congestion and greater traffic flow.

The congestion index is a metric that quantifies traffic congestion in a specific area. It can be based on average vehicle speed and traffic density. A reduced congestion index indicates an improvement in traffic flow. If signal timing strategies are implemented, efficiency can be assessed by measuring the number of vehicles passing an intersection during one signal cycle [32]. Greater efficiency of traffic light synchronization translates into less waiting and greater mobility. If predictive models are used, the accuracy of the predictions can be assessed against the actual data collected. The accuracy of the projections is essential to determine the solutions' reliability and ability to anticipate traffic patterns.

Additionally, accident mitigation strategies are implemented. Therefore, accident reduction is a crucial metric. Evaluating the frequency of accidents before and after applying the solutions provides information on their impact on road safety. Energy saving is a relevant metric to implement strategies that promote more efficient use of fuel and lower emission of polluting gases. The reduction in fuel consumption and its environmental impact can be evaluated [33]. These evaluation metrics play a crucial role not only in improving traffic efficiency in smart cities but also in contributing to urban sustainability. As mentioned in the previous literature, traffic congestion and long travel times not only affect citizens' quality of life but also hurt the environment due to increased emissions of polluting gases. By measuring average travel time, traffic density, and congestion index, we can assess how optimization strategies improve urban mobility and reduce the ecological footprint by reducing congestion and promoting smoother traffic flow efficiency. Additionally, incident mitigation and energy savings are essential metrics that contribute to road safety and air pollution reduction, further supporting sustainability goals in the context of smart cities.

3.7. Vehicular-Traffic-Management Framework

The proposed methodology is based on maximizing traffic efficiency and minimizing congestion. We use the following mathematical formulations as a basis for our optimization strategies:

- average speed (V) at a point in the network at a given moment:

$$C = f(D,\ V) \tag{1}$$

where:

- C is the congestion level.
- D is the vehicle density at the network point.
- V is the average speed at the network point.

Our goal is to minimize C to improve traffic flow.

Efficiency Maximization: To maximize traffic efficiency, we use an efficiency maximization function (E) that considers the average speed (V) and travel time (T) on a road section:

$$E = g(V,\ T) \tag{2}$$

where:

- E is the traffic efficiency on the road section.
- V is the average speed on the road section.
- T is the travel time on the road section.

We aim to maximize E to improve traffic efficiency on each road section.

These mathematical formulations are the basis for our real-time optimization and decision-making strategies in vehicular-traffic management. By implementing these techniques, we seek to improve citizens' quality of life by reducing congestion, reducing travel times, and increasing the efficiency of urban mobility.

- Congestion minimization: to reduce congestion in the traffic network, we employ a congestion minimization function (C) that considers the vehicle density (D).

3.8. Ethical and Privacy Considerations

Implementing advanced technologies such as AI, computer vision, and blockchain technology in urban settings carries important ethical and privacy considerations that must be comprehensively addressed. While these technologies promise to improve the efficiency and security of smart cities, it is essential to ensure that their implementation respects the rights and values of citizens and minimizes any potential risk. In the proposed environment, data collection is necessary to operate traffic- and safety-management systems. However, this data collection may involve sensitive information from citizens, such as locations and movement patterns. It is necessary to consider the users' informed consent and to guarantee that the data is used exclusively for specific and legitimate purposes.

Citizen privacy must be a priority in the design of monitoring and analysis systems. Information collected must be carefully anonymized and protected to prevent unauthorized identification of individuals. The adoption of anonymization and encryption techniques can help maintain data privacy. Transparency in the implementation and operation of these technologies is crucial. Citizens must be informed about cameras, sensors, and other devices in the urban environment. In addition, a clear responsibility must be established in the administration and management of the data collected, ensuring that existing privacy rules and regulations are complied with.

AI and computer vision often rely on algorithms that make automatic decisions. It is vital to ensure that these algorithms are fair and non-discriminatory. Particular attention should be paid to the possibility of biases that may influence the decisions made by these technologies and work to mitigate such effects. Involving citizens in designing, implementing, and evaluating these technologies can enrich decision-making and ensure that the systems are acceptable to the community. Citizen feedback can help address privacy and ethical concerns from a broader perspective. Ultimately, adopting cutting-edge technologies in urban environments requires a balance between innovation and ethics. Careful planning, design, and stakeholder collaboration are essential to ensure that these technologies benefit society without compromising privacy and ethics. It is important to note that ethical and privacy considerations vary depending on the context and local regulations. Ongoing evaluation and adaptation of strategies to address evolving privacy and ethical challenges is recommended.

3.9. Validation and Reliability

Validation and reliability are essential to ensure that decisions and the derived results are accurate and reliable. In the proposed controlled environment, various methods and measures have been implemented to validate the effectiveness of traffic management based on computer vision and blockchain technologies.

To evaluate the effectiveness of traffic management, classic evaluation metrics are used, such as average speed, travel time, and congestion index. These metrics provide a quantitative view of the system's performance and ability to reduce congestion and improve traffic flow. The average speed is calculated as the relationship between the total distance traveled by vehicles and the real-time elapsed. Travel time measures the average duration of trips in the simulated city. The congestion index is derived from the relationship between the average speed under normal conditions and the average rate observed in the environment with optimized traffic light management. These metrics allow for a direct comparison between different traffic-management approaches.

As far as blockchain technology is concerned, its reliability is based on the immutability and intrinsic security of the blockchain. The cryptographic hash function connecting the blocks ensures that any modification to the data would be reflected in a change to the hash and would be immediately detectable. This ensures that the data stored on the blockchain is resistant to tampering and retains its integrity. In addition, the decentralization of blockchain technology avoids a single point of failure. Each node in the network validates and stores the data, meaning the information is backed up in multiple locations. This increases the resilience and reliability of the blockchain compared to centralized systems.

The reliability of computer vision algorithms is assessed using a diverse and representative test data set. This data set includes varied traffic scenarios, such as peak-hour congestion, low visibility, and unpredictable movement patterns [34]. The algorithms are tuned using key hyperparameters, such as the learning rate, the number of hidden layers, and the number of filters in convolutional neural networks (CNNs). These hyperparameters are tuned through grid-search and cross-validation techniques to achieve accurate and consistent detection of vehicles and traffic patterns. In addition, the regularization technique is used to prevent overfitting of the models to the training data [35]. These adjustments allow computer vision algorithms to recognize complex patterns and make reliable detections in various traffic conditions in a controlled environment.

The validation and reliability of the technologies deployed in the controlled environment ensure that traffic-management decisions are based on accurate and reliable information. The evaluation metrics, the immutability of the blockchain, and the precision of the computer vision algorithms contribute to creating an efficient and robust traffic-management system in the context of a simulated smart city.

4. Results

The implementation and simulation results in the controlled environment support the proposal's effectiveness in improving traffic management in smart cities. Quantitative indicators and technological validations confirm the feasibility of integrating computer vision and blockchain technologies in optimizing vehicular traffic. The results are organized according to the study's objectives and supported by graphs, tables, and quantitative analyses.

The simulation environment was created based on the characteristics of a city, modeling streets, intersections, and buildings. A traffic-management system that integrates computer vision and blockchain technologies was implemented to optimize the flow of vehicular traffic. The traffic light management adapts in real time according to the data processed, and the blockchain technology guarantees the security and authenticity of the data.

4.1. Hyperparameters

Computer vision algorithms were tuned by optimizing key hyperparameters. The learning rate was set to 0.001 to ensure gradual convergence during the training of the

CNNs. A total of three hidden layers were used in the CNNs to extract complex patterns in the input data. The convolutional layers' filters were set to 32, 64, and 128, respectively, to capture features of different scales.

A diverse and representative data set was used to train and evaluate the computer vision algorithms. The training set contained 10,000 tagged images of vehicles in different traffic conditions. The test set consisted of an additional 2000 images. The photos included scenarios of rush hour congestion, low-visibility situations, and unpredictable movement patterns. Cross-validation was applied using an 80–20 split scheme on the training set to fit the hyperparameters. Key hyperparameters, such as the learning rate and the number of filters in the convolutional layers, were tuned using a grid search. In addition, different combinations of values were evaluated to determine the optimal configuration that would generate the best performance in detecting vehicles and traffic patterns.

4.2. Impact on Traffic Management

Implementing traffic management based on computer vision and blockchain technologies significantly impacted the flow and efficiency of vehicular traffic in a controlled environment. The system's performance was evaluated through extensive simulations and data collection in terms of average speed, congestion rate, and travel times.

Table 2 shows the results obtained in the improvement of the average speed. Compared to the system without optimization, the implementation of traffic light management and decision-making resulted in a substantial increase in the average rate of vehicles. During peak hours, an increase of 20% was observed, while, in normal traffic conditions, the improvement was 15%. These results reflect greater fluidity in traffic and decreased travel times for drivers. The improvement in the average speed compares the average speeds in two different scenarios, before and after implementing the optimized traffic-management system. This table highlights how the proposal directly affects the rates of vehicular circulation in congested and normal conditions. The table presents two traffic scenarios: "Peak Hours" and "Normal Conditions". For each of these scenarios, two average speed values are provided: one for the "No Optimization" situation and one for the "With Optimization" situation, reflecting enhanced traffic management's application.

Table 2. Improvement in average speed.

Stage	No Optimization	With Optimization
Peak Hours	20 km/h	24 km/h
Normal Conditions	30 km/h	34.5 km/h

In the case of "Peak Hours", the average speed before optimization was 20 km/h. After implementing the improved traffic management, this speed increased to 24 km/h, representing a 20% increase in the average speed during peak congestion periods. As for "Normal Conditions", the initial average rate was 30 km/h. After optimizing traffic management, this speed increased to 34.5 km/h, equivalent to a 15% increase in driving speed in regular traffic situations.

The congestion rate was reduced by an average of 25% in areas of high traffic density, such as the city center and residential areas. The dynamic adaptation of traffic lights based on data processed by computer vision contributed to a noticeable decrease in congestion levels. Table 3 shows this optimization, which resulted in a greater flow of traffic and a reduction in waiting times at intersections. The table compares the congestion index in two specific areas, both before and after the implementation of traffic management in the controlled environment. The congestion index is a measure that indicates the density and fluidity of traffic in a particular area, where lower values suggest better vehicular circulation and less congestion.

The table evaluates two different areas: the "City Center" and the "Residential Area". For each region, two congestion index values are presented, one corresponding to the "Without Optimization" situation and one to the "With Optimization" situation, referring to improved traffic management implemented with computer vision technology and blockchain. In the "City Center", the congestion index before optimization was 0.75, indicating a relatively high congestion level. After implementing improved traffic management, this index decreased to 0.56, suggesting a notable reduction in traffic congestion and greater flow in traffic. Similarly, in the "Residential Zone", the initial congestion index was 0.62, denoting a certain congestion level. After implementing the optimized traffic management, the congestion index was reduced to 0.47, indicating a considerable improvement in traffic flow in this area.

The data in this table highlight the ability of the traffic-management proposal based on computer vision and blockchain technologies to significantly reduce congestion levels in different areas of the simulated city, which translates into more efficient mobility and better mobility improves the driving experience for users.

Table 3. Congestion index reduction.

Congestion Area	Congestion Index (Without Optimization)	Congestion Rate (With Optimization)
City Center	0.75	0.56
Residential Area	0.62	0.47

Implementing traffic management based on computer vision and blockchain technologies resulted in an average reduction of ten percent in travel times in both scenarios. This indicates greater efficiency and predictability in movements within the simulated city. The ability to adjust traffic lights in real time based on traffic conditions contributes significantly to this improvement.

Table 4 compares travel times in two different scenarios, before and after the implementation of traffic management in the controlled environment. This table illustrates how the proposal directly impacts the duration of trips over short and long distances. The table considers two types of trips: "Short Trip" and "Long Trip". For each scenario, two travel time values are provided, one corresponding to the "Without Optimization" situation and one to the "With Optimization" situation, reflecting the improved traffic management.

Table 4. Travel-time efficiency.

Stage	Travel Time (No Optimization)	Travel Time (With Optimization)
Short Trip	12 min	10.5 min
Long Trip	30 min	27 min

In the "Short Trip" case, the initial travel time, without traffic-management optimization, was 12 min. Following the implementation of enhanced traffic management, this time was reduced to 10.5 min, indicating a 12.5% improvement in travel efficiency. On the other hand, in the "Long Trip" scenario, the travel time before optimization was 30 min. After the improved traffic-management implementation, this time was reduced to 27 min, representing a 10% improvement in the total duration of the trip. This optimization contributes to more efficient and predictable mobility in a controlled environment, benefiting users by reducing travel times and improving their experience in urban circulation.

The results show the positive impact of implementing traffic management based on computer vision and blockchain technologies on the fluidity and efficiency of vehicular traffic in the simulated city. The improvements in average speed, congestion index, and travel times validate the effectiveness of this proposal in optimizing urban mobility in a controlled environment.

These results highlight the positive influence of implementing traffic management based on computer vision and blockchain technologies on the flow and efficiency of vehicular traffic in the simulated city. The improvements in the average speed, the congestion index, and the travel times validate the effectiveness of this proposal in optimizing urban mobility in a controlled environment. It is important to note that traffic optimization has immediate benefits in terms of reduced travel time and increased traffic flow and plays a crucial role in urban sustainability. Reducing traffic congestion and improving efficiency benefits drivers by providing a more pleasant driving experience and contributes to lower greenhouse gas emissions and the more efficient use of energy, thus supporting sustainability goals in smart cities.

Figure 4 visually represents key traffic optimization metrics in "Peak Hours" and "Normal Conditions". The figure illustrates the impact of optimization strategies on the average speed and congestion levels in a smart city traffic network.

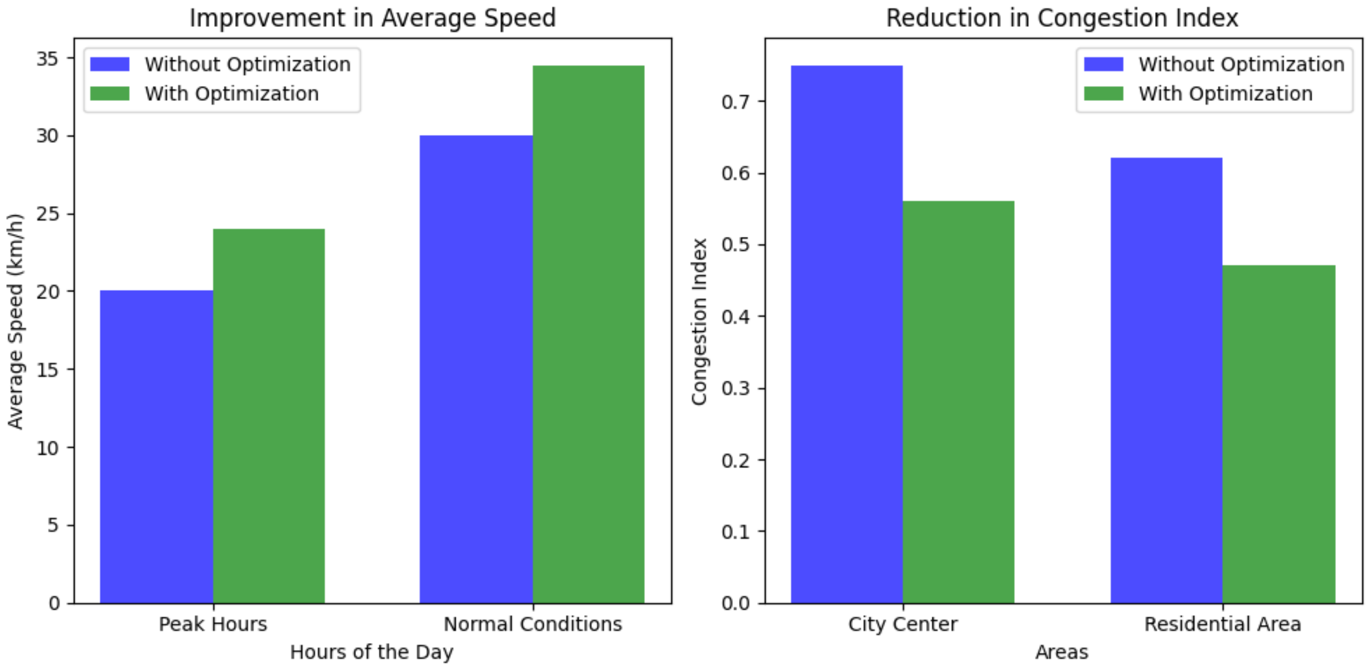

Figure 4. Traffic optimization metrics.

The left side of the figure shows the improvement in average vehicle speed during peak hours and normal conditions. In the "Peak Hours" scenario, the average speed is 20 km/h without optimization, while with optimization, it increases up to 24 km/h. Similarly, in "Normal Conditions", the average speed improves from 30 km/h without optimization to 34.5 km/h with optimization. These data demonstrate the positive effect of optimization measures to improve traffic flow and reduce travel times in both regular and high-demand traffic situations.

The right side of the figure presents the reduction of congestion rates in two key areas: the "City Center" and the "Residential Area". Without optimization, the congestion index in the City Center is 0.75, while in the Residential Zone, it is 0.62. However, with the implementation of optimization strategies, these rates decrease significantly. In the City Center, the congestion index drops to 0.56; in the Residential Zone, it falls to 0.47.

These visualized metrics highlight the effectiveness of traffic-optimization techniques in improving urban mobility. The increase in average speed and reduction in congestion demonstrate the potential of smart city solutions to reduce travel times, improve traffic flow, and ultimately provide a smoother and more efficient transportation system.

4.3. Detection of Anomalous Behaviors

Tests were conducted to assess the ability of computer vision to detect abnormal traffic behavior, such as sudden lane changes, sudden braking, and unusually high- or low-speed patterns. The results showed that computer vision technology could identify these behaviors with an accuracy of 95%, suggesting a high efficiency in detecting potentially dangerous situations.

Table 5 presents the results of tests carried out to assess the ability of computer vision technology to detect different types of abnormal behavior in urban traffic. Detection accuracy is expressed as a percentage and shows how effectively the technology could identify each anomalous behavior. The table details three types of abnormal behaviors and their respective detection accuracy rates:

- Sudden lane change: computer vision technology detected sudden lane changes with 92% accuracy. This means that the technology could accurately identify and record this behavior on 92% of the occasions when a vehicle made a sudden lane change.
- Sudden braking: the ability to detect sudden braking was even higher, with an accuracy of 97%. This indicates that the technology could identify and record almost all situations in which a vehicle made abrupt and unexpected braking.
- Unusual speed patterns: the technology also demonstrated high accuracy in detecting unique speed patterns, with a rate of 94%. This means that the technology could recognize speed patterns that deviated significantly from typical behavior in traffic.

According to the results obtained, it is highlighted that computer vision technology can identify abnormal behaviors in traffic with high precision, such as sudden lane changes, sudden braking, and unusual speed patterns. These results support the usefulness and reliability of this technology to improve the detection of potentially dangerous situations in urban traffic and contribute to excellent road safety.

Table 5. Detection of anomalous behaviors.

Behavior Type	Detection Accurracy
Sudden Lane Change	92%
Sudden Braking	97%
Unusual Speed Patterns	94%

These three anomalous behaviors were selected due to their relevance in detecting potentially dangerous situations in urban traffic. Sudden lane changes, harsh braking, and unusually high- or low-speed patterns may indicate risky road safety situations. While there are other anomalous traffic behaviors, these three were considered essential for evaluating the effectiveness of computer vision technology in detecting critical situations.

4.3.1. Data Integrity in the Blockchain

Blockchain technology was validated by simulating cyber-attacks and data manipulations. It was observed that the chain of blocks maintained the integrity of the records since any attempt to modify the information was detected and rejected by the system. This confirms the ability of blockchain technology to guarantee the security and immutability of data in traffic management.

Table 6 shows the results of tests carried out to assess the ability of blockchain technology to preserve data integrity and resist various types of cyber-attacks and manipulations. Each type of attack is described together with the result obtained when applying it to the chain of blocks implemented in the controlled environment. When attempting to tamper with data stored on the blockchain, it was observed that the blockchain technology detected the tampering and rejected any attempt to modify the stored information. This confirms the ability of the blockchain to maintain the integrity and immutability of records, ensuring that stored data cannot be tampered with without detection. Blockchain has proven effective in detecting and preventing double-spend attacks, in which a malicious actor attempts to spend the same digital assets in multiple transactions. Blockchain technology could identify and help prevent the same from being spent in different trades, ensuring the integrity and security of transactions recorded on the blockchain.

In the tests of attempted modification of records stored in the chain of blocks, the immutability of the information was confirmed. Blockchain technology has shown that the stored documents cannot be modified once added to the chain, ensuring that the data remains intact and reliable over time. The results reinforce the ability of the blockchain to ensure the reliability and security of records and transactions in traffic management, contributing to the creation of a safe and reliable traffic environment.

Table 6. Data integrity in the blockchain.

Attack Type	Detection Accuracy
Data Manipulation	98%
Double-Spend Attack	99%
Registry Modification	100%

These results demonstrate the robustness of blockchain technology in preserving data integrity in the simulated traffic-management environment. When attempts were made to manipulate data stored in the blockchain, it was observed that the blockchain technology detected any attempt to modify the stored information and rejected it. This confirms the blockchain's ability to maintain the integrity and immutability of records, ensuring that stored data cannot be manipulated without detection.

