Enhancing Vehicle Lifecycle Management Through Blockchain-Driven Predictive Maintenance and Federated Learning

Mritunjay Shall Peelam, Kunjan Shah and Vinay Chamola
Department of Electrical and Electronics Engineering, BITS Pilani, Pilani Campus, India 333031
Email: mritunjay.peelam@pilani.bits-pilani.ac.in, f20190072@pilani.bits-pilani.ac.in, vinay.chamola@pilani.bits-pilani.ac.in

Biplab Sikdar
Department of Electrical and Computer Engineering, National University of Singapore, Singapore 119077
Email: bsikdar@nus.edu.sg

***Abstract*—In recent years, the automotive industry has increasingly adopted blockchain technology to enhance vehicle lifecycle management and predictive maintenance. This paper presents a blockchain-enabled framework that integrates data from various stakeholders, including manufacturers, service providers, and vehicle owners, to create a transparent and immutable vehicle history record. The proposed solution utilizes predictive maintenance with Federated Learning (FL) algorithms to analyze real-time vehicle data, ensuring timely and efficient maintenance. By utilizing blockchain technology, the framework ensures data integrity, security, and accessibility, addressing common issues such as fraud, data manipulation, and information asymmetry. The proposed system aims to reduce maintenance costs, improve vehicle performance, and enhance user experience by providing reliable and secure vehicle lifecycle management.**

I. Introduction

Lifecycle management, including vehicle identification, registration, and maintenance, is a crucial aspect of the automotive industry, ensuring proper ownership and tracking of vehicles [1]. Current vehicle registration and identification systems face several challenges, such as fraud and counterfeiting, lack of transparency, limited accessibility, inefficiencies and high costs, data privacy concerns, and outdated information [2–4]. These challenges are highlighted in Figure 1. There is a need to move from the centralized single authority system to a decentralized system wherein multiple entities participate to reach a consensus on the system's state [5, 6]. To handle potential delays in real-time data processing, federated learning is used to process data locally on edge devices, minimizing the need for central cloud processing [7]. Lightweight encryption techniques

Fig. 1: Challenges faced by conventional vehicle management systems.

like X25519 can reduce computational overhead, speeding up data transmission. Prioritizing critical data for real-time transmission ensures timely processing while utilizing high-throughput blockchain protocols helps to maintain fast and efficient transaction handling [8].

A. Vehicle Predictive Maintenance

Vehicle predictive maintenance involves remote diagnostics, monitoring, positioning, and roadside assistance within a Fleet Management System (FMS) [9, 10]. Although advanced solutions are not yet standard in commercial vehicles, basic systems for monitoring components like brake pads are available [11, 12]. Using data from sensors and IoT devices, predictive maintenance forecasts potential failures and estimates component lifespan using AI techniques. This approach enables timely maintenance, reduces unexpected downtimes, and optimizes costs, ultimately enhancing vehicle reliability and safety [13, 14]. Figure 2 shows a system where vehicle data is collected, analyzed in the cloud, and accessed via various interfaces for real-time maintenance alerts and decision-making. The decentralized nature of blockchain can introduce latency in real-time vehicle data processing and predictive maintenance. To address this, edge computing handles diagnostics at the source, and faster consensus algorithms or hybrid blockchain models are used to speed up processing. Critical data is prioritized for transmission, while non-essential data is minimized to optimize system performance [15].

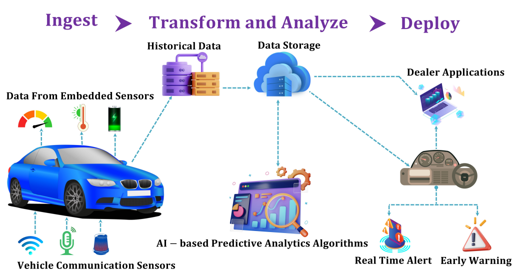

Fig. 2: Working of Vehicle Predictive Maintenance Solutions: Data Acquisition, Cloud Processing, and Real-Time Monitoring Interfaces.

B. Salient Contributions

This work presents a novel system addressing vehicle identification, registration, and maintenance challenges with enhanced security, privacy, and reliability. Key contributions include:

- *Integration of IPFS, Blockchain, and Cryptography:* Enhancing security and data integrity through a combination of IPFS, blockchain, and cryptography.
- *Life Cycle Tracking:* Ensuring a tamper-proof and verifiable record of the vehicle's life cycle from manufacturing to maintenance.
- *Encryption and Blockchain Performance Evaluation:* Identifying Cosmos blockchain as optimal due to its superior transaction times and throughput.
- *Predictive Maintenance with Federated Learning:* Introducing a federated learning mechanism for timely maintenance while preserving user data privacy.

II. Related Work

The literature review begins with exploring the current landscape surrounding vehicle registration and management systems. Rosado *et al.* [1] propose a Hyperledger Fabric-based car registration system to enhance interoperability among government agencies and streamline information exchange within the European Union. Hossain *et al.* [2] introduce a blockchain-based distributed ledger framework to replace slower, centralized vehicle registration systems with faster and more transparent processes, emphasizing government oversight. Benarous *et al.* [16] suggest a blockchain system for vehicle registration that ensures transparency and traceability by recording transactions on a public blockchain. Njoroge *et al.* [17] develop a blockchain-based prototype to manage vehicle transactions using an agile development approach. James *et al.* [18] addresses the issue of multiple vehicle registrations and advocates for a mobile application-based system to simplify the registration process. Tejas *et al.* [19] created a system using optical character recognition (OCR) to read license plates and retrieve vehicle information, aiming to eliminate the need for physical documents. Guerreiro *et al.* [20] report on blockchain projects in food supply chains and car registration systems, applying different process designs and Hyperledger Fabric implementations. Sanepara *et al.* [21] propose blockchain technology to address fraud and inefficiencies in vehicle processes, aiming for a more secure and reliable system. Compared to traditional centralized methods, which are vulnerable to breaches, fraud, and data manipulation, the blockchain and federated learning framework ensure greater security by decentralizing data storage and using cryptographic techniques. Nguyen DC *et al.* [22] preserves privacy by processing data locally, while existing systems often expose sensitive information during centralized processing

III. Methodology

This section is divided into 3 phases: pre-registration, registration, and post-registration. Figure 3 represents the architecture of the blockchain-based state tracking system to maintain each vehicle state in a tamper-proof and verifiable manner. This architectural representation illustrates a step-by-step scenario of exploring the InterPlanetary File System (IPFS) and blockchain validation to implement the proposed model. Each phase incorporates mathematical models

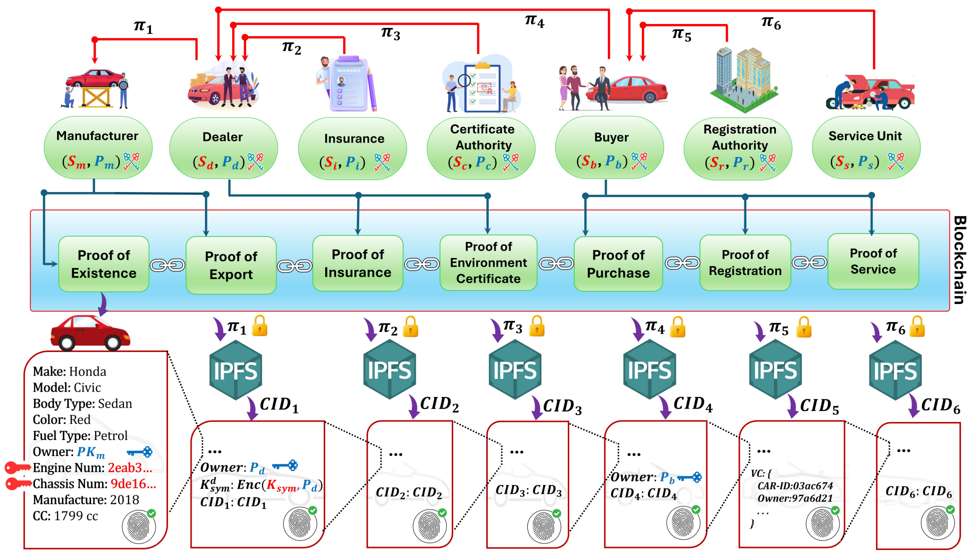

Fig. 3: IPFS-based CAR-ID Generation with Blockchain Validation for Streamlined Preregistration and Registration of Vehicles.

and cryptographic techniques to ensure secure and efficient vehicle lifecycle management using blockchain and federated learning. The system efficiently scaled with increasing vehicles and transactions by using blockchain and federated learning, distributing the workload across the network. This ensured smooth operation and prevented overloading. Including performance data on transaction processing times and scalability under various load, conditions has improved the evaluation.

A. Pre-registration Phase

In this section, the vehicle's lifecycle from manufacture to registration involves generating document proofs at each stage: manufacturing, distribution, insurance, certification, and trading. Initially, the vehicle's details are recorded on the Blockchain as 'Proof of Existence' with the manufacturer as the owner. As the vehicle is transported, ownership is transferred through an encrypted proof π_1, recorded as 'Proof of Export.' Insurance is secured, and the document is encrypted as π_2, uploaded to IPFS, and recorded as 'Proof of Insurance' with the IPFS Content Identifier CID_2. Compliance certificates are encrypted as π_3, uploaded to IPFS, and recorded as 'Proof of Certification' with CID_3. Finally, during purchase, proofs π_4 are generated, encrypted with the RA public key P_r, and recorded as 'Proof of Purchase,' updating the $Owner$ field with the buyer's public key P_b.

B. Registration Phase

In this phase, the vehicle owner must contact the Registration Authority to provide a Vehicle Certificate and register the vehicle, which includes an on-ground inspection by the Registration Authority. The Registration Authority acts as a trusted entity, verifying the correctness of vehicle proofs and issuing a verifiable registration certificate. The registration phase comprises four stages: proof verification, generation of vehicle credentials, field verifiable signature, and proof of registration. During proof verification, all necessary documents, including the vehicle's chassis and engine number and purchase invoice, are retrieved from the IPFS Content Identifiers stored in the $ProofofPurchase$ block. Once the Registration Authority verifies these documents, it generates a verifiable Vehicle Credential, which includes vehicle details and owner details and assigns a registration number in the format $SSAAYYXXXX$, similar to the current system. This number is further printed as a number plate on the vehicle, and a new identifier, $CAR-ID$, is introduced to reference the vehicle in the blockchain model. For example, the $CAR-ID$ of a private SUV car manufactured in May 2024 registered as $SS00AA0000$ is represented as:

```
U1MwMEFBMDAwMA-MTcxODQ0NTg1MjI4NQ-U1VW-MDU-
MjAyNA-MA
```

The signed Vehicle Credential, containing sensitive information like the owner's name, address, chassis number, and engine number, is used

TABLE I: Comparative analysis of blockchain-based systems for vehicle lifecycle management.

Authors	Data Security	Processing Efficiency	Cost Reduction	Scalability	Data Traceability	Throughput	Encryption Time (X25519)	CPU Utilization (X25519)
Rosado T *et al.* [1]	✓	✗	✓	✗	✓	✓	✗	✗
Hossain MP *et al.* [2]	✓	✗	✗	✗	✓	✓	✗	✗
Tejas B *et al.* [19]	✗	✓	✗	✗	✗	✗	✗	✗
Syed TA *et al.* [4]	✓	✗	✗	✓	✓	✓	✗	✗
Corazza MV *et al.* [9]	✓	✗	✗	✓	✓	✗	✗	✗
Markudova D *et al.* [11]	✗	✓	✓	✗	✓	✓	✗	✗
Sanepara V *et al.* [21]	✓	✓	✓	✓	✓	✓	✗	✗
Proposed Scheme	✓	✓	✓	✓	✓	✓	2.23s	23.1%

to create a verifiable proof presentation called π_5. This proof presentation, excluding sensitive details, is then published on the blockchain as a $ProofofRegistration$ transaction, officially marking the vehicle's registration.

C. Post Registration Phase

This section highlights two critical use cases of the fully traceable blockchain-based registration and identification mechanism. The first use case involves Vehicle Certificate Verification, where third-party service providers or inspectors, such as traffic police, can verify vehicle ownership and related details like insurance and PUC certificates by generating a verifiable presentation proof. This proof can be generated in real-time on mobile devices as QR codes, allowing for easy, privacy-preserving validation. The second use case uses the blockchain as a comprehensive logbook for predictive maintenance using Federated Learning (FL). The system addresses resource-constrained environments using federated learning, which processes data locally on vehicles, minimizing the need for centralized computation. To reduce the computational burden, the framework uses lightweight models and efficient encryption techniques, ensuring that devices with limited processing power can still participate effectively without overwhelming resource usage. Vehicles, denoted by their IDs $i \in 1, 2, \ldots, N$, collect performance data vectors $D_{i,k}$ at regular intervals and contribute to a global model managed by a trusted aggregator. The model is updated iteratively with locally trained gradients $W_{i,k}$, where the gradient is calculated as:

$$\Delta W_{i,k} = W_{i,k} - \Theta_{k-1}, \tag{1}$$

It is protected against gradient inversion attacks through Paillier homomorphic encryption. The encrypted model parameters are then aggregated to update the global model Θ_k, with contributions weighted by the credit scores $C_{i,k}$. The credit score of each vehicle is updated based on the recall performance $\text{Recall}_{i,k}$, calculated as:

$$\text{Recall}_{i,k} = \frac{\text{TP}}{\text{TP} + \text{FN}} \tag{2}$$

Ensuring that honest contributions are rewarded while discouraging malicious behavior. Finally, contributors are incentivized proportionally to their credit scores, with the updated global model available for vehicles to use in maintenance prediction after decryption.

IV. Results

To assess the performance of the proposed model, we have used a workstation with an i5-10210U CPU, 20 GB installed RAM, and an x64-based processor running Windows 10 pro (version 22H2). Code scripts were written in Python (Python stable version 3.11.5). All the required libraries were installed in the Python Virtual Environment setup, and in the same environment, the simulations were run. Our experimental setup also requires some dummy files with known sizes, which helps us estimate the benchmark performances. Every time vehicle servicing is done, a Proof of Service transaction is pushed onto the Blockchain, which appends the IPFS Content ID of the service receipts (called π_6) to the vehicle state. Figure 4 illustrates the average encryption time for various algorithms across different file sizes, plotted on a logarithmic scale. Encryption time generally increases with file size but not linearly. For files under 1000 KB, the time difference between algorithms is minimal, while for larger files (100 MB), X25519 performs the best, taking 2.23 seconds compared to X448's 2.30 seconds. X25519 consistently outperforms other algorithms and scales more efficiently with

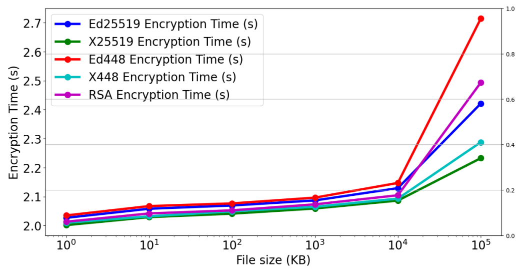

Fig. 4: Average Encryption Time for Ed25519, X25519, Ed448, X448, and RSA Algorithms Across Different File Sizes.

file size. The CPU utilization during encryption is also measured, with each algorithm tested 20 times to determine the average usage. Figure 5 shows the

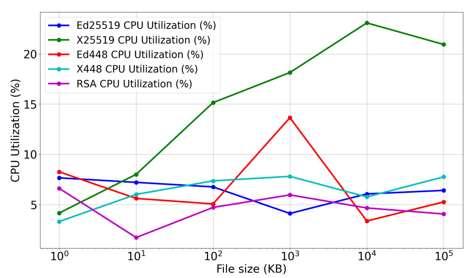

Fig. 5: Average CPU Utilization for Ed25519, X25519, Ed448, X448, and RSA Algorithms Across Different File Sizes.

average CPU utilization for each algorithm across different file sizes, with RSA having the lowest usage and X25519 peaking at 23.1%, except for smaller files (∼1 KB), while X448 and Ed25519 maintain around 7%. X25519 is ideal for high-end systems, whereas X448 offers a balance of speed and low CPU usage. In the context of Blockchain, which records vehicle states and handles around 55 transactions per minute due to high automotive production volumes, a comparison of Ethereum, IOTA Shimmer, and COSMOS blockchains was conducted using sample transactions for various proofs.

Our experiment focuses on detecting vehicle engine failures due to compressor leakage by continuously monitoring the target. The problem is modeled as a classification task using three machine learning methods: Single Layer Feedforward Neural Network (SLFN), Random Forest (RF), and Support Vector Machines (SVM). A simulation of a turbocharged engine system based on the WLTP driving cycle generated a dataset with 125,700 data points, split into 100,500 for training and 25,200

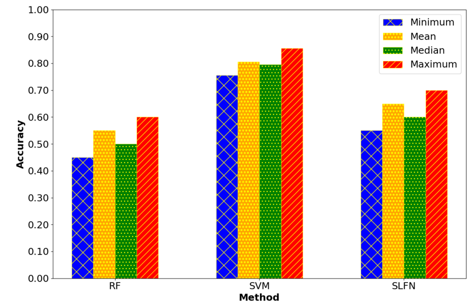

Fig. 6: Accuracy Statistics for Selected Machine Learning Methods.

for testing. The SLFN has 100 neurons with a hyperbolic tangent activation, SVM uses a Gaussian kernel, and RF employs 100 classification trees. The recall was calculated over 50 runs, with the results plotted in Figure 6.

V. Conclusion

This paper presents a novel approach to vehicle lifecycle management using blockchain, cryptography, federated learning, and IPFS. Our model addresses fraud, inefficiencies, and data privacy by decentralizing vehicle registration and identification, enhancing security, efficiency, and data traceability. The system simplifies registration, removes administrative hurdles, and provides a tamper-proof ledger. Federated learning-based predictive maintenance reduces downtime and optimizes costs. Our evaluation shows that the proposed cryptographic and blockchain techniques ensure data security and privacy, with performance analysis confirming the system's practicality and efficiency.

References

[1] T. Rosado, A. Vasconcelos, and M. Correia, “A Blockchain Use Case for Car Registration,” *Essentials of Blockchain Technology*, pp. 205–234, 2020.

[2] M. P. Hossain, M. Khaled, S. A. Saju, S. Roy, M. Biswas, and M. A. Rahaman, “Vehicle registration and information management using blockchain based distributed ledger from bangladesh perspective,” in *2020 IEEE Region 10 Symposium (TENSYMP)*. IEEE, 2020, pp. 900–903.

[3] A. F. Abdoun and H. Yazdifar, “Smart city development, blockchain for the vehicle registry: a study in Romania,” *International Journal of . . .*, 2021. [Online]. Available: http://eprints.bournemouth.ac.uk/

36091/%0Ahttp://eprints.bournemouth.ac.uk/36091/1/SMARTC$\sim$1.PDF

[4] T. A. Syed, M. S. Siddique, A. Nadeem, A. Alzahrani, S. Jan, and M. A. Khattak, "A Novel Blockchain-Based Framework for Vehicle Life Cycle Tracking: An End-to-End Solution," *IEEE Access*, vol. 8, no. June, pp. 111 042–111 063, 2020.

[5] D. Puthal, N. Malik, S. P. Mohanty, E. Kougianos, and C. Yang, "The blockchain as a decentralized security framework [future directions]," *IEEE Consumer Electronics Magazine*, vol. 7, no. 2, pp. 18–21, 2018.

[6] N. Vashistha, M. M. Hossain, M. R. Shahriar, F. Farahmandi, F. Rahman, and M. M. Tehranipoor, "echain: A blockchain-enabled ecosystem for electronic device authenticity verification," *IEEE Transactions on Consumer Electronics*, vol. 68, no. 1, pp. 23–37, 2021.

