Abstract: Road toll tax contributes significantly in the economic development of any nation. In developing countries, the toll tax collection is carried out either manually or electronically. However, both approaches suffer from various challenges, including prolonged waiting times, lack of transparency, high operational costs, and concerns regarding data security and privacy. This research aims to address these challenges using a blockchain-based system. The proposed system employs advanced image processing techniques, specifically “You Only Look Once” version 5 (YOLOv5), to accurately capture and store vehicles’ registration numbers in a local server situated at toll plazas. Subsequently, the vehicle identification, along with the driver’s credentials, is transmitted to an application server, where an Ethereum smart contract verifies the information and automatically deducts the toll charges from the driver’s account. The results from this study indicate that the proposed system effectively reduces vehicle waiting time and facilitates uninterrupted vehicular movement. Additionally, the system ensures transaction transparency, safeguards the security and privacy of vehicle details, facilitates non-stop payments, rendering unnecessary cash payments or radio-frequency identification scanning at toll booths, and incorporates a decentralized architectural framework to enhance security and mitigate potential system failures.

Keywords: blockchain, smart contract, E-payment, decentralized toll tax collection, intelligent transportation management system

1 Introduction

The transport sector is a key contributor to the economic and social development of any country. Efficient transportation methods are closely linked to a nation’s economic performance [1], with a strong correlation between the distance traveled and Gross National Product [2]. Every day, more and more automobiles are added to the road for passengers and freight transportation. The vehicles must wait a considerable period of time to pay the toll tax amount (TA) at toll plazas, resulting in high traffic congestion [3]. Hence, this accelerates the need for an automated toll collecting system to minimize road congestion and thereby decrease waiting times and vehicle fuel consumption.
In developing countries, road tolls are collected using one of the two methods: manual or electronic. In the manual method of toll collection, a toll collector collects the toll fee in cash from the vehicle driver, and the receipt is issued to the driver. The manual toll collection approach has several issues. For instance, vehicles have to wait for a very long time in the queue in order to pay the toll fee, and the problem turns severe during peak hours [3]. Moreover, the manual toll collection also lacks transparency and trust between the stakeholders as no record is maintained that how many and which vehicles have crossed the toll plaza [4]. Further, the absence of records also makes it difficult to track and trace unregistered and stolen vehicles. Finally, the approach incurs high operational costs as two persons are required at each toll gate. One for dealing the cash with driver and the other for opening and closing of the gate.

In electronic toll tax collection (ETC), a toll fee is collected by deducting an amount from a prepaid radio-frequency identification (RFID) passive tag. The tag, installed on the wind shield of a vehicle, usually carries the basic information such as driver data, vehicle id, and available balance in the user account [5,6]. A tag reader installed on the toll gate reads and routes the tag data to a host computer. This host computer is connected to a central server through the internet, and data validation is done on the server side [7]. The one obvious advantage of this approach is that the driver does not need to stop the vehicle at the toll plaza; consequently, it ensures smooth traffic flow. Further, it reduces the high operational costs and efforts incurred in manual toll collection. In addition to this, a record of passing by vehicles is maintained in the central database that can be used to track the vehicles. Despite the advantages of the RFID approach, the system has its unique challenges. One of these is reading a noisy tag. It means that the tag reader may face glitches or failures while reading tags. The process results in the wastage of time, thus annoying drivers in the queue. Also, many a times tags have insufficient balance, hence, driver has to pay the toll fee in cash. Interoperability is another issue [8] as contractors use different RFID standards. Hence, a vehicle must carry multiple RFID tags for speed passage through the toll gate. Due to the openness of radio waves and readability of tag information from a short distance (10 cm to 30 m), the RFID approach suffers from major security and privacy threats. For instance, tags are vulnerable to tempering [2], cloning, and traceability (Figure 1). Therefore, attackers can gain access and subsequently use the information for malicious purposes.

![Figure 1: Existing RFID system working with flaws.](image-url)
The blockchain technology has the capacity to address these problems in a decentralized manner [9]. In such systems, security is often considered to be robust and resilient due to several inherent characteristics of such systems. For example, they rely on consensus mechanisms and provide transparency, as the entire transaction history or state of the system is visible to all participants [10]. In this study, we proposed a blockchain-driven system that automatically collects the toll tax at toll plazas in an efficient manner. The proposed system uses image processing technique, i.e., YOLOv5 [11], to read the vehicles, registration number, which is subsequently stored at toll plazas’ local storage/server. The vehicle id along with driver’s credentials are sent to the application server. Ethereum smart contract authenticates the vehicle data and collects toll charges automatically from the driver’s digital wallet. The results show that the proposed system reduces vehicle waiting time in the toll queue and hence saves on fuel consumption. By regulating the flow of vehicles through toll collection points, authorities can prevent congestion and ensure a smoother traffic experience on highways and expressways [12]. The major contributions of this proposed smart toll collection system over the existing RFID based systems are listed as follows:

- **An automated toll collection framework**: We develop a novel framework that provides the transparency of the transacted data as well as security and privacy of the vehicle details.
- **Non-stop payment**: The proposed system does not require the vehicle to stop at the booth for cash payment or RFID scanning.
- **Decentralized system**: As compared to existing systems, it is a decentralized system with lost cost, saves time, and reduces fuel consumption.

The article is organized into six sections. Section 2 overviews the background and related works. The proposed approach is in Section 3 followed by experimental design and results in Section 4. Section 5 presents the limitations of this work. This study concludes in Section 6 with future directions.

## 2 Literature review

Blockchain technology has taken its roots in many application areas such as energy trading, healthcare, intelligent transportation, vehicular networks, and smart toll collection [13]. The decentralized architecture of blockchain offers the advantages like secure data storage and payment in a transparent manner. In this regard, Galande et al. [1] show that the manual toll collection process results in long queues of vehicles at toll plazas and more fuel consumption by vehicles. They proposed a global positioning system (GPS)-based electronic toll collection system to address the issues in manual toll collection. GPS technology helps us to determine the vehicle coordinates for toll charges calculation. The solution requires that vehicle drivers possess a GPS-enabled cell phone for toll payment. However, the proposed solution depends upon the GPS service availability in the vicinity of the toll plaza that is often absent or suffer from weak signal strength on the highways.

Previous studies [3,19] proposed an RFID-based toll deduction system to overcome the traffic congestion problem at toll booths, reducing the operating cost and saving the toll payment time. The vehicles carry RFID tags that contain the vehicle data and owner information. The proposed system scans the RFID tag placed on the vehicle and compares the credentials with the central database to charge the toll amount. The toll tax is automatically deducted from the driver’s account and a notification is sent to the driver. Vehicle owners must top up the account to cross the toll plaza. However, the system suffers limitations such as data privacy, data immutability, and transparency due to its centralized nature.

Sathya et al. addressed the traffic congestion problem at the toll gate by introducing the pre-paid tax approach. In the proposed scheme, the driver must register himself at the portal. Once registered, stored credentials can be used to pay the toll amount in advance using UPI. The transaction is saved in the database against the driver. At the toll plaza gate, cameras are used to read the vehicle number plate and subsequently use the vehicle registration number to verify the toll payment in the database. However, the advance payment causes inconvenience to the user. Further, image recognition during peak times may suffer latency causing long queues of vehicles.
Das et al. [12] argued that the intelligent transportation management system for toll collection ensures confidentiality, availability, immutability, privacy and security, transparency, reduced crossing time, less traffic congestion, and less fuel consumption.

Xiao et al. [14] developed a blockchain-driven toll tax payment system. They collect the toll amount in the heterogeneous environment. The proposed public edge-sharing system design was helpful in validating the test bed for the experiments. The smart contract supports the system for record maintenance of an agreement and splitting the payment. However, the system only operates starting and ending of payment using a decentralized node, while the rest of the transactions are performed on-off between participants.

Dayana et al. [16] developed a decentralized application based on blockchain for toll payment collection. Dayana et al. [16] implemented toll gate automation with a predefined route based on blockchain. Deng and Gao [17] proposed a blockchain-based toll management system where a payment scheme is used for the transactions.

Ying et al. [18] used the autonomous build platform using blockchain technology for secure communication. Their system uses the platoon payment at each toll collection. Sahoo et al. [20] used GPS to track vehicle movement. They used Ethereum smart contracts to carry out business logic. Their results show that every transaction between vehicle owners and the authorities is traceable, immutable, transparent, and trustworthy. However, the proposed solution is costly as it involves real-time vehicle tracking. The approach is also not feasible because the user must confirm his starting location and ending location that is not available in many cases.

Soner et al. [21] proposed the toll management system uses smart contracts to enhance parties’ agreements and QR codes for payments. This system offers trust, security, and ease of use. After user verification, it is added to the blockchain and, hence, then it is able to make a transaction. In this system, the generated QR code of the user is scanned by the QR code scanner and the user’s details are displayed on the beneficiary’s account. The user then enters the route details and confirms the entire payment of toll in a single transaction.

Tanveer and Javaid [22] proposed the use of smart contracts for the payment of toll fees. The RFID system installed at the roadside can read the vehicle details and subsequently execute a smart contract to deduct the toll fee from user’s bank account. However, the involvement of a third party (e.g., bank) for toll payment incurs additional costs, e.g., transaction fee charges.

Zhang et al. focused on the security of announcement messages in Internet of Vehicles (IoV). They proposed a blockchain-based data sharing system where IoV is divided into multiple regions. The communications are distributed on a parent blockchain and an auxiliary blockchain for each region. The parent blockchain is controlled by all the system’s entities, while each auxiliary blockchain is maintained by the entities in an area and utilized to boost the throughput of the parent blockchain.

Table 1: Comparison of the existing systems

<table>
<thead>
<tr>
<th>Reference</th>
<th>Easy to use</th>
<th>App</th>
<th>Technique</th>
<th>Smart contract</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiao et al. [14]</td>
<td>—</td>
<td>N</td>
<td>Blockchain</td>
<td>Y</td>
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<tr>
<td>Cai et al. [15]</td>
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<td>Y</td>
<td>Blockchain</td>
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<td>Dayana et al. [16]</td>
<td>Y</td>
<td>N</td>
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<td>Deng et al. [17]</td>
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<td>Blockchain</td>
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<tr>
<td>Ying et al. [18]</td>
<td>—</td>
<td>Y</td>
<td>Blockchain</td>
<td>N</td>
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<tr>
<td>Laghari et al. [3]</td>
<td>N</td>
<td>N</td>
<td>RFID</td>
<td>N</td>
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<tr>
<td>Rashid and Abbas [19]</td>
<td>N</td>
<td>N</td>
<td>RFID</td>
<td>N</td>
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<tr>
<td>Das et al. [12]</td>
<td>Y</td>
<td>N</td>
<td>Blockchain, OCR</td>
<td>Y</td>
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<tr>
<td>Sahoo et al. [20]</td>
<td>N</td>
<td>N</td>
<td>Ethereum, GPS</td>
<td>Y</td>
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<tr>
<td>Soner et al. [21]</td>
<td>Y</td>
<td>N</td>
<td>Blockchain, OCR</td>
<td>Y</td>
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<td>Tanveer and Javaid [22]</td>
<td>—</td>
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<td>Ethereum</td>
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<td>Das et al. [24]</td>
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<tr>
<td>Das et al. [25]</td>
<td>Y</td>
<td>N</td>
<td>Blockchain</td>
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<tr>
<td>Banerjee et al. [10]</td>
<td>—</td>
<td>N</td>
<td>Blockchain</td>
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<tr>
<td>Banerjee et al. [26]</td>
<td>Y</td>
<td>N</td>
<td>Blockchain</td>
<td>Y</td>
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<tr>
<td>Proposed</td>
<td>Y</td>
<td>Y</td>
<td>Blockchain, OCR</td>
<td>Y</td>
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</table>
Das et al. [24] suggested blockchain applications, challenges, and opportunities for intelligent transportation system. They also proposed a blockchain-based security management framework for smart cities as one of many applications [25]. Banerjee et al. [10] provided an overview of the fundamental principles and practical applications of digital twins (DTs) and blockchain in the field of transportation. They explored use cases such as autonomous vehicles, smart logistics, and mobility as a service. They also proposed a sustainable safety management framework [26] for connected vehicles through the integration of blockchain. They introduced an AI-enabled vehicle smart device (AVSD) designed for vehicular communications. The AVSD has the capability to lower energy consumption by reducing computational costs in vehicular communications. The system employs smart contracts to automatically identify vehicles and establish secure communication channels among vehicles and emergency service stations, such as hospitals, police stations, and fire stations.

The above literature highlights the fact that ETC systems based on RFID technology cause traffic congestion at the toll plazas. Also, these suffer from the problems such as data integrity, data security, privacy, fuel consumption, and transparency of the transacted data over the internet. It can also be observed that (Table 1) most of the studies have not used blockchain technology and are difficult to use with lack of an application. Therefore, it triggers a need for a system that is easy to use, secure, and automated.

3 Proposed methodology

In a traditional tollbooth system, each vehicle waits at the booth for payment processing that puts each subsequent vehicle on hold, causing traffic congestion. In this section, we propose a blockchain-driven solution for a cashless, fast, and track-able scheme that divides the tollbooth operation into multiple processes. The proposed system consists of the following components:

- Vehicle registration on blockchain,
- Vehicle identification unit,
- Tollbooth local server (TLS), and
- Blockchain network.

3.1 Vehicle registration on blockchain

In the proposed system, the vehicles are registered through a registration portal. The vehicle owner’s metamask account is created with vehicle details such as vehicle number plate, vehicle type, owner citizenship no, owner name, and contact number (Figure 2). This information is saved on the blockchain as registration
details, and every vehicle is identified through a number plate. After successful registration, the system recognizes the vehicle for the toll tax collection process, as shown in Figure 3. The algorithm for vehicle registration on the blockchain network is given in Algorithm 1.

![Figure 3: Workflow of the proposed model.](image_url)

**Algorithm 1. Vehicle registration**

\[ 
\begin{align*}
\text{vList} &= \text{list of registered vehicles} \\
\text{Pr}_{gov} &= \text{private key of contract owner (i.e., Government)} \\
V_{np} &\rightarrow \text{vehicle number plate} \\
V_t &\rightarrow \text{vehicle type} \\
V_o &\rightarrow \text{owner} \\
V_{oc} &\rightarrow \text{owner contact} \\
V_{ocn} &\rightarrow \text{owner citizenship no} \\
V_{ow} &\rightarrow \text{vehicle owner wallet address} \\
V_{py} &\rightarrow 0 \quad \triangleright \text{payable} \\
V_f &\rightarrow 0 \quad \triangleright \text{existing fine} \\
V_{cf} &\rightarrow \text{true} \quad \triangleright \text{clearance flag} \\
V_{df} &\rightarrow \text{false} \quad \triangleright \text{defaulter flag} \\
\text{stamp} &\rightarrow \text{current timestamp} \\
V &= \{V_{np}, V_t, V_o, V_{oc}, V_{ocn}, V_{ow}, V_f, V_{cf}, V_{df}, \text{stamp}\} \\
TX &\leftarrow E(\text{Pr}_{gov}, V) \\
\text{post} \ TX \text{ on blockchain} \\
\text{vList} \text{ has information of } V 
\end{align*} \]
3.2 Vehicle identification unit

The vehicle identification unit consists of two processing points to recognize the vehicle, i.e., detection point and signal point. The detection point is deployed at 100 m before the exit point so that each entering vehicle is identified. This point plays an important role in determining the vehicle information, clearance, and toll tax exemption. When a vehicle passes the detection point, the installed camera captures the number plate of the vehicle and process it to determine the vehicle number. Then, this information is sent to the TLS detection queue. The algorithm for vehicle initial detection is given in Algorithm 2.

Algorithm 2. Initial detection

\[ Q_d \text{ is detection queue} \]
\[ img_v \text{ is captured vehicle image} \]
\[ V_{np} \leftarrow \text{detectNumberPlate}(img_v) \]
\[ enQueue(Q_d, V_{np}) \]

The signal point is deployed at the exit of the tollbooth. It informs the tollbooth server that the vehicle has been exited from the tollbooth and direct the TLS to perform the transaction.

3.3 TLS

TLS is responsible for the toll tax collection process. The server is guarded by a firewall and works in coordination with detection points. It continuously monitors the detection queue and subsequently fetches the vehicle information when a vehicle number plate is detected by the detection point. To calculate the toll tax
of a vehicle, it needs the vehicle details from the blockchain such as vehicle type, fine, and tax exemption. In general, blockchain query is a slow process. To address this issue, TLS maintains a local cache of the vehicle’s information to speed up the query process (Figure 4). The cache contains the copy of frequently passing by vehicles, and each entry is synchronized to keep it up to date. As soon as a tollbooth or law enforcement agency changes vehicle clearance status, the information is passed to all tollbooths so that they can update their local cache. So, every query to get vehicle information is checked against the cache. In case of a cache miss, TLS fetches the information from blockchain. The algorithm for vehicle processing at TLS is given in Algorithm 3.

**Algorithm 3.** Processing entry list at TLS

$L_e$ is entryList
$Q_{tx}$ is transaction queue
$V_{np}$ is exited vehicle
$Tx ← getItem(L_e, V_{np})$
$enQueue(Q_{tx}, Tx)$

For each vehicle in the detection queue, the TLS server looks for a clearance flag to look for any malicious vehicle and a category flag to look for the vehicle toll exemption. If the vehicle is malicious, then, the server informs the nearest police station with the captured image of the vehicle. It helps the law enforcement agencies to streamline their operations about vehicle theft and malicious activities. After performing the clearance check, the vehicle number plate, along with vehicle type and TA for that vehicle category, is put into the entry list at TLS. The entry list contains information about the vehicles that have entered the tollbooth range, and toll tax from these vehicles is collected. The algorithm for processing transaction queue at TLS is given in Algorithm 4.

**Algorithm 4.** Processing transaction queue at TLS

$Q_{tx}$ is transaction queue

while true do

$Tx ← deQueue(Q_{tx})$
$balance ← walletBalance(Tx_{vc})$

if balance $<$ $Tx_{payable}$

$V_{fr} ← true$
$V_f ← getFine(V_f)$
$V_{py} ← Tx_{payable}$
$postTxBlockchain(E(Pr_{gov}, V))$

else
$r ← doPayment(E(Pr_{gov}, Tx))$

if $r$
$V_f ← 0$
$V_{py} ← 0$
$postTxBlockchain(E(Pr_{gov}, V))$

else
$enQueue(Q_{tx}, Tx)$
end if
end if
end while
3.4 Blockchain network

After TLS receives confirmation of the vehicle exit from the signal point, it takes that vehicle information from the entry list and prepares the transaction to perform on the blockchain. The transaction processing on the blockchain requires determining hashes, which is a time-taking process, and it is not feasible for a real-time system like toll tax collection. It is not easy to pay a lot of gas fees to perform the transaction on a priority basis; thus, TLS maintains a local transaction queue. Hence, the prepared transaction is put in the transaction queue. A separate process takes the transaction queue, determines the vehicle balance, and by relying on the trust of vehicle, it performs the transaction on the blockchain. If the vehicle owner has not enough balance, then, a penalty is charged and the vehicle is marked as defaulter.

4 Experimental analysis

4.1 Experimental setup

For experimentation, we simulated the vehicle entry and exit using the Python programming language. The local tollbooth server application is also written in Python to handle the vehicle queue, and the MySQL database is used for the local cache. Smart contracts code is written and experimented with solidity language using Remix that is a web-based platform. Then, we deployed that smart contract at Infura, which is blockchain as a service platform. To interact with Infura (BaaS), we used the Web3 library of Python for the sake of performing transactions. The applications for detection, signal processing, and local tollbooth server are deployed on Intel Corei7 systems, each having 8 GB of RAM. We connected these systems using 1 Gbps LAN and provided the internet connection of 8 Mbps with TLS to connect with a blockchain network.

4.2 Results and discussion

This section illustrates the experimental results of the incorporated smart contract for a secure, reliable, and fast toll tax transaction system. The smart contract reduces the risk of errors associated with manual toll collection, ensures that transactions are executed according to predefined rules, and ensures that all stakeholders, including authorities and users, have access to a tamper-resistant and transparent record of toll transactions. The results show that the blockchain integration enables the toll tax payment system transparent, trustworthy, fast, and secure. The metamask account was created to deploy and perform transactions on blockchain. In real, government is the owner of the data and deploys the smart contract to take the ownership. For the experimental purpose, we deployed the contract from a metamask account to act as government department. The result of smart contract deployment is shown in Figure 5.

![Smart contract has been deployed successfully.](image)
We registered 10,000 vehicles on the blockchain and manually put 200 vehicles information in the local cache.

4.2.1 Detection point delay

We generated a total of 500 vehicles in the simulation using Python application at a regular interval of 1 s, for measuring the delay at the detection point. The vehicles were generated in such a way that first 80 of the vehicle information is found from the local cache, and the rest of the vehicle information is distributed in such a way that 90% of the vehicle information need to be accessed from the blockchain. The simulation was started and the result of simulation is presented in Figure 6.

The detection point system booted fully at 7 s and started processing vehicles. First, 80 vehicles are processed by detection point quickly as the information was present in the local cache, and the detection point did not fetch their information from the blockchain. From 80 vehicles to on-wards, a mixed number of requests were received, the upper edge of the graph line shows that information was fetched from the blockchain, while the lower edge shows that the information was fetched from the local cache that increased the identification time.

Figure 6: Vehicle processing at the detection point.

Figure 7: Gas consumption of posted transactions.
4.2.2 Gas consumption

We run the system to process 1,000 vehicles to find out the gas consumption for the payments. The vehicle payment information varies, i.e., some vehicles are not cleared, few are penalized; hence, the transaction size is different. Therefore, the gas fee is different for each transaction. Figure 7 shows the gas consumption for processing transactions of 1,000 vehicles.

![Figure 8: Posting the vehicle transactions on the blockchain.]

4.2.3 Transaction processing time

To measure the transaction processing time, we generated 1,000 vehicles to enter the detection point using simulation. The vehicles are generated in such a way that 10% of the vehicles have insufficient wallet balance, and 5% of the vehicles are tax exempted. After the vehicles are processed from the detection point, their information is saved in the list. The signal point processed that list finally to perform payment transactions at the exit. Upon the vehicle exit, the signal point removed that vehicle information from the list, prepared the transaction according to the algorithm, and put that prepared transaction information in queue. That queue is processed to perform transactions on the local blockchain, and the results are shown in Figure 8.

In this system, the vehicle passes the toll plaza at a threshold speed, with a 30 km/h maximum speed. As a result, passing vehicle through the toll plaza saves more time. The green line in Figure 9 shows that the

![Figure 9: Comparative analysis of the number of vehicles served through a tollgate using the proposed system.]

...
number of vehicles served fully through an automated blockchain-based system, and the blue line shows the
time taken to fully serve the vehicles using the manual system. The results clearly show that the automated
system performs better than the manual system.

5 Threats to validity

This study helps to the automation of the road toll tax system in an efficient and transparent manner,
considering data security and privacy issues. However, this work has some limitations. First, the proposed
system needs to be evaluated in a real environment. Second, the gas fee value can be a constraint. Third, with
the rising number of transactions, the processing and validation time of the blockchain network for those
transactions may become strained.

6 Conclusion

This research presents a blockchain-based automated toll collection system as a promising solution to the
challenges faced by traditional toll collection methods in developing countries. It reduces operational costs,
saves time, and enhances efficiency compared to existing RFID-based systems. By combining image processing,
blockchain, and smart contracts, the system offers improved efficiency, transparency, and convenience for
both drivers and toll operators.

The proposed system leverages image processing technology, YOLOv5 algorithm, to read and store vehi-
cles’ information at the toll plaza local server. Subsequently, the vehicle and driver’s credentials are trans-
mited to a remote server, where the Ethereum smart contract verifies the information and automatically
deducts the toll charges from the account wallet. The system eliminates the need for cash payments or RFID
scanning at toll booths, thus ensuring a smooth fast toll collection process. Further, the decentralized nature of
the system makes it robust against potential failures in a centralized system. The introduction of blockchain
technology adds an additional layer of security and trust, mitigating issues related to data tampering, cloning,
and traceability.

Future research can focus on scalability, and further enhancing the security aspects of the system to
ensure its successful implementation in real-world scenarios.

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worked on the proposed methodology and wrote the original draft. Sunday Adeola Ajagbe analysed the results
and contributed in draft writing, whereas Matthew O. Adigun reviewed the article.

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Blockchain-enabled intelligent toll management system