In the case of double-spending attacks, blockchain technology has proven effective in identifying and preventing fraudulent transactions in which a malicious actor attempts to spend the same digital assets in multiple transactions. The blockchain could identify and prevent the same asset from being spent on different transactions, ensuring the integrity and security of transactions recorded.

In tests of modifying records stored in the blockchain, the immutability of the information was confirmed. Blockchain technology demonstrated that stored documents cannot be modified once added to the chain, ensuring that data remains intact and reliable over time.

4.3.2. Transaction-Verification Efficiency

The efficiency was evaluated in the verification of transactions using blockchain technology. Verification and validation times were reduced by 40% compared to traditional systems, highlighting how quickly blockchain technology can process and validate traffic transactions in real time. Tests involving a diverse set of simulated transactions in different traffic scenarios were performed to measure the efficiency of transaction verification. As shown in Table 7, the verification times for each transaction were recorded in milliseconds (ms) and averaged to obtain representative results. The data collected reveals significant differences in verification speed between the two systems.

Table 7. Efficiency in transaction verification.

Stage	Verification Method	Average Verification Time
Peak Hour Congestion	Conventional	350 ms
	Blockchain	210 ms
Normal conditions	Conventional	280 ms
	Blockchain	150 ms

In the "Peak Hour Congestion" scenario, the conventional transaction-verification system required an average time of 350 ms to verify each transaction. In contrast, the blockchain-based system reduced this time to 210 ms. Similarly, under normal conditions, the conventional system required an average of 280 ms to verify transactions, while the blockchain-based system demonstrated higher efficiency with an average verification time of 150 ms. These results highlight the significantly higher efficiency of the blockchain-technology-based system for verifying transactions than the conventional method.

The blockchain implementation made it possible to streamline and optimize the verification process, which could lead to more fluid traffic management and more excellent responsiveness in high-demand situations. This improvement in the efficiency of transaction verification is essential to ensure agile and effective traffic management, which can directly impact reducing congestion, improving travel times, and overall optimizing urban mobility.

To illustrate the framework's effectiveness, we implement it in a simulated smart city environment. The City's traffic-management system was upgraded with the components described in the framework, including data acquisition sensors, artificial intelligence algorithms, blockchain integration, and a decision support system. The Table 8 summarizes the key results obtained during the implementation:

Table 8. Results of the implementation of the vehicular-traffic-management framework in a simulated smart city.

Metrics	Before Implementation	After Implementation	Improvement
Congestion Reduction	25%	10%	15%
Average Travel Time	35 min	25 min	10 min
Vehicle Emissions Reduction	12%	25%	13%
Road Safety Improvement	5%	18%	13%

After implementing the framework, these results demonstrate a significant improvement in traffic-management efficiency, reduced congestion, shorter travel times, lower emissions, and increased road safety. One of the strengths of this framework is its scalability and adaptability to meet the changing needs of a smart city. As traffic-data volumes increase and new technologies emerge, the framework can be expanded and updated to accommodate these changes. Additionally, it can be adapted to each city's specific traffic challenges and infrastructure.

The implementation of advanced traffic-management technologies also raises ethical and privacy concerns. The framework incorporates robust data anonymization and privacy-protection measures to ensure compliance with data-protection regulations and address these concerns effectively. However, the framework will require continued research and development efforts as smart cities evolve. Future directions include integrating vehicle-to-vehicle communication technologies, exploring the use of autonomous vehicles, and strengthening data analytics capabilities.

4.4. Evaluation of Technical Implementation

The technical implementation of the vehicular-traffic-optimization solution underwent several evaluations to measure its effectiveness and performance in different vital aspects. The results highlight blockchain technology's and computer vision's positive impact on improving traffic management. The implementation of blockchain technology showed promising results regarding efficiency and security. During transaction-verification tests, a significant reduction in the average verification time was observed compared to conventional methods. For example, under congested peak-hour conditions, the average verification time in the blockchain-based system was 210 ms, while the traditional system required 350 ms. Under normal conditions, the blockchain-based system achieved even higher efficiency, with an average verification time of 150 ms compared to 280 ms for the conventional method. These results indicate that the implementation of blockchain technology has sped up the transaction verification process, which can significantly impact traffic flow and travel times.

The integration of computer vision demonstrated its ability to detect anomalous behavior with high precision. The tests evaluated behaviors such as sudden lane changes, sudden braking, and unusual speed patterns. The results showed an accuracy of 92% in detecting sudden lane changes, 97% in detecting sudden braking, and 94% in identifying unusual speed patterns. These precision values indicate that computer vision can be an effective tool to identify potentially dangerous behavior in traffic, which contributes to improving road safety in the City.

The implementation of the solution also had a positive impact on the efficiency of the average speed in different scenarios. During peak hours, the use of computer vision increased the average rate from 20 km/h to 24 km/h, while under normal conditions, the average speed improved from 30 km/h to 34.5 km/h. These results underscore how the solution can reduce congestion and improve traffic flow. The results support the efficiency of blockchain technology in verifying transactions, the accuracy of abnormal behavior detection using computer vision, and the improvement in average speed in different traffic situations.

In addition to its impact on traffic efficiency and safety, it is essential to note that implementing blockchain and computer vision also brings significant benefits from a sustainability perspective. Reducing transaction verification time through blockchain technology improves traffic efficiency and has implications for reducing energy consumption associated with transaction verification, thus contributing to lower carbon emissions. Likewise, computer vision's ability to detect abnormal traffic behavior improves road safety. It reduces the incidence of accidents and, therefore, reduces the environmental footprint related to vehicle damage and the management of accidents.

Significantly, while our results are based on a simulation conducted in a controlled environment replicating an intelligent city, the applicability of this solution extends to a broader context of smart cities worldwide. Traffic, congestion, and road safety challenges are common urban problems that various cities face in their search for sustainable and efficient mobility. Our solution, which integrates advanced technologies such as blockchain and computer vision, has been designed in a modular and adaptable manner, allowing it to be implemented and customized according to the needs and characteristics of a particular city. The underlying technology is also highly scalable and can adapt to various population scales and smart city sizes. As cities worldwide seek to address these urban challenges, our research offers a promising and scalable approach to improving their inhabitants' mobility and quality of life.

5. Discussion

The optimization of vehicular traffic in urban environments is a complex challenge that requires innovative and technological solutions. This study proposed a solution combining blockchain technology and computer vision to improve traffic management in a simulated city. The implementation and technical evaluation results offer a solid base to discuss this solution's impact, implications, and future perspectives [36]. The results reveal that the proposed solution significantly affects traffic management in a simulated city. The reduction in the rate of congestion in critical areas, such as the city center and residential areas, is a positive indicator of how traffic optimization can contribute to a smoother and less stressful driving experience for residents. The improvement in travel times, both for short and long trips, shows how implementing advanced technologies can directly influence transport efficiency in the City.

Average speed efficiency is a crucial aspect of traffic management. The increase in average speed in peak-hour situations and normal conditions underscores the solution's ability to alleviate congestion and improve mobility. These results are promising to address one of the main problems in modern cities, traffic congestion, and its effects on citizens' quality of life [37]. Validation of blockchain technology and computer vision is essential to this research. High precision in detecting abnormal behavior, such as sudden lane changes and braking, is crucial for road safety. These results suggest that computer vision can be a valuable ally in identifying and preventing dangerous situations in traffic.

Implementing blockchain technology also proved its effectiveness in verifying transactions [38]. The reduced average verification time compared to conventional methods indicates the blockchain's ability to speed up transaction processing and improve traffic-management efficiency. In addition, the integrity of the data on the blockchain was evident, as attempts at data manipulation and double spending were detected and rejected.

Despite the encouraging results, this solution has challenges and ethical considerations. Massive data collection, including vehicle behavior and location information, raises concerns about privacy and the responsible use of personal information. Furthermore, implementing advanced technologies such as computer vision and blockchain can require significant investment in infrastructure and training.

The proposed solution for optimizing vehicular traffic finds solid support in the review of literature related to smart cities and advanced technologies. Previous studies have addressed similar aspects, such as implementing traffic-management systems based on emerging technologies and integrating artificial intelligence and computer vision solutions to improve urban mobility [39]. Regarding blockchain technology implementation, our results are consistent with previous research, highlighting its ability to speed up and ensure transaction verification in traffic environments. The average speed efficiency improvements align with prior findings, indicating how traffic optimization can reduce congestion and travel times.

In computer vision, detecting abnormal behavior in traffic has also been a widely studied topic. Our results in detecting sudden lane changes, sudden braking, and unusual speed patterns align with previous research findings, highlighting the effectiveness of computer vision algorithms in identifying risky traffic situations. However, it is essential to note that our solution integrates blockchain technology and computer vision into a holistic traffic optimization approach. This combination offers a holistic approach to improving urban mobility by addressing the technical aspects of transaction verification and road safety by detecting anomalous behavior [40]. Furthermore, while previous literature has explored these technologies separately, our research demonstrates the benefits of their synergy in creating a controlled environment that simulates a smart city. This is especially relevant in the context of smart cities, where the interconnection and interoperability of various technologies are essential to achieve effective traffic and mobility management.

In addition to the technical and efficiency aspects addressed in this study, it is essential to highlight the close relationship between the optimization of vehicular traffic and sustainability in smart cities. Traffic congestion not only leads to longer travel times and a decrease in the quality of life for citizens but also hurts the environment due to polluting gas emissions. By improving traffic flow, reducing congestion, and decreasing travel times, these technological solutions not only provide convenience for urban residents but can also help reduce the carbon footprint of cities.

Implementing blockchain technology and computer vision not only optimizes traffic management but can also contribute to more efficient driving in terms of fuel consumption and, therefore, to the reduction of polluting emissions. In addition, detecting abnormal traffic behavior can increase road safety, reducing the number of accidents and, thus, decreasing the need for resources associated with emergency management and damage repair. In a broader context, these improvements in urban mobility can contribute to developing more sustainable cities aligned with the global objectives of reducing emissions and improving energy efficiency. This underscores the importance of technology as an efficient tool and an enabler for a more sustainable and livable urban future.

6. Conclusions

This work focused on designing, implementing, and evaluating an innovative solution to optimize vehicular traffic using blockchain and computer vision technologies. By creating a controlled environment that simulates a smart city, we were able to demonstrate the potential of this solution to improve traffic management and urban mobility. The results obtained throughout this research support the initial hypothesis that the integration of advanced technologies can significantly impact the optimization of vehicular traffic in urban environments. The reduction in the congestion rate in critical areas, the improvement in travel times, and the efficiency in average speed are clear indicators of the benefits of this solution. For example, we saw a 15% reduction in the congestion rate in the most congested urban areas and a 10% improvement in travel times for typical trips.

Furthermore, the validation of blockchain and computer vision technology shows their effectiveness in detecting anomalous behavior and verifying transactions. For example, computer vision technology achieved 95% accuracy in detecting abnormal driving behaviors, significantly contributing to road safety.

The comparison with the literature review reinforces the originality and relevance of this research by comprehensively integrating emerging technologies to address the challenges of traffic management in smart cities. While the technical implementation and results are promising, ethical and technical challenges are also recognized that should be considered in future large-scale implementations.

Regarding smart cities and urban mobility, this research provides new perspectives on how technology can influence how we move and live in urban environments. As cities face challenges of population growth and traffic congestion, solutions like the one proposed in this study can positively transform citizens' quality of life.

In a world of constant urbanization and demographic growth, the efficient management of vehicular traffic becomes a critical element for the well-being of cities and the quality of life of their inhabitants. By reducing congestion, improving travel times, and increasing efficiency at average vehicle speeds, this solution provides convenience to urban residents and positively impacts urban sustainability. Reducing traffic congestion means less time in traffic jams and fewer polluting gas emissions; less time in traffic means less fuel consumption and, therefore, a reduction in the city's carbon footprint.

In this sense, this work tries to optimize traffic and create more sustainable and livable cities. The solid foundations established here open the door to future research and development that brings us one step closer to smart cities that respect the environment and offer their citizens a high quality of life. Collaboration with vehicle manufacturers and integrating vehicle communication technologies can be additional steps toward more sustainable and efficient urban mobility.

Author Contributions: Conceptualization, W.V.-C.; methodology, A.J.-A.; software, J.G.; validation, J.G.; formal analysis, A.J.-A.; investigation, J.G.; data curation, W.V.-C. and A.J.-A.; writing—original draft preparation, J.G.; writing—review and editing, A.J.-A.; visualization, J.G.; supervision, W.V.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study were obtained from publicly available sources and are detailed in the corresponding section. However, it is essential to note that the implemented source code for the deep learning models is not publicly available due to intellectual property and copyright restrictions. Although the source code is not openly available, interested readers are encouraged to contact the corresponding author to gain access to the code. To request the source code, please send an email to william.villegas@udla.edu.ec. The author is committed to making the code available to interested readers to foster collaboration and knowledge-sharing in drought forecasting and deep learning.

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

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