Integrating Digital Payment and Monitoring Systems in On-Street Parking Services: A Cyber-Physical System Approach

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ABSTRACT

Urban parking management faces persistent challenges related to transaction transparency, operational accountability, and inefficient manual payment systems. This study introduces an integrated on-street parking solution based on a Cyber-Physical System (CPS) framework that connects physical parking operations with digital transactions and real-time monitoring. The proposed system employs an Android POS device as a unified terminal for QRIS-based digital payment, receipt generation via Bluetooth printer, and automated data synchronization to a monitoring dashboard. The implementation follows a human-centered design approach, integrating software and hardware layers to enhance usability and transaction reliability. Functional testing involving 50 transactions from 10 simulated users yielded an average transaction time of 22.8 seconds, a printing success rate of 98%, and an average user satisfaction score of 4.6 out of 5. These results indicate that the system operates efficiently and delivers a seamless user experience under variable network conditions. Beyond technical performance, the study emphasizes the novel contribution of CPS integration in public service digitalization, demonstrating how a low-cost and replicable architecture can enhance transparency, traceability, and data-driven decision-making in parking management. The findings highlight that coupling digital payment systems with real-time monitoring not only improves operational efficiency but also strengthens accountability within public urban service ecosystems.

KEYWORDS

I. INTRODUCTION

RAPID urban population growth has significantly increased the demand for efficient mobility infrastructure, including reliable and responsive parking systems. One of the most common forms of parking in urban environments is on-street parking, which offers convenience but also presents complex challenges in terms of space management, regulation, and most critically payment mechanisms [1], [2]. In many Indonesian cities, on-street parking payment systems still rely on manual methods such as paper tickets and cash transactions. These conventional systems are vulnerable to revenue leakage, fare manipulation, and difficulties in supervision [3]. Furthermore, the lack of public awareness and compliance regarding parking rules exacerbates the inefficiency and disorder in public spaces [4]. These limitations underscore the urgent need for a digital transformation of on-street parking management.

Digital payment integration has emerged as a strategic priority in public service modernization, driven by initiatives like QRIS (Quick Response Code Indonesian Standard), which enables payments through a unified QR code linked to multiple digital financial service providers [5], [6]. Although QRIS adoption is increasing, its integration with real-time monitoring systems and dedicated Android-based POS devices, particularly within the context of on-street parking, remains underexplored [7].

To enhance operational efficiency and transparency, a new approach is needed one that integrates software, hardware, and communication networks within a unified ecosystem. This is where Cyber-Physical Systems (CPS) play a transformative role. CPS enables dynamic interactions between physical and digital entities in real-time distributed systems [8], [9]. In the realm of urban mobility, CPS has been increasingly applied in traffic monitoring, intelligent transportation systems (ITS), and the management of public infrastructure [10], [11]. And the parking domain, several studies have explored IoT-based systems for slot availability detection [12], [13], and RFID-based solutions for vehicle identification [14]. However, most of these technologies are tailored to off-street parking environments, such as shopping malls or private garages, where the physical and operational parameters are more predictable [15]. Furthermore, integration with digital payment systems remains partial or absent in many cases.

Notably, Android-based POS devices have proven effective in portable retail applications [16], [17]. Yet, their potential in public sector services, especially in managing regulated spaces like on-street parking, has not been fully harnessed. Although

some mobile-based parking prototypes exist, they rarely integrate sensor technology, real-time data processing, and digital payment into a single cohesive system [18], [19].

