



# Decentralized Asset Tracking and Maintenance for Railway Systems

A Hybrid Blockchain Approach

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## • Context & Motivation

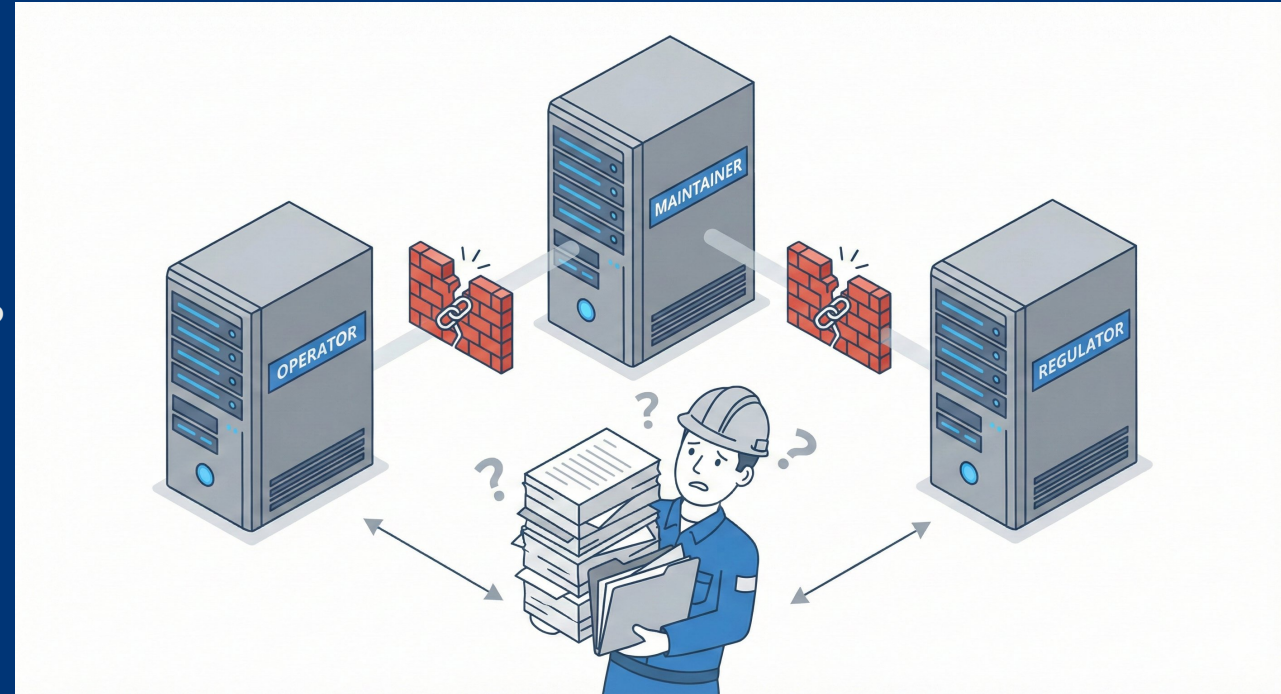


- Critical Industry: Railways move billions of passengers and tons of cargo.
- Complex Assets: A single train has thousands of parts (wagons, brakes, wheels).
- Safety First: Failure of a single part can lead to derailment or loss of life.
- The Need: We need a perfect, auditable history of every component from manufacture to retirement.



# • Problem Statement

- **Data Silos:** Operators, Maintainers, and Regulators use different, unconnected databases.
- **Lack of Trust:** How can an operator verify a maintenance report from a third-party crew?
- **Inefficiency:** Reliance on paper logs and manual data entry causes delays and errors.
- **Vulnerability:** Centralized databases can be altered or hacked.





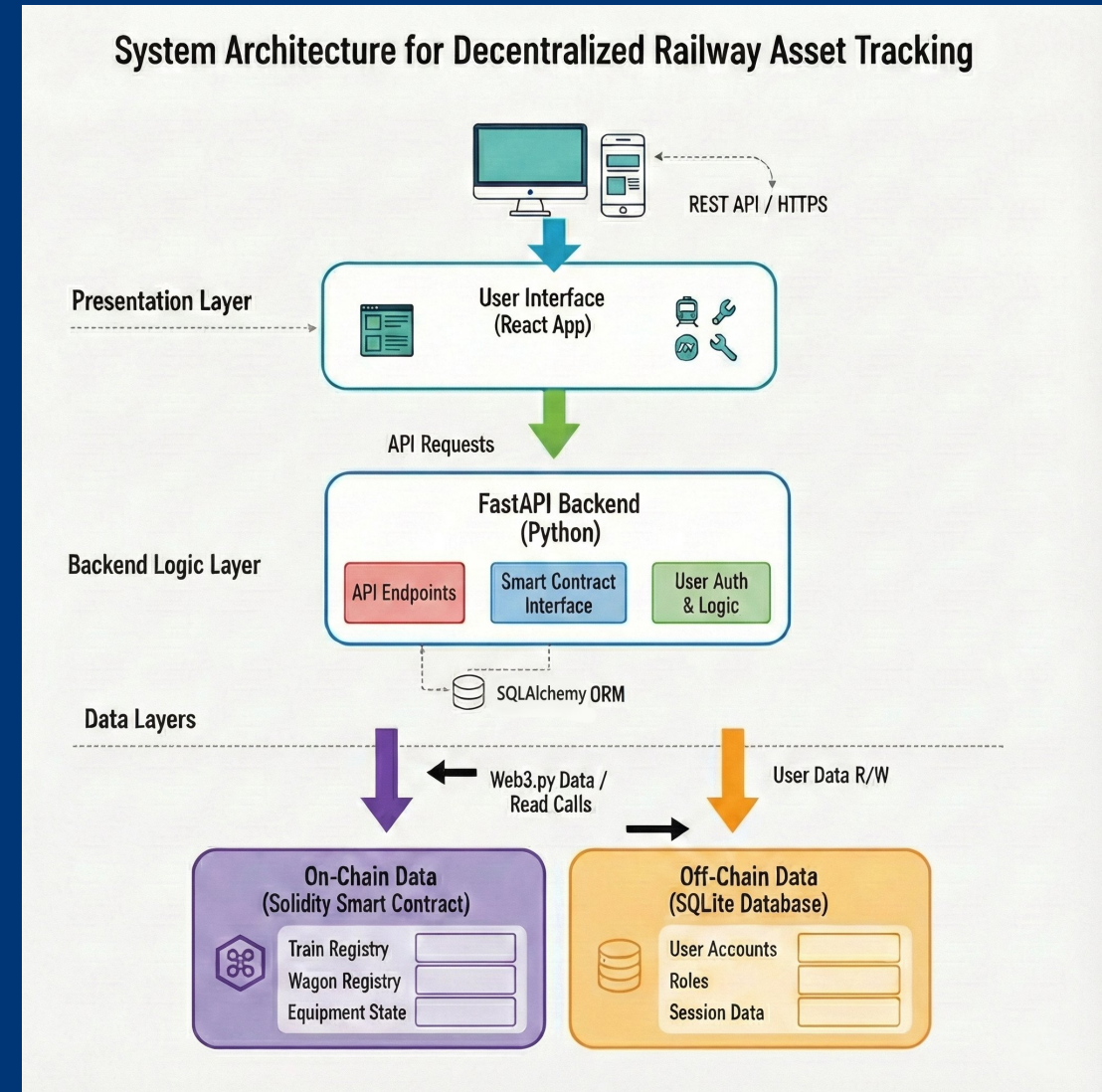
## • Challenges of a Pure Blockchain Approach

- **Scalability & Speed:** Public blockchains are slow (15s+ latency). A user cannot wait 15 seconds just to log in.
- **High Cost (Gas):** Storing large data (images, daily logs) on-chain is prohibitively expensive.
- **Privacy:** Public blockchains are transparent. We cannot store sensitive user data (passwords, employee names) on a public ledger.
- A "Pure DApp" is not practical for enterprise maintenance.



# • Proposed Solution: A Hybrid Architecture

- The Concept: Intelligent Data Separation.
- **Off-Chain (The Speed Layer):**
  - User Authentication & Non-critical data.
  - Result: Instant performance & Privacy.
- **On-Chain (The Trust Layer):**
  - Critical Asset Registry & Maintenance Status.
  - Result: Immutability & Transparency where it matters.

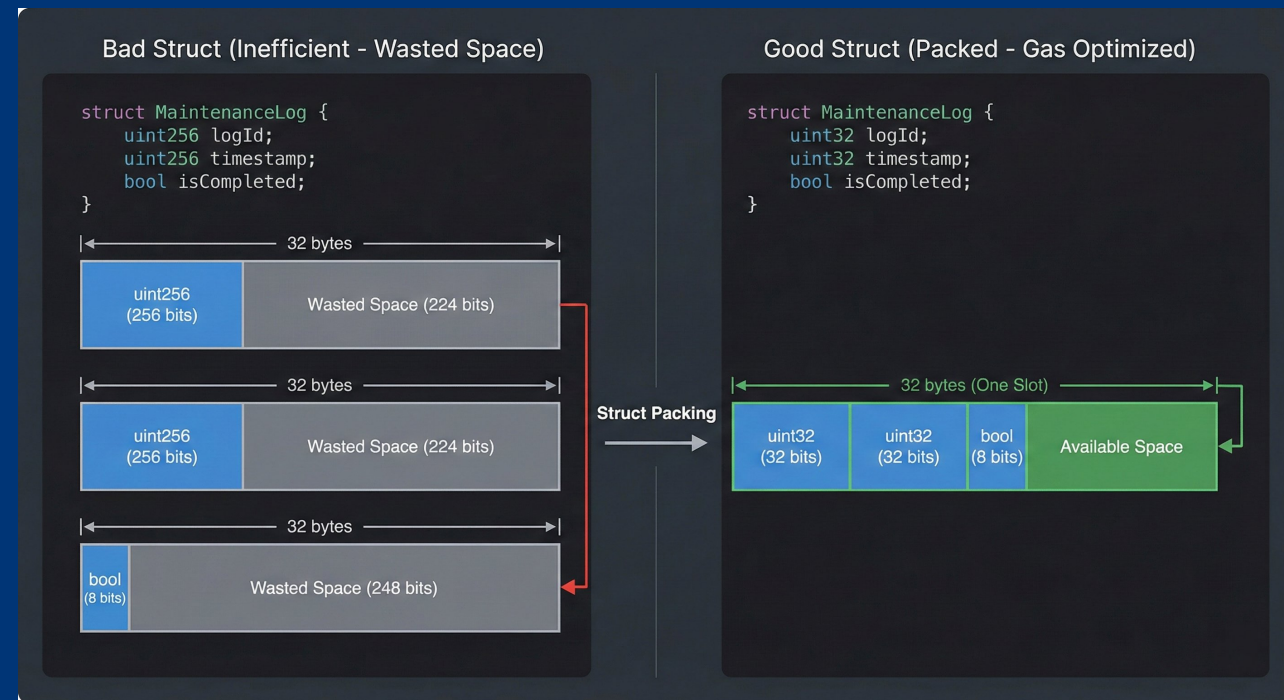






# • Technical Deep Dive - Gas Optimization

- **The Challenge:** Writing data to Ethereum is expensive. Standard code (uint256) wastes space.
- **Technique 1:** Struct Packing: Used uint32 for IDs and Timestamps.
- **Result:** Fits multiple variables into a single 32-byte storage slot.
- **Technique 2:** Custom Errors: Replaced expensive string messages (e.g., `require(..., "Error")`) with gas-efficient codes (`error NotActive()`).
- **Technique 3:** Optimized Mappings for  $O(1)$  lookups.





## • Layer 2 - The Intelligent Middleware

- **Technology:** Python (FastAPI) with Pydantic & SQLAlchemy.
- **Blockchain Gateway:** Exclusively manages all RPC communication with Alchemy and the Sepolia network.
- **Benefit:** Hides blockchain complexity (Gas, Nonce, Signatures) from the user.
- **Data Guard:** Validates inputs via Pydantic schemas before sending to the chain, preventing wasted gas on failed transactions.
- **Security:** Manages the administrative private key and user authentication (JWT).



# • Layer 3 - The User Interface


- **Technology:** React, TypeScript, & TailwindCSS.
- **Design Philosophy:** "Mobile-First".
- **Key Features:**
  - Dashboard: Real-time status overview.
  - Schematic Addressing: Uses Z1-L-F codes to locate parts instantly.
  - QR Scanning: Fast access to asset history.

### Equipment Details – #26

**Engine**  
ID: 26  
Supplier: FIAT  
Wagon Location: Z1-R-F  
Last Maintained: 8/25/2025, 7:16:24 PM  
Manufacturer Address: Brandschenkestrasse 100, 8002 Zürich, Switzerland

**Wagon ID: 26**  
Operational: Not Operational  
Origin Country: Switzerland

**QR Code**



Scan to open: <https://train.azabarg.it/equipment/26>  
[Print](#)

**Asset Traceability**

**Train**  
ID: 23  
Name: Al Andalus Train  
Manufacturer: Spain Industries  
Origin Country: Spain  
Manufacturer Address: C. del Camino de los Vinateros, 118, Moratalaz, 28030 Madrid, Spain

→

**Wagon**  
ID: 26  
Name: LUX-77  
Type: Passenger  
Purchase Year: 2025  
Origin Country: Spain  
Manufacturer Address: Carrer de Colón, 27, Ciutat Vella, 46004 València, Valencia, Spain

→

**Equipment**  
ID: 26  
Type: Engine  
Supplier: FIAT  
Operational: No  
Last Maint: 8/25/2025, 7:16:24 PM  
Origin Country: Switzerland  
Manufacturer Address: Brandschenkestrasse 100, 8002 Zürich, Switzerland  
Wagon Location: Z1-R-F

**Equipment Location in Wagon**

Saved Location: **Z1-R-F**

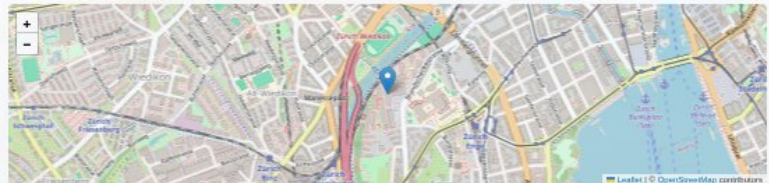
Overhead (O)			Floor (F)			Underframe (U)		
		FRONT			FRONT			FRONT
L	Z1	R	L	Z1	R	L	Z1	R
L	Z2	R	L	Z2	R	L	Z2	R
L	Z3	R	L	Z3	R	L	Z3	R
L	Z4	R	L	Z4	R	L	Z4	R
L	Z5	R	L	Z5	R	L	Z5	R
L	Z6	R	L	Z6	R	L	Z6	R

**Z1-R-F** [Copy Address](#)

■ Overhead (O) ■ Floor (F) ■ Underframe (U) Front at top (Z1)

**Manufacturer Location**

Brandschenkestrasse 100, 8002 Zürich, Switzerland







# • Key Feature - Progressive Web App (PWA)

- **The Problem:** Railyards and tunnels often have no internet connection.
- **The Solution:** PWA with Service Workers.
- **Capabilities:**
  - Installable: Works like a native app on Android/iOS.
  - Offline Caching: App shell loads instantly without network.





# • Evaluation Methodology

## ➤ Environment:

- Production: Deployed on Hetzner (CX22) Cloud VPS (Dockerized).
- Blockchain: Sepolia Testnet (PoS) via Alchemy Node.

## ➤ Metrics Measured:

- 1. Gas Cost: Hardhat Gas Reporter (Units).
- 2. System Latency: Chrome Network Analysis (Time to First Byte).
- 3. Frontend Quality: Google Lighthouse Audit.





# • Results I - Smart Contract Gas Analysis

- Comparison between a "Naive" (standard) contract and "Optimized" contract.

## ➤ Key Findings:

- addEquipment: 15% Gas Reduction (Struct packing effectiveness).
- addWagon: 7% Gas Reduction.

## ➤ Economic Impact:

- On Layer 2 (e.g., Optimism), a maintenance update costs <\$0.02.
- This proves economic feasibility for large-scale fleets.

➤ Function	➤ Naive (Gas Units)	➤ Optimized (Gas Units)	➤ Savings
➤ addTrain	➤ 272,502	➤ 273,072	➤ 0.00%
➤ addWagon	➤ 499,453	➤ 460,450	➤ 7.00%
➤ addEquipment	➤ 387,053	➤ 326,530	➤ 15.00%
➤ updateEquipment	➤ 55,070	➤ 55,745	➤ -1.00%



## • Results II - System Performance (Latency)

- **Read Operations (Off-Chain):**
  - Asset Retrieval: 255 ms (Instant UX).
  - Login/Auth: 727 ms (Secure hashing).
- **Write Operations (On-Chain):**
  - Asset Creation: 13.72 s (Block Confirmation).
- The hybrid model successfully isolates the blockchain delay to only critical writes.

Name	Status	Type	Time
token/	200	xhr	727 ms
trains/	200	xhr	255 ms
update-train/	200	xhr	13.72 s



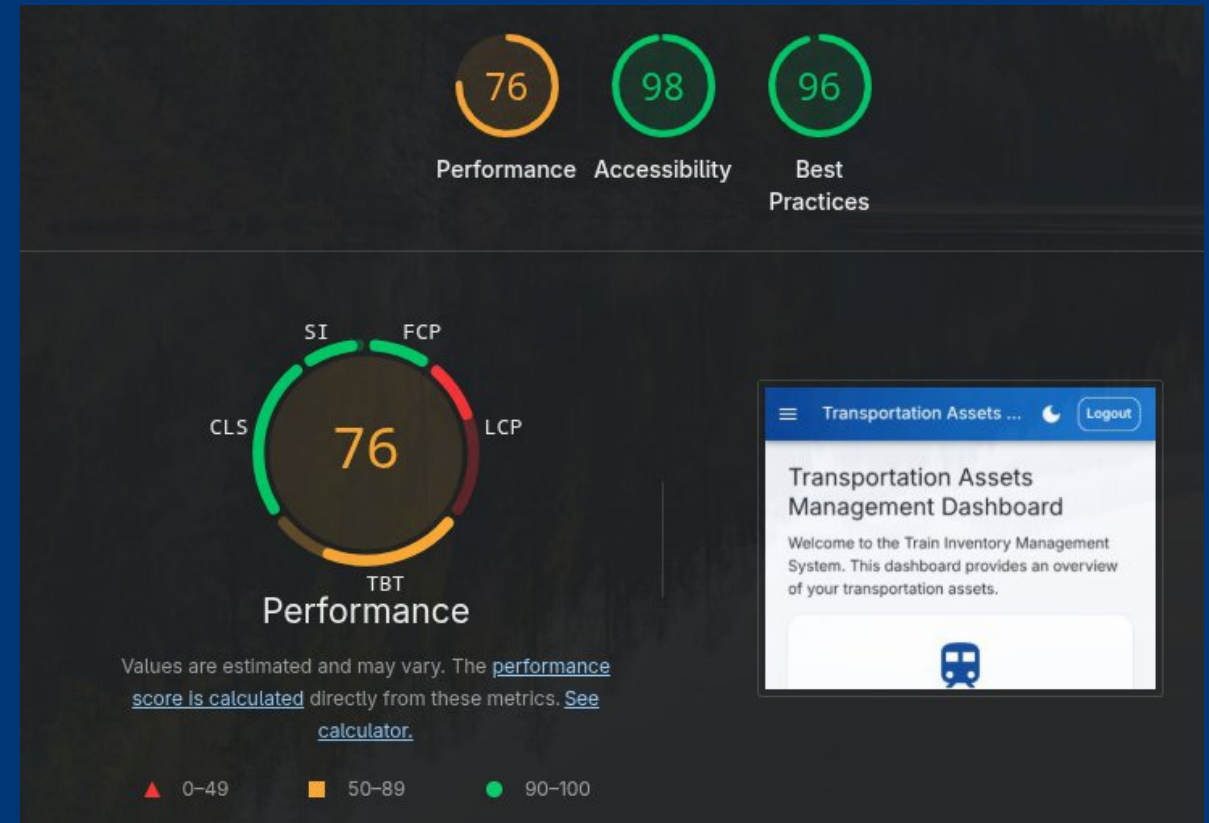
# • Results III - Frontend Quality & PWA

## ➤ Lighthouse Audit Scores:

- Accessibility: 98/100 (Excellent for diverse staff).
- Best Practices: 96/100 (Secure & Modern).
- Performance: 76/100 (Solid for a rich SPA).

## ➤ PWA Verification:

- Service Worker: Active (Offline support confirmed).
- Manifest: Valid (Installable on Android/iOS).







## • Conclusion & Impact

- **Addressed the Gap:** Moved beyond "theoretical frameworks" to a working full-stack system.
- **Solved the Trilemma:** Balanced Trust (Blockchain), Privacy (Off-chain DB), and Usability (PWA).
- **Final Verdict:** The system provides a single, immutable source of truth for railway assets without sacrificing operational speed.



## • Future Work & Q&A

- Future Improvements:
- IoT Integration: Automatic mileage updates via sensors. Thank You!
- Consortium Deployment: Move from Sepolia to Hyperledger Fabric for enterprise privacy.
- Advanced PWA: "Background Sync" for queuing offline transactions.