[7] M. S. Peelam, M. Gera, V. Chamola, S. Zeadally *et al.*, "A review on emergency vehicle management for intelligent transportation systems," *IEEE Transactions on Intelligent Transportation Systems*, 2024.

[8] M. S. Peelam, K. Shah, and V. Chamola, "V-track: blockchain-enabled iot system for reliable vehicle location verification," *Digital Communications and Networks*, 2024.

[9] M. V. Corazza, S. Magnalardo, A. Musso, E. Petracci, M. Tozzi, D. Vasari, and E. de Verdalle, "Testing an innovative predictive management system for bus fleets: outcomes from the ravenna case study," *IET Intelligent Transport Systems*, vol. 12, no. 4, pp. 286–293, 2018.

[10] V. Chamola, A. Goyal, P. Sharma, V. Hassija, H. T. T. Binh, and V. Saxena, "Artificial intelligence-assisted blockchain-based framework for smart and secure emr management," *Neural Computing and Applications*, vol. 35, no. 31, pp. 22 959–22 969, 2023.

[11] D. Markudova, S. Mishra, L. Cagliero, L. Vassio, M. Mellia, E. Baralis, L. Salvatori, and R. Loti, "Preventive maintenance for heterogeneous industrial vehicles with incomplete usage data," *Computers in Industry*, vol. 130, p. 103468, 2021.

[12] V. Hassija, V. Saxena, and V. Chamola, "A mobile data offloading framework based on a combination of blockchain and virtual voting," *Software: Practice and Experience*, vol. 51, no. 12, pp. 2428–2445, 2021.

[13] A. Munir, "Safety assessment and design of dependable cybercars: For today and the future," *IEEE Consumer Electronics Magazine*, vol. 6, no. 2, pp. 69–77, 2017.

[14] V. Hassija, G. Bansal, V. Chamola, V. Saxena, and B. Sikdar, "Blockcom: A blockchain based commerce model for smart communities using auction mechanism," in *2019 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2019, pp. 1–6.

[15] A. K. Sharma, M. S. Peelam, B. K. Chauasia, and V. Chamola, "Qiotchain: Quantum iot-blockchain fusion for advanced data protection in industry 4.0," *IET Blockchain*, 2023.

[16] "Blockchain-based forgery resilient vehicle registration system," *Transactions on Emerging Telecommunications Technologies*, vol. 33, no. 10, pp. 1–18, 2022.

[17] N. T. Njoroge, "A blockchain-based prototype for car registration," Ph.D. dissertation, Strathmore University, 2020.

[18] I. James, G. Ansa, and I. Udoeka, "Conceptual framework on overcoming the challenges of multiple vehicle registration in nigeria: A mobile application approach," *IOSR Journal of Mobile Computing and Application*, vol. 3, no. 5, pp. 1–3, 2016.

[19] B. Tejas, D. Omkar, D. Rutuja, K. Prajakta, and P. Bhakti, "Algorithm," pp. 1317–1320, 2017.

[20] S. Guerreiro, D. Silva, T. Rosado, A. Vasconcelos, M. Correia, and P. Sousa, "Decentralized Business Process Control using Blockchain An experience report from two applications: Food Supply Chain and Car Registration," *Enterprise Modelling and Information Systems Architectures (EMISAJ)*, vol. 15, no. 15, pp. 15:1–41, 2020. [Online]. Available: https://coinmarketcap.com/

[21] "Complete vehicle registration process using blockchain technology," *International Research Journal of Engineering and Technology*, no. May, pp. 7120–7124, 2020. [Online]. Available: www.irjet.net

[22] D. C. Nguyen, M. Ding, Q.-V. Pham, P. N. Pathirana, L. B. Le, A. Seneviratne, J. Li, D. Niyato, and H. V. Poor, "Federated learning meets blockchain in edge computing: Opportunities and challenges," *IEEE Internet of Things Journal*, vol. 8, no. 16, pp. 12 806–12 825, 2021.