This research aims to address these gaps by designing and implementing an on-street parking system grounded in CPS principles, integrating QRIS-based digital payment and Android POS. The system is intended to simplify transaction flows, enhance data traceability, and generate actionable insights for municipal parking authorities. By building a system that seamlessly connects physical infrastructure and digital services, this study contributes to more efficient, transparent, and user-friendly on-street parking operations. It also positions itself within the broader trajectory of public sector digital transformation, aligned with Indonesia's smart city agenda [20], [21].
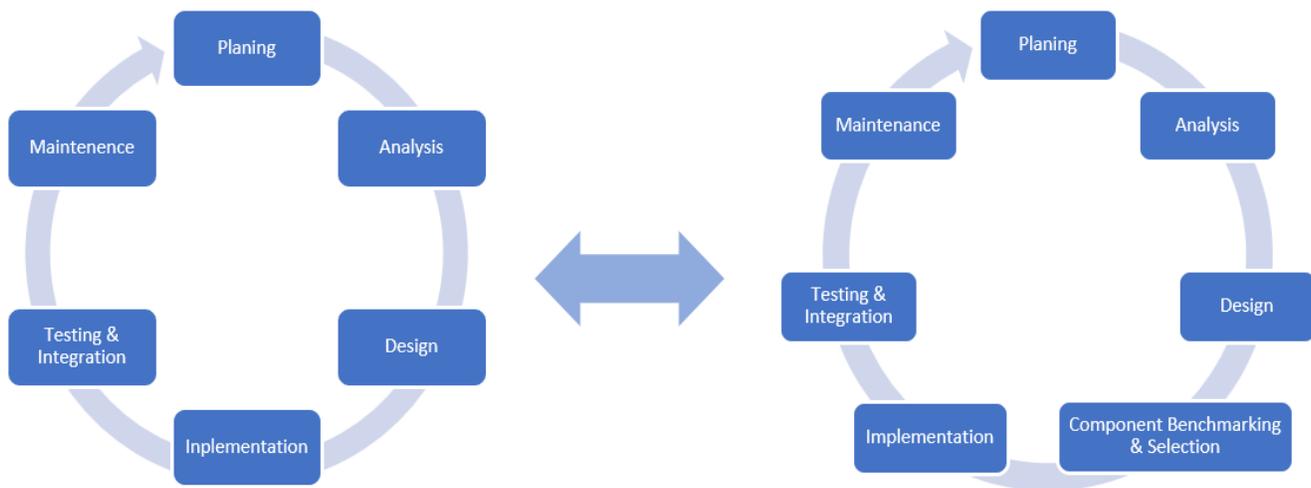
II. METHODS

This study adopts a system engineering approach that combines the Software Development Life Cycle (SDLC) and the Hardware Development Life Cycle (HDLC) to address the complexity of developing an integrated parking system involving software development, digital payment integration, and hardware-software interaction as in Fig. 1. This dual-framework approach aligns with the principles of Cyber-Physical Systems (CPS), in which software and hardware components are interlinked to enhance the performance, responsiveness, and reliability of urban public service systems [8], [9].

Fig. 1. system engineering approach that combines the Software Development Life Cycle (SDLC) and the Hardware Development Lifecycle (HDLC).

A. Planning and Requirement Analysis

The initial phase involves system planning, including the identification of functional and non-functional requirements as well as a comprehensive literature review of current technologies relevant to this domain, such as QRIS [5], Android POS [7], and smart parking sensors [12], [13]. The research team also performed risk assessment to anticipate potential implementation issues, such as internet dependency, and payment security concerns.

User-centered requirement analysis was conducted through stakeholder engagement and contextual inquiry with on-street parking users and field attendants. This stage provided insights into user behavior and highlighted obstacles such as low adoption of non-cash methods and a lack of tariff transparency [22], [23].

B. System Design

The system architecture consists of two major subsystems. (1) A mobile application developed for Android devices (software subsystem). (2) An integrated POS and receipt printing mechanism using Android POS devices (hardware subsystem). The system was designed using a modular, service-oriented architecture (SOA) that includes: a vehicle registration module, QRIS scanning module, payment verification, receipt printing, and a monitoring dashboard for

parking operators. Interoperability was ensured by adopting JSON-based data exchange through encrypted HTTP(S) protocols [24].

To support extensibility and minimize device lock-in, the design employed a loosely coupled integration approach, allowing flexibility across different Android POS devices and printer models. Communication protocols and data synchronization methods were selected based on best practices in mobile payment systems [25].

C. Component Selection and Benchmarking

Hardware benchmarking was conducted to compare multiple Android POS and Bluetooth printer options. Evaluation criteria included QRIS compatibility, transaction response time, and developer SDK availability. Component quality assessment followed Design for Reliability (DfR) and Total Cost of Ownership (TCO) methodologies to ensure sustainability and maintainability in real-world deployments [26], [27]. This selection strategy is aligned with current literature emphasizing the importance of open system compatibility, particularly for scalable CPS-based public service systems [14], [28].

D. Implementation and Integration

The implementation phase proceeded in parallel for both software and hardware components. Agile development was

used, with two-week sprint cycles to accommodate continuous improvement and feature refinement based on early testing feedback [29]. End-to-end transaction workflows from vehicle registration to QRIS payment scanning and receipt printing—were simulated under different network conditions to test resilience and system tolerance to latency.

E. System Testing and Evaluation

The system was evaluated using two strategies. (1) Functional testing (black-box method) to verify each module operates as intended. (2) Performance testing, focusing on metrics such as average response time, print accuracy, and transaction error rate. An initial usability test with ten simulated users was conducted in a controlled environment to assess system accessibility and acceptance. Evaluation metrics were aligned with Human-Centered Design (HCD) principles [30] and the ISO/IEC 25010 software quality standard [31].

F. Methodological Limitations

It is important to note that the maintenance phase was excluded from this study's scope, as the focus was on system prototyping, implementation, and validation. Nevertheless, the system architecture was intentionally designed to support future extension, particularly through the integration of real-time parking sensors such as ultrasonic detectors, camera-based systems, or low-power wide-area network (LPWAN) technologies [32], [33].

1. Materials

This object of study is justified because it represents a real-world, operational implementation of a Cyber-Physical System within a public service context, rather than a conceptual or laboratory prototype. Focusing on an Android-based on-street parking system integrated with QRIS digital payment allows the research to directly address practical challenges in urban parking management, including cash handling risks, delayed reporting, and weak supervisory control. The use of an Android POS device ensures that transaction execution, receipt printing, and data logging occur within a single embedded platform, enabling accurate observation of system performance under realistic constraints. Moreover, real-time monitoring by management staff provides measurable indicators of transparency, accountability, and operational efficiency. Therefore, this system constitutes an appropriate and relevant object for evaluating CPS effectiveness in smart urban infrastructure.

The materials and equipment used in the experiment include:

- Android POS device (Iware AP-02EX, Android 13, 3GB/32GB, 4G): This device served as the central terminal for running the parking application, scanning and verifying QRIS payments, processing data, and displaying the user interface throughout the transaction process.
- External Bluetooth Printer (Iware C5813, 58mm thermal): Used to print parking receipts as proof of payment. The printer connects to the Android POS via Bluetooth and supports 58mm thermal paper. Testing focused on compatibility, printing speed, and connection stability.
- Internet Connection (WiFi from the Android POS device): All QRIS verification and data synchronization processes

relied on the internal WiFi connectivity of the Android POS. Testing was conducted under both stable and fluctuating signal conditions to assess system resilience to connectivity issues.
- Simulated local server (cloud-based mockup): This component stored transaction records, managed historical payment data, and provided a centralized dashboard for administrative monitoring.
- Simulated vehicle and transaction data: Used as input for system testing, including vehicle information, parking durations, and dummy transactions with QR codes that comply with QRIS national standards.

Several factors such as the technical specifications of the Android POS, the performance of the external printer, and the stability of the internet connection directly influence system responsiveness, transaction success rates, and overall user experience. Accordingly, all experiments were conducted under varied scenarios to ensure the system performs reliably under real-world conditions.

2. Tasks and Methods

This methodological structure is justified by the need for clarity, reproducibility, and analytical rigor in system-based experimental research. Because the study evaluates an integrated Cyber-Physical System rather than isolated components, it is essential to explicitly document how materials, data flows, and system interactions were operationalized during experimentation. Detailing data analysis procedures, evaluation metrics, and calculation methods ensures transparency and enables independent verification of results. Furthermore, the use of simulated users requires a clear separation between operational execution and analytical assessment. Dividing the methodology into Tasks and Design and Analysis allows systematic tracing from user actions and system responses to measured outcomes and performance indicators. This structure aligns with established experimental design practices in information systems and CPS research, strengthening internal validity and methodological coherence.

2.1. Tasks

During the system development and experimental stages, each research team member was assigned specific responsibilities based on their field of expertise. Additionally, ten simulated participants were involved during the final usability testing phase. The following table outlines the main task distribution within the research team:

Name	Main Tasks
Firmansyah Maulana Sugiartana Nurusuwars (Informatics)	Designed the research framework; coordinated faculty and student team members; developed the machine-to-machine and machine-to-server communication systems; ensured data synchronization and transaction security.
Asep Andang (Electrical Engineering)	Responsible for hardware development; selected and tested physical components (Android POS, printer); integrated Internet of Things (IoT) capabilities to support automation.
Rahmi Nur Shofa (Information Systems)	Focused on software development, especially the Human-Machine Interface design; ensured UI/UX alignment with user needs; tested interface responsiveness and usability.

Meanwhile, the test participants were instructed to simulate

a complete parking process starting from entering vehicle data, scanning the QRIS code, verifying the payment, receiving the printed receipt, and finally providing feedback on the ease of use and transaction experience.

2.2. Design and Analysis

From the researchers' perspective, the experiment was designed as a functional system evaluation, using end-to-end test scenarios and both quantitative and qualitative data collection. Key elements of the design and analysis include:

- Material Manipulation: Android POS devices were configured to run the parking application. Tests were performed under both stable and unstable Wi-Fi network conditions. An external Bluetooth printer was also tested as an alternative when the internal printer had formatting issues.
- Evaluation Metrics:
  ✓ Response time (from input initiation to receipt printing).
  ✓ Print success rate and formatting alignment
  ✓ User satisfaction, measured on a Likert scale
  ✓ Transaction *error rate*
- Data Collection: Each transaction was automatically logged and supplemented with direct observation by the research team to identify technical issues and user interaction challenges.
- Data Analysis:
  ✓ Quantitative data were analyzed descriptively to evaluate system response time, success rate, and reliability.
  ✓ Qualitative feedback from users was analyzed using thematic coding to identify perceptions of usability, UI-related barriers, and improvement suggestions.

This approach provides a comprehensive understanding of system performance from both technical and user experience perspectives, in line with Human-Centered Design principles [30] and ISO/IEC 25010 software quality standards [31].

III. RESULTS

A. System Development and Implementation

This research successfully produced a prototype of an on-street parking system based on Android POS, supporting digital payments via QRIS, receipt printing through an internal or external Bluetooth thermal printer, and real-time transaction logging. The application was developed with a clean, responsive interface following the principles of Human-Machine Interaction and User-Centered Design [30], [31].

The system runs stably on the Android POS Iware AP-02EX (Android 13) and connects wirelessly to the Iware C5813 58mm Bluetooth thermal printer. The external printer was selected as a practical solution to the internal printer's limitation in handling multi-line alignment commands, as identified during early tests, thereby ensuring consistent formatting accuracy, reliable receipt rendering, and smoother transaction workflows under real operational conditions.

The system was tested in full usage scenarios from vehicle data input and QRIS scanning via the POS camera, to payment validation over internal WiFi and receipt printing. All successful transactions were automatically recorded in a local log system and displayed on a web-based monitoring dashboard, enabling real-time supervision, transaction traceability, audit readiness, and post-transaction analysis for operational evaluation and system reliability assessment.

B. Functional Evaluation

System testing was conducted using a black-box approach to validate each function independently of the internal code structure. Based on 50 trial transactions performed by 10 simulated users, the following metrics were recorded:

- Average transaction time: 22.8 seconds (SD ±3.4 seconds)
- Successful print rate: 98% (49 out of 50 transactions)
- System error rate: 2% (1 failed print due to Bluetooth disconnection)
- User satisfaction (Likert scale 1–5): average score of 4.6

These results indicate that the system performs reliably under standard WiFi conditions. The transaction time is significantly faster than other digital parking systems, which typically range from 30 to 40 seconds per transaction [34], [35].

TABLE 1. SYSTEM PERFORMANCE SUMMARY

Metric	Description	Result	Remark
Average Transaction Time	Mean time to complete one parking payment (n=50)	22.8 seconds	Stable performance under standard WiFi conditions
Printing Success Rate	Percentage of successful receipt prints	98%	One failure due to Bluetooth interruption
User Satisfaction (Likert 1–5)	Average subjective usability score from 10 participants	4.6 / 5.0	High perceived ease of use and reliability

As shown in Table 1, the system demonstrates a high level of stability and efficiency, with nearly perfect print success and strong user satisfaction. The average transaction time of 22.8 seconds indicates that the system can handle payments effectively in real operational environments.

C. User Experience Evaluation

Feedback from trial participants indicated that the transaction process was perceived as efficient and easy to follow, particularly due to the interface's progressive step-by-step flow. This aligns with interface design principles emphasizing clarity and visual consistency [30], [36]. Most participants expressed increased confidence in using QRIS for parking payment, citing greater transparency in pricing and the presence of printed receipts as proof. Many noted that manual payments often led to confusion about rates and ticket authenticity. Some user suggestions for future enhancement included:

✓ Saving digital receipts (e.g., PDF format)
✓ Adding audio notification upon successful payment
✓ Enabling automatic synchronization to a central server when a connection is available

D. Monitoring and Logging Validation

The web-based monitoring dashboard displays transaction recaps including license plate numbers, timestamps, and payment status. Data log validation was performed by matching internal log files with dashboard displays and cross-

referencing with real-time user actions. The system achieved 100% accuracy in:
- ✓ Recording vehicle license numbers
- ✓ Logging timestamps
- ✓ Capturing QRIS payment status

This real-time, structured transaction logging feature provides a strong foundation for future data-driven parking management systems, in line with smart city practices in other urban areas [10], [11], [37].

E. Technical Challenges

During implementation and testing, several technical challenges were encountered:
- ✓ Internal POS printer limitations in handling multi-line formatting, leading to the adoption of a more stable external printer.
- ✓ Bluetooth connection instability during initial tests in areas with high radio frequency interference.
- ✓ WiFi dependency: in cases of weak connectivity, QRIS validation was delayed or failed.

These issues were addressed through solutions such as adopting a more reliable external printer and implementing offline data caching with deferred synchronization, adopting a store-and-forward protocol commonly used in smart transportation systems. This approach ensures transaction continuity during network disruptions, preserves data integrity, and guarantees eventual consistency once connectivity is restored, thereby improving system robustness, fault tolerance, and operational reliability in real-world deployment conditions [38].

IV. Discussion

The results of this research indicate that the implemented Cyber-Physical System (CPS)-based on-street parking system can address long-standing issues in parking management, particularly those related to payment transparency, field officer accountability, and real-time data tracking. By digitizing transaction flows through QRIS and Android POS devices, the system minimizes cash handling and reduces opportunities for fraud or revenue leakage. Automated receipt generation and centralized logging further strengthen auditability and operational control. In addition, real-time data availability supports supervisory monitoring and data-driven decision making, enabling authorities to evaluate performance, optimize resource allocation, and improve service quality. Collectively, these outcomes demonstrate that CPS adoption offers a robust, scalable foundation for modernizing urban parking governance.

A. Transaction Efficiency

The average transaction time of 22.8 seconds categorizes the system as a fast-response parking service, outperforming many existing digital parking solutions that typically require 30 to 40 seconds per transaction [34], [35]. This improvement is primarily attributed to the seamless real-time interaction between the physical components (Android POS and Bluetooth printer) and the cyber layer (QRIS payment validation and server synchronization) within the CPS framework.

From a broader Cyber-Physical System (CPS) perspective, this level of transaction efficiency indicates that the closed-loop feedback mechanism between sensing, processing, and actuation is functioning effectively allowing the system to adapt dynamically to network latency or device communication delays. The reduced transaction time not only benefits users through quicker service and lower congestion but also enhances system stability by minimizