Available at https://journalenrichment.com/index.php/jr/

Enrichment: Journal of Multidisciplinary Research and Development

Pneumatic Lock for Manhole and Bottom Loader on Fuel Tank Trucks: A Cloud-Based Digital Interlock System for Secure and Sustainable Fuel Distribution

Alvian Pratama*, Saiful Hamzah, Ahmed Syarif, Giyarto, Muhammad Wisnu Cakrawiguna

PT Pertamina, Indonesia

Email: alvian.pratama@pertamina.com*, saiful.hamzah@pertamina.com, ahmed.syarif@pertamina.com, ahmed.syarif@pertamina.com, muhammad.cakrawi

Abstract

Fuel distribution through road tank trucks plays a crucial role in downstream petroleum supply chains; however, it remains highly vulnerable to fuel theft, adulteration, and unauthorized access during transportation. Conventional mechanical sealing systems applied to manholes and bottom loading valves are widely recognized as weak security measures due to their susceptibility to manipulation and lack of digital traceability. These limitations result in transport losses, safety incidents, customer disputes, and regulatory non-compliance. This study presents the design, implementation, and performance evaluation of a Pneumatic Manhole Lock (P-Man) integrated with a digital spool lock and cloud-based interlock system for fuel tank trucks. The proposed solution combines physical pneumatic locking mechanisms with geofencing, one-time password (OTP) authentication, and real-time digital audit trails. Access to fuel compartments is strictly restricted to authorized locations and verified users, ensuring that opening actions can only occur at designated fuel stations. The system was implemented and tested on operational fuel tank trucks with multiple compartment configurations. Field results demonstrate a 77% reduction in sealing and verification time, complete prevention of unauthorized valve opening outside geofenced areas, significant reduction in transport loss, and a substantial increase in customer satisfaction from 42% to 93%. In addition, the system enhances safety performance and strengthens governance through transparent, auditable distribution records. The findings indicate that integrating pneumatic interlock systems with digital authorization provides a robust, scalable, and sustainable solution for improving fuel distribution security, operational efficiency, and regulatory compliance.

Keywords: pneumatic lock; fuel tank truck; manhole interlock; bottom loader; digital seal

INTRODUCTION

Road-based fuel transportation remains the backbone of downstream petroleum logistics, particularly in regions with extensive retail fuel station networks. Despite advancements in fleet management systems, GPS tracking, and digital dispatching platforms, physical access points on fuel tank trucks—namely manholes and bottom loading valves—remain the weakest links in distribution security. These components are commonly protected using manual mechanical seals, which provide minimal resistance against deliberate manipulation and offer no reliable digital evidence of access events (Choudhury et al., 2025; Ssemuddu, 2017; Svenblad, 2024; Vidaković & Vinko, 2023).

Numerous incidents of fuel theft and adulteration have been attributed to unauthorized access during transit, often occurring in remote or poorly monitored locations (Devi et al., 2023; Ifeanyichukwu et al., 2023; Vitiello et al., 2025). Such incidents not only result in direct financial losses but also pose serious risks to safety, environmental integrity, and corporate reputation (George et al., 2024; Guo et al., 2023; Settembre-Blundo et al., 2021; Wang et al., 2019). Furthermore, disputes between fuel terminals, transporters, and fuel stations frequently arise due to discrepancies between dispatched and received volumes, exacerbated by the absence of verifiable access logs (Olalekan Ahmed, 2025; Rana, 2025; Siluthanyi, 2017).

Regulatory authorities increasingly demand higher levels of transparency and accountability in fuel distribution, particularly for subsidized or regulated fuel products (Asmelash, 2022; Bernhardt et al., 2025; Rentschler & Bazilian, 2017). Traditional manual sealing practices are no longer sufficient to meet these requirements. Consequently, there is a growing need for integrated security solutions that combine physical enforcement with digital verification and traceability (Akter et al., 2024; Asmelash, 2022; Hossain et al., 2024; Idika et al., 2023).

Previous studies on fuel distribution security have largely focused on monitoring-based approaches such as GPS tracking, RFID-enabled seals, barcode systems, and closed-circuit television (CCTV). While these technologies improve visibility and post-event investigation, they do not actively prevent unauthorized access. In many documented cases, fuel theft was detected only after losses had already occurred.

Research in industrial safety systems highlights the effectiveness of interlock mechanisms, particularly in hazardous environments where human error and unsafe actions must be minimized. Pneumatic interlocks are widely used in chemical processing, oil and gas facilities, and industrial machinery due to their intrinsic safety, mechanical reliability, and suitability for explosive atmospheres. However, their application in fuel transportation security remains limited (Chen et al., 2021; Nilsson, 2023).

More recent studies emphasize the importance of cyber–physical systems, where mechanical components are tightly integrated with digital control and monitoring platforms. Such systems offer enhanced resilience by combining physical barriers with logical authorization rules. Despite this, literature addressing the integration of pneumatic locking mechanisms with cloud-based geofencing and digital authentication in fuel logistics is scarce.

This study contributes to the existing body of knowledge by presenting a practical, field-implemented solution that bridges mechanical safety engineering and digital logistics systems, addressing both prevention and traceability requirements.

A structured risk assessment was conducted to identify the dominant causes of fuel loss and security incidents in fuel transportation. The analysis employed Root Cause Analysis (RCA) to explore causal relationships, Pareto analysis to prioritize risk contributors, and Failure Mode and Effects Analysis (FMEA) to quantify severity, occurrence, and detectability.

The assessment revealed that the absence of a digital, multi-factor interlock system constituted the most critical risk factor. Manual sealing systems scored the highest Risk Priority Number (RPN) due to their ease of manipulation, lack of detection capability, and inability to restrict access based on location or authorization.

Secondary contributing factors included human error during seal verification, limited supervision along transportation routes, and insufficient integration between physical security devices and digital monitoring systems. Collectively, these weaknesses resulted in elevated risks across quality, cost, delivery performance, safety, and stakeholder trust.

System Architecture and Design (Detailed Explanation)

The proposed system comprises four primary components:

1. Pneumatic Manhole Lock (P-Man),
2. Digital Spool Lock (Interlock Valve),
3. Cloud-Based Control Platform (SmartMT), and
4. User Authentication Interface.

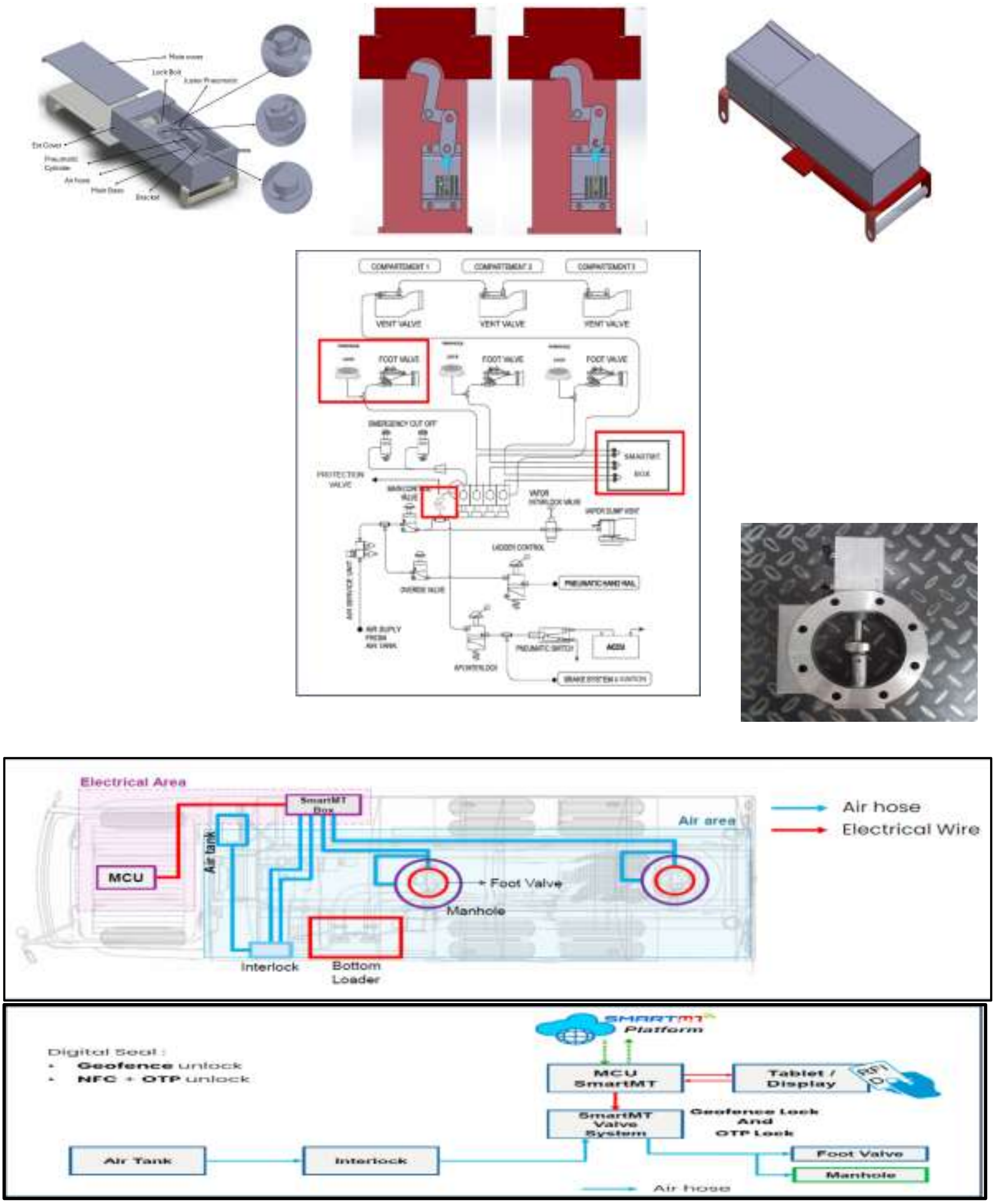

Figure 1. Figure 1. Components of the Pneumatic and Digital Interlock System: (a) Pneumatic Manhole Lock (P-Man) Assembly, (b) Digital Spool Lock Mechanism, (c) Control Unit Interface, (d) Cloud Platform Dashboard, (e) RFID and OTP

Authentication Flow, (f) System Integration Overview, (g) Geofencing Logic Diagram
Source: Author's Design and Prototype Documentation (2023)

The P-Man replaces conventional mechanical manhole bars with a steel pneumatic actuator powered by the truck's compressed air system. A protection valve ensures pressure stability and system safety. The digital spool lock functions as a gatekeeper, preventing pneumatic pressure release unless all authorization conditions are satisfied.

The cloud platform manages geofence definitions, OTP generation, access validation, and event logging. Authentication at fuel stations is performed using RFID cards and OTP codes delivered to authorized personnel. This architecture ensures that physical unlocking is impossible without digital approval, effectively eliminating unauthorized access.

This research addresses these challenges by introducing a pneumatic and digital interlock system designed to physically prevent unauthorized access while simultaneously generating reliable digital audit trails. The study aims to evaluate the effectiveness of this system in enhancing security, efficiency, safety, and sustainability within real-world fuel distribution operations. This research offers significant benefits across key operational and strategic dimensions. Operationally, the system enhances efficiency by reducing seal verification time by 77% and achieves cost savings through the prevention of fuel loss and the elimination of manual seals. In terms of security and governance, it provides a transparent and verifiable digital audit trail, thereby strengthening accountability and regulatory compliance. Furthermore, by restricting access to authorized locations only, the system directly improves workplace safety and mitigates environmental risks. At the relational level, the transparency and reliability offered by this system have been proven to dramatically increase customer satisfaction and trust.

METHOD

The research methodology consisted of system design, prototype development, controlled testing, and operational field trials. The system was installed on fuel tank trucks with 16 kL and 24 kL capacities, representing common fleet configurations.

Testing protocols included pneumatic pressure stability tests, leak detection over extended durations, actuator response time measurement, geofence recognition delay analysis, OTP delivery reliability assessment, and system integration validation. Operational trials were conducted under both supervised and autonomous conditions to reflect real distribution scenarios. Performance indicators were measured before and after implementation to quantify improvements in efficiency, security, and stakeholder satisfaction.

RESULTS AND DISCUSSION

The results demonstrate substantial improvements across multiple operational dimensions. Seal installation and verification time decreased from approximately 15 minutes to 3.5 minutes, yielding a 77% efficiency gain. No unauthorized manhole or bottom loader openings were recorded outside authorized geofenced locations throughout the trial period.

Transport loss indicators exceeded target performance levels, indicating effective loss prevention. Customer satisfaction surveys showed a dramatic increase from 42% to 93%, reflecting improved trust and transparency. These outcomes confirm that the system not only enhances security but also delivers measurable operational and relational benefits.

Table 1. Performance Improvement Analysis Based on Panca Mutu Framework

Panca Mutu	Initial Issue / Problem Impact	Initial Improvement Target	Final Improvement Result (After Implementation)	Technical Notes / Evaluation	Conclusion
Quality	No digital system available to track seals and compartment opening, resulting in the absence of an audit trail (who–when–where).	**85%** of MT SmartMT shipments at FT Ujung Berung utilize multi-key lock/unlock system and are recorded in SmartMT historical data.	**99.92%** of Smart MT shipments successfully conducted using SmartMT system, where lock/unlock operations are strictly controlled.	**14,618 out of 14,640 shipments** were successfully executed using SmartMT. **12 failed shipments** were caused by router signal issues, which were resolved through router replacement on the affected trucks.	**Beyond target**
Cost	Transport loss during distribution from supply point to fuel stations, with **52 loss incidents** equivalent to **1,741 liters**.	Achieve **100%** Transport Loss KPI.	Transport Loss KPI at FT Ujung Berung achieved **110% performance index**, with **zero complainable cases** in the ODI system.	Potential cost avoidance achieved: annual throughput of **1.6 million liters** with loss tolerance (0.15%) equivalent to **IDR 24.3 billion**, plus savings from eliminating existing manual seals amounting to **IDR 300 million**.	**Beyond target**
Delivery	Manual seal installation and verification require up to **15 minutes**, with high potential for verification errors and incorrect seal installation.	Reduce seal installation and verification time at terminal and fuel stations by **50%** (target: 8 minutes).	Seal installation and verification using SmartMT require only **3.5 minutes**, representing a **77% reduction**.	Time reduction of **11.5 minutes per shipment** results in daily operational time savings of **35 minutes**, equivalent to energy cost savings of **IDR 2,749,000 per month**.	**Beyond target**
Safety	Potential unsafe actions by tanker	Zero accidents caused by oil	**100%** of SmartMT-equipped tank	**100% prevention** of illegal opening	**Meets target**

Panca Mutu	Initial Issue / Problem Impact	Initial Improvement Target	Final Improvement Result (After Implementation)	Technical Notes / Evaluation	Conclusion
	drivers, including **19 incidents** of stopping in black zones. Manhole and bottom loader could be opened outside designated locations, causing spills and potential fatalities.	spills during fuel delivery.	trucks cannot be forcibly opened outside designated geofence locations, achieving **zero accidents** related to oil leakage.	incidents during trial period across all shipments.	
Morale	Low customer (fuel station) satisfaction toward existing cargo security system, with survey result of **42%**.	Increase customer satisfaction to **90%**.	Post-implementation customer satisfaction survey shows an increase to **93%** after P-Man and Spool Lock deployment.	Implementation of OTP-based authorization at fuel stations and SmartMT system training improved awareness and mitigated incorrect unloading incidents.	**Beyond target**

Source: Field Trial Data and Operational Records from FT Ujung Berung Depot (2023)

Sustainability and ESG Implications (Expanded)

The system supports sustainability objectives by reducing fuel loss and minimizing the risk of environmental contamination. From a social perspective, improved safety reduces exposure to hazardous incidents for drivers and fuel station operators. Governance benefits include transparent audit trails that facilitate regulatory compliance and accountability.

The integration of physical and digital controls aligns with Environmental, Social, and Governance (ESG) principles and supports long-term sustainable fuel distribution practices.

CONCLUSION

This study demonstrates that the Pneumatic Manhole Lock and digital spool lock system provides an effective and scalable solution to longstanding security challenges in fuel distribution. By combining physical pneumatic enforcement with cloud-based digital authorization, the system significantly improves security, efficiency, safety, and compliance. The solution is suitable for large-scale deployment and offers strong potential for replication across fuel logistics networks. Future research should focus on cybersecurity resilience, advanced analytics integration, and broader application to other hazardous material transportation systems.

REFERENCES

Akter, S., Hussain, M. I., Bhuiyan, M. K. I., Sumon, S. A., Hossain, M. I., & Akhter, A. (2024). Enhancing Data Integrity and Traceability in Industry Cyber Physical Systems (ICPS) through Blockchain Technology: A Comprehensive Approach. *Available at SSRN 5041397*.

Asmelash, H. (2022). The regulation of environmentally harmful fossil fuel subsidies: From obscurity to prominence in the multilateral trading system. *European Journal of International Law*, *33*(3), 993–1023.

Bernhardt, L., Breiderhoff, X., & Dewenter, R. (2025). New Evidence on Price Effects of Transparency Regulations in European Fuel Markets. *Journal of Industry, Competition and Trade*, *25*(1), 4.

Chen, C., Li, C., Reniers, G., & Yang, F. (2021). Safety and security of oil and gas pipeline transportation: A systematic analysis of research trends and future needs using WoS. *Journal of Cleaner Production*, *279*, 123583.

Choudhury, S., Costa, F., Manara, G., & Genovesi, S. (2025). Combating the Counterfeit: A Review on Hardware-Based Anticounterfeiting Technologies. *Applied Sciences*, *15*(18), 10298.

Devi, J. Y., Murki, K., Hanmanthu, B., Ram, A., & Kamran, M. (2023). An efficient novel approach for detection of fuel monitoring system through IoT sensors for a sustainable environment. *E3S Web of Conferences*, *430*, 1095.

George, A. S., Baskar, T., & Srikaanth, P. B. (2024). Cyber threats to critical infrastructure: assessing vulnerabilities across key sectors. *Partners Universal International Innovation Journal*, *2*(1), 51–75.

Guo, D., Chen, H., Wu, R., & Wang, Y. (2023). AIGC challenges and opportunities related to public safety: a case study of ChatGPT. *Journal of Safety Science and Resilience*, *4*(4), 329–339.

Hossain, M. I., Steigner, T., Hussain, M. I., & Akther, A. (2024). Enhancing data integrity and traceability in industry cyber physical systems (ICPS) through Blockchain technology: A comprehensive approach. *ArXiv Preprint ArXiv:2405.04837*.

Idika, C. N., James, U. U., Ijiga, O. M., & Enyejo, L. A. (2023). Digital Twin-Enabled Vulnerability Assessment with Zero Trust Policy Enforcement in Smart Manufacturing Cyber-Physical System International Journal of Scientific Research in Computer Science. *Engineering and Information Technology*, *9*(6).

Ifeanyichukwu, O., Mustapha, A., Edafe, U., & Hussaini, H. A. (2023). Security Check Points and Police Extortion: A Study of Road Transport Corridors in Imo State, Nigeria. *Sch Int J Law Crime Justice*, *6*(10), 522–533.

Nilsson, J. (2023). *A changing energy security environment–a review of alternative energy carriers for light duty vehicles*.

Olalekan Ahmed, T. (2025). *Exploring the Impact of Infrastructural Deficiencies on Logistics Efficiency in Nigeria.*

Rana, S. (2025). *Freight Distribution During Disasters: Measuring and Improving Operational Performance of Critical Systems*. Massachusetts Institute of Technology.

Rentschler, J., & Bazilian, M. (2017). Policy monitor—principles for designing effective fossil fuel subsidy reforms. *Review of Environmental Economics and Policy*.

Settembre-Blundo, D., González-Sánchez, R., Medina-Salgado, S., & García-Muiña, F. E. (2021). Flexibility and resilience in corporate decision making: a new sustainability-based risk management system in uncertain times. *Global Journal of Flexible Systems Management*, *22*(Suppl 2), 107–132.

Siluthanyi, M. M. (2017). *The role of transport in logistics and freight movement of liquid fuels in Gauteng province*. University of Johannesburg (South Africa).

Ssemuddu, J. (2017). *Electronic evidence management: adoption of standard operating procedures for admisability of electronic evidence in the Ugandan courts of law*. Kampala International University, School of Computing and Information Technology.

Svenblad, T. (2024). *Adapting digital forensics processes for quantum computing: Insights from established industry guidelines supplemented by qualitative interviews*.

Vidaković, M., & Vinko, D. (2023). Hardware-based methods for electronic device protection against invasive and non-invasive attacks. *Electronics*, *12*(21), 4507.

Vitiello, V., Benazzi, A., & Trucillo, P. (2025). Smart Card-Based Vehicle Ignition Systems: Security, Regulatory Compliance, Drug and Impairment Detection, Through Advanced Materials and Authentication Technologies. *Processes*, *13*(3), 911.

Wang, Q., Tai, W., Tang, Y., & Ni, M. (2019). Review of the false data injection attack against the cyber-physical power system. *IET Cyber-Physical Systems: Theory & Applications*, *4*(2), 101–107.