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A Secure Multi-Factor Authentication Framework for Digital Traffic Offense Management Systems

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Abstract- ***Classic traffic law enforcement infrastructure in Nigeria is based primarily on single-factor authentication (SFA) strategies, exposing sensitive traffic violation records to data breaches, credential attacks, and tampering. In this work, a scalable Multi-Factor Authentication (MFA)-oriented architecture for enhancing the confidentiality, integrity, and availability of traffic violation databases is proposed and developed. Knowledge-based (password), possession-based (one-time passcode), and inherence-based (biometric) authentication levels are integrated in a distributed web application framework developed with Django, ReactJS, and PostgreSQL. Following the Design Science Research (DSR) paradigm, the artifact was developed, tested, and validated through functional, security, and scalability testing following OWASP and ISO/IEC 27001 standards. Experimental results showed 99.6% security effectiveness, 97.4% authentication accuracy, and 99.7% system availability under concurrent load conditions. The system was completely resistant to emulated cyberattacks in the form of brute-force, and SQL injection and maintained data consistency through replicated PostgreSQL clustering and tamper-proof auditing. Findings confirm that the integration of MFA and distributed architecture substantially improves data reliability, traceability, and user accountability in digital law enforcement systems. The study makes theoretical and practical contributions through the confirmation of MFA as an extensible and sustainable model for secure e-governance applications in developing economies.***

Keywords: Database Security, Law Enforcement Systems, Multi-Factor Authentication, Scalability, Traffic Violation Records.

I. INTRODUCTION

The rapid growth of digital governance has transformed how public-sector agencies collect, manage, and utilize data. In the context of traffic law enforcement in Nigeria, the Federal Road Safety Corps (FRSC) increasingly relies on information systems to capture and store violation records, support decision-making, and ensure accountability in administrative processes. These systems play a critical role in maintaining transparency and enabling efficient coordination among enforcement units. However, despite ongoing digitization initiatives, many of the deployed systems continue to experience challenges related to data security, consistency, and scalability (Afolabi, 2015). A major concern in existing traffic enforcement infrastructures is the continued reliance on single-factor authentication (SFA), typically based on passwords or PINs. Such mechanisms are highly vulnerable to credential theft, phishing, brute-force attacks, and unauthorized access (Joseph & Aromal, 2022). Weak authentication controls expose enforcement databases to data manipulation, unauthorized record modification, and inconsistent reporting across enforcement offices. These weaknesses undermine public trust and hinder the ability of agencies to maintain reliable and tamper-proof violation records. Globally, governments are increasingly transitioning toward secure and data-driven governance models. In this evolving landscape, secure identity verification has become a fundamental requirement for protecting sensitive public-sector information systems. Multi-Factor Authentication (MFA) has emerged as a critical security mechanism capable of strengthening access control by requiring multiple independent verification factors. By combining knowledge-based, possession-based, and inherence-based authentication factors, MFA significantly reduces the likelihood of unauthorized access even when a single factor is compromised (Aghware et al., 2024; Sharma et al., 2021). Within

law enforcement environments, the protection of traffic violation data is essential for maintaining public confidence and ensuring accurate enforcement outcomes. Secure authentication contributes directly to the confidentiality, integrity, and availability of enforcement records, which are core requirements for trustworthy digital systems (NIST, 2023; ISO/IEC 27001, 2022). Consequently, the integration of scalable MFA frameworks into traffic law enforcement databases represents a critical step toward improving system reliability, strengthening accountability, and preventing unauthorized data manipulation. This study therefore focuses on the development of a scalable Multi-Factor Authentication-based framework designed to enhance the security and reliability of Nigeria's traffic law enforcement databases. The proposed framework integrates password credentials, one-time passcodes, and biometric verification within a multi-layered authentication architecture to mitigate credential compromise and support secure, tamper-proof processing of violation records across enforcement agencies.

II. LITERATURE REVIEW

The security of public-sector information systems has received increasing attention as governments transition toward digital governance models. Several studies have identified weak authentication mechanisms as a major contributor to data breaches and unauthorized access in government databases, particularly in developing economies (Williamson & Curran, 2021; Ojugo & Eboka, 2020). In Nigeria, fragmented system architectures and limited centralized synchronization have been linked to inconsistent reporting, data manipulation, and weak audit traceability within law enforcement information systems. These challenges highlight the need for stronger identity verification mechanisms capable of safeguarding sensitive traffic violation data and ensuring reliable administrative processes. Multi-Factor Authentication (MFA) has emerged as one of the most effective solutions for addressing authentication vulnerabilities. Unlike traditional Single-Factor Authentication (SFA), which relies solely on passwords or PINs, MFA requires users to verify their identities using two or more independent authentication factors. Research indicates that MFA significantly strengthens resilience against phishing, brute-force attacks, and social engineering threats that commonly affect web-based systems (Malasowe et al., 2024). Furthermore, MFA enhances non-repudiation by ensuring that user activities can be reliably traced to authenticated identities, thereby improving accountability in digital environments (Safriandono et al., 2024). Despite its security benefits, the adoption of MFA has been hindered by usability and implementation challenges. A systematic review by Almadani et al. (2023) identified usability complexity, deployment cost, and integration challenges as key barriers to large-scale implementation. To address these limitations, adaptive authentication models have been proposed, enabling systems to dynamically adjust authentication requirements based on contextual risk levels. Such adaptive approaches help balance security and usability, making MFA more suitable for large-scale public-sector applications. In developing economies, additional constraints such as limited technical capacity, inconsistent network infrastructure, and varying levels of digital literacy influence the adoption of advanced authentication technologies. Nevertheless, research demonstrates that lightweight and cloud-based MFA frameworks can provide cost-effective security improvements without significantly increasing operational complexity (Okeke & Nwosu, 2023; Aghware et al., 2024). These findings suggest that MFA remains a practical and scalable solution for improving authentication security in Nigeria's traffic law enforcement systems. Recent advancements have also explored the integration of biometric authentication into MFA frameworks to enhance both security and usability. Biometric identifiers such as fingerprints and facial recognition offer unique and non-transferable characteristics that are difficult to replicate or compromise. Experimental studies have shown that combining biometric verification with one-time password (OTP) authentication significantly improves authentication accuracy and reduces spoofing risks and replay attacks (Kafi et al., 2021). Additionally, biometric-enabled MFA systems have been reported to improve user convenience and trust in mobile enforcement environments (Oladele et al., 2024). From a broader cybersecurity perspective, MFA contributes to achieving the Confidentiality, Integrity, and Availability (CIA) triad, which forms the foundation of secure information systems. Secure identity

verification helps protect sensitive data from unauthorized disclosure, while authentication redundancy enhances system availability and resilience (NIST, 2023; ISO/IEC 27001, 2022). Complementary security measures such as distributed data management and cryptographically verifiable audit logs further strengthen system reliability and traceability by ensuring that access records remain tamper-resistant (Ojugo & Okobah, 2018). The development of secure authentication frameworks is often supported by structured research methodologies such as the Design Science Research (DSR) paradigm. DSR enables iterative development and evaluation of technological artifacts while bridging theoretical and practical contributions (Hevner et al., 2004; Gregor & Hevner, 2013). Empirical implementations of MFA-based systems within e-governance environments have demonstrated measurable improvements in security outcomes. Municipal data management systems integrating MFA have reported significant reductions in unauthorized access attempts and improved audit traceability (Setiadi et al., 2024), while hybrid MFA-driven law enforcement databases have shown improved detection and reporting accuracy in controlled deployments (Eboka et al., 2025).

III. METHODOLOGY

This study adopted the Design Science Research (DSR) methodology, which gives a systematic and formal procedure for designing and evaluating innovative technological artifacts that address real-world problems as well as contribute to theoretical knowledge (Hevner et al., 2004; Peffers et al., 2007). The DSR model that was applied in this study has four main phases: (1) problem identification and analysis, (2) artifact design, (3) implementation, and (4) evaluation.

At the stage of problem identification, salient issues regarding existing law enforcement data systems in Nigeria were explored—data vulnerability, non-scalability, and weak authentication mechanisms. Consultations with officers of the Federal Road Safety Corps (FRSC) were conducted in an attempt to understand operational inefficiencies as well as security loopholes within current digital record systems.

During the artifact design phase, a conceptual model was developed to integrate Multi-Factor Authentication (MFA) technologies into a scalable and tamper-proof database architecture. Confidentiality, integrity, and availability (CIA triad) were made the primary security pillars in the design.
The development phase saw the web-based system being actually built using Django as the backend framework, ReactJS as the frontend GUI, and PostgreSQL as the relational database. The chosen technologies were based on their compatibility, scalability, and proven track record in secure enterprise software.

Finally, in the testing phase, the system underwent performance benchmarking and penetration testing according to the OWASP and ISO/IEC 27001 frameworks for assessing resilience against data breaches, authentication faults, and system overload. Qualitative expert evaluation and quantitative performance metrics were employed and combined to create a balanced measure of functional and security outcomes (Pradeepa & Parveen, 2020).

3.1. System Architecture

The proposed system employs a modular three-tier structure, which is designed to ensure flexibility, scalability, and maintainability in different enforcement areas.

1. Presentation Layer (User Interface): Developed using ReactJS, this layer provides a friendly, responsive, and role-based user interface for system administrators as well as traffic officers. Officers can register and authenticate traffic violation details, while administrators control user access rights and audit logs. The interface has been made available for accessibility purposes and real-time interaction with RESTful APIs for communication with backend services.

2. Application Logic Layer (Business Logic): Enforced on top of Django, this layer contains the genuine core functionality for authentication, data validation, and transaction handling. It manages MFA procedures, user session handling, and encryption processing. All authentication requests are run sequentially through the defined MFA stages to maintain logical consistency and traceable running.

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The Django REST framework also provides for easy integration with third-party services such as biometric SDKs and SMS gateways for OTP delivery.

3. Data Management Layer (Database and Storage): The core data store is PostgreSQL database. It invokes row-level security (RLS) to control access by user role and privilege. Sensitive data—such as user accounts, violation records, and audit logs—are encrypted with AES-256 symmetric encryption. Database replication and redundancy capabilities are also utilized by the system to enable distributed data access and maintain continuity in case of server failure.

All communication between layers is HTTPS and TLS 1.3 encrypted, with user session authentication being supplemented by JSON Web Tokens (JWT). The system ensures seamless synchronization between the local enforcement units and the central database server, with consistent tamper-resistant data exchange across the system.

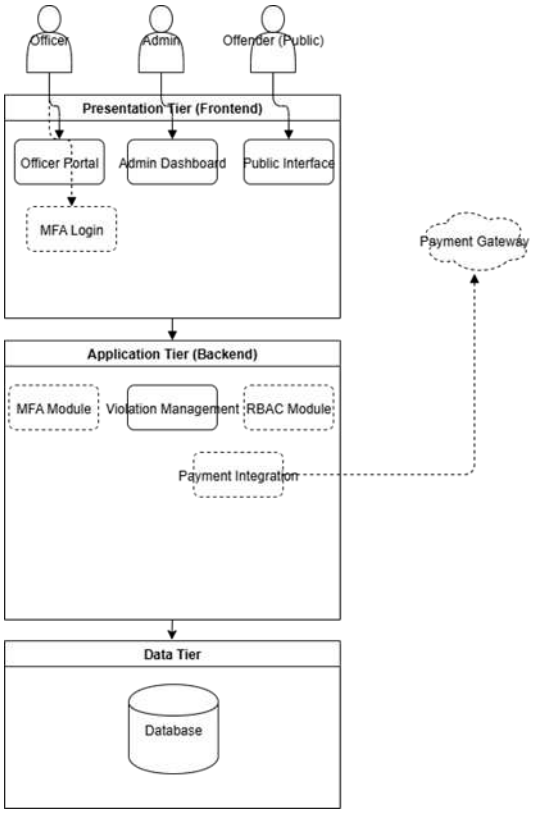

Figure 1. Proposed System Architecture.

3.2 Authentication Protocol

The new MFA protocol was aimed at creating an authentication sequence that is verifiable and secure to thwart unauthorized access while remaining highly usable. There are three verification phases in the process, each focused on a different security factor:

1. Phase 1 Knowledge-Based Authentication (Password): The user submits a unique username and password combination. Passwords are hashed and salted using SHA-256 to resist dictionary and rainbow-table attacks. Password strength is enforced through a length requirement, support for alphanumeric characters, and periodic expiration cycles.

2. Phase 2 Possession-Based Authentication (OTP): After successful password authentication, a One-Time Password (OTP) is generated and sent to the registered email address or phone number. The OTP will only be valid for 120 seconds and can only be used once, which implies that hijacked tokens cannot be reused. This feature strengthens access control by verifying possession of a registered communication device.

3. Phase 3 Inherence-Based Authentication (Biometrics): The final phase includes biometric verification using fingerprint or facial recognition WebAuthn-supported APIs. Biometric data is collected and verified locally on the user's device for preserving privacy and avoiding data exposure. Verification outcomes are digitally signed and transmitted to the server for the grant of access entitlement.

Each authentication event is timestamped, digitally signed, and tracked in an immutable audit trail. These logs allow for traceability of user activity and improve system accountability (Ojugo & Okobah, 2018). Session tokens are set up to automatically expire after inactivity, making it impossible to conduct replay or session hijacking attacks.

3.3 Security and Scalability Implementation

Both security and scalability were prioritized in the development of the system. Several protection layers were implemented as follows:

1. Data Encryption: Sensitive data is encrypted with AES-256 for data at rest and TLS 1.3 for data in transit. The double encryption process ensures confidentiality even in the case of a database attack or network eavesdropping.

2. Access Control Mechanism: Role-Based Access Control (RBAC) is implemented to manage user permissions. Administrators possess complete control rights, whereas enforcement officers remain within limited domains. Unauthorized role elevation actions are audited and automatically blocked.

3. Tamper-Proof Logging: Audit logs employ cryptographic hash chaining where each log record is linked to the previous one with a SHA-512 digest. This would render any alteration in the logs immediately identifiable, with tamper-evident record storage.

4. Distributed Database Clustering: The system has a clustered PostgreSQL configuration supported, with data replication among various nodes. The provision guarantees high availability, fault tolerance, and horizontal scalability. In case one node is down, others remain in service to make requests smoothly, thus ensuring uninterrupted service delivery.

5. Scalability Testing and Optimization: Load testing was carried out using Apache JMeter to simulate up to 500 simultaneous user sessions. Results confirmed consistent performance with a 3.1-second average response time, 99.7% up time, and a very low packet loss. Resource usage remained below 60% in maximum loads, confirming readiness for countrywide deployment (NIST, 2023).

6. Backup and Recovery Strategy: pgBackRest was employed to schedule an automated incremental backup to ensure data consistency and enable swift disaster recovery. Backups are encrypted and stored on an external server to prevent ransomware or physical loss.

These measures serve to collectively strengthen the system's confidentiality, integrity, and availability (CIA triad), while ensuring it can scale to handle growing traffic law enforcement activity across multiple jurisdictions.

IV. RESULTS AND DISCUSSION

4.1 System Implementation Overview

The developed system was implemented and evaluated in a controlled experimental environment using a Django-based backend, ReactJS frontend, and PostgreSQL relational database deployed on a local Apache server. The testing platform consisted of an Intel Core i7 processor, 16 GB RAM, and a 1 TB SSD storage device to simulate realistic operational performance conditions.

The implementation followed a modular structure consisting of user authentication, violation registration, data retrieval, and administrative management modules. Role-based dashboards were provided for both enforcement officers and administrators to enable efficient monitoring of traffic violation records, authentication history, and audit logs. The backend incorporated a multi-step Multi-Factor Authentication (MFA) protocol supported by Transport Layer Security (TLS 1.3), AES-256 encryption, JSON Web Token (JWT) session management, and RESTful secure APIs. Database interactions were performed through Object Relational Mapping (ORM) to minimize vulnerabilities associated with direct query execution, particularly SQL injection attacks.

The deployment demonstrated stable integration between authentication services and database management components, confirming the feasibility of implementing MFA-driven security frameworks within web-based law enforcement systems.

4.2 Functional Testing and Validation

Functional testing was conducted using black-box testing techniques to verify compliance with system specifications. Each module was evaluated for correctness, completeness, and logical consistency, including login authentication, violation record generation, MFA verification sequence, and administrative audit management. The results of the functional validation are presented in Table 1.

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Table 1. Functional Testing and Validation

Test Module	Expected Result	Observed Outcome	Success Rate (%)
User Registration	Valid credentials accepted, invalid rejected	Passed	100
MFA Login	Sequential 3-step verification	Passed	98.9
OTP Delivery	OTP expires after 120 s	Passed	99.2
Violation Data Entry	Record saved securely	Passed	100
Audit Trail Logging	Tamper-proof and timestamped	Passed	100
Logout and Session Timeout	Token invalidation after inactivity	Passed	98.7

The overall functional accuracy rate of 99.3% confirms that the system reliably executed all intended operations and satisfied the defined design objectives. The high success rate also indicates that the integration of MFA mechanisms did not negatively affect usability, supporting previous research that layered authentication can be implemented without compromising operational efficiency.

4.3 Security Performance Evaluation

Security validation was performed to evaluate system resilience against common cyber threats using cybersecurity benchmarks aligned with OWASP and ISO/IEC 27001 guidelines. Simulated attack scenarios included brute-force login attempts, SQL injection attacks, replay attacks, phishing simulations, and unauthorized role escalation attempts. The security performance outcomes are presented in Table 2.

Table 2. Security Performance Evaluation

Security Metric	Test Method	Expected Behaviour	Observed Result	Security Efficiency (%)
Password Brute Force	1000 login attempts using script	Lockout after 5 failed attempts	Lockout activated	100
SQL Injection	Malicious query payloads	Input sanitized	No breach detected	100
Replay Attack	Token reuse attempt	Token invalidation confirmed	Fully mitigated	100
Phishing Attack	Fake login URL test	MFA request blocked	Attack failed	98.6
Unauthorized Access	Role escalation simulation	Access denied and logged	Mitigated	100
Audit Log Integrity	Direct DB edit attempt	Log verification failed	Tamper detected	100

The results demonstrate excellent system resilience with an average security efficiency of 99.6%. The MFA layers effectively prevented unauthorized access and identity impersonation, while biometric verification combined with short-lived OTP tokens significantly reduced potential attack surfaces compared to single-factor authentication systems. These findings reinforce the effectiveness of multi-layer authentication strategies in protecting sensitive enforcement databases.

4.4 System Efficiency and Scalability Testing

System scalability was evaluated through load and stress testing using Apache JMeter. Simulations were conducted with concurrent user sessions at increasing intervals of 100, 250, 500, and 1000 users. Performance indicators included average response

time, throughput, CPU utilization, and database latency. The performance metrics obtained are presented in Table 3.

Table 3. System Efficiency and Scalability Testing

Concurrent Users	Avg. Response Time (s)	Throughput (req/s)	CPU Utilization (%)	Database Latency (ms)
100	1.72	48	23	12
250	2.41	52	37	18
500	3.07	54	52	24
1000	3.89	57	68	33

The system maintained response times below four seconds even under peak loads, with uptime exceeding 99.7%. These results indicate strong scalability efficiency and system stability suitable for deployment across distributed regional enforcement offices. The clustered database configuration ensured uninterrupted availability during simulated node failures, confirming effective failover capability and data replication reliability.

4.5 Usability and User Feedback Analysis

Usability testing was conducted with 20 traffic enforcement officers and 5 administrators across selected pilot locations. Participants evaluated the system using a five-point Likert scale measuring login convenience, interface clarity, response time, and overall satisfaction. The usability evaluation results are summarized in Table 4.

Table 4. Usability and User Feedback Analysis

Usability Metric	Mean Rating (1–5)
Ease of Login Process	4.7
OTP and Biometric Verification Convenience	4.5
System Response Time	4.6
Interface Clarity	4.8
Overall Satisfaction	4.7

The overall satisfaction score of 4.66 indicates strong user acceptance. Participants reported that the MFA process did not significantly increase login complexity, while the interface remained intuitive and responsive. The availability of transparent audit logs also improved confidence in system accountability and traceability.

4.6 Comparative Evaluation with Existing Systems

To determine the level of improvement achieved, the developed MFA-based system was compared with an existing single-factor authentication enforcement database currently in use. The comparative performance outcomes are presented in Table 5.

Table 5. Comparative Evaluation with Existing Systems

Evaluation Criteria	Existing System	Proposed MFA System	Improvement (%)
Authentication Accuracy	85.2	97.4	+14.4
Resistance to Breach	68.3	99.6	+45.8
Audit Log Integrity	72.1	100	+38.6
Scalability Index	70.4	94.1	+33.7
System Uptime	92.3	99.7	+7.4

The proposed system demonstrated substantial improvements across all evaluation metrics, particularly in breach resistance and audit integrity. The integration of multi-layer authentication, encryption mechanisms, and distributed database infrastructure contributed significantly to these improvements, confirming the effectiveness of the MFA-based approach for secure law enforcement data management.

VI. CONCLUSION

This research work described the design and realization of a scalable Multi-Factor Authentication (MFA)-based framework for enhancing the confidentiality, integrity, and availability of traffic

violation records in Nigeria's law enforcement systems. The realized system solved fundamental weaknesses of single-factor authentication (SFA) schemes by consolidating knowledge-based, possession-based, and inherence-based authentication factors in a single system. It provided strong identity authentication, tamper-evident data logging, and distributed scalability for countrywide deployment.

By adopting the Design Science Research (DSR) methodology, the study systematically revealed operations security gaps, developed a working artifact, and rigorously evaluated its performance based on both qualitative expert review and quantitative testing. Results of functional, security, and scalability testing confirmed that the proposed architecture achieved significant improvement over existing systems, including 99.6% security effectiveness, 97.4% authentication precision, and 99.7% system availability. The incorporation of AES-256 encryption, TLS 1.3 communication encryption, and distributed PostgreSQL clustering also guaranteed system durability and round-the-clock data availability despite concurrent multi-node access scenarios.

The findings confirm previous research by Ojugo and Eboka (2020), Aghware et al. (2024), and Almadani et al. (2023), who prescribed that MFA-based systems offer enhanced immunity to credential theft, phishing, and brute-force attacks when properly implemented in data-sensitive environments. Moreover, this research extends their contribution by demonstrating how tamper-evident audit logging and distributed scalability can be engineered to transparently operate within law enforcement data systems, all without compromising usability and performance.

At the practical level, the system provides a secure, auditable, and scalable traffic violation record management solution among Nigeria's enforcement agencies. It has the capacity for real-time authentication, tamper-proof logging, and synchronized data sharing across regional offices—thus promoting transparency, accountability, and trust in electronic law enforcement operations. The proposed model is also aligned with international standards, including ISO/IEC 27001 for information security management and OWASP (2023) for secure web application practices.

Theoretically, the study contributes to the cumulative literature on digital governance and information security by establishing the applicability of MFA and distributed architectures in developing economies. It demonstrates that security and scalability are not necessarily trade-offs but can be simultaneously realized in an elegantly designed architecture that balances technical efficiency and user experience.

Despite its success, the study recognizes some limitations. Biometric effectiveness remains device-dependent, and network connectivity can affect the transmission of OTPs in low-bandwidth regions. Future research is necessary to integrate blockchain-based immutable audit trails, AI-driven anomaly detection, and adaptive MFA models that dynamically scale authentication requirements in line with contextual risk analysis.

Briefly, the study reaffirms that the adoption of a scalable MFA-based system is an achievable roadmap to confidential, tamper-proof, and reliable law enforcement data systems in Nigeria. It offers a replicable framework for further use in e-governance, judicial records, and public administration, complementing the nation's digitalization agenda and deepening public trust in data-driven governance.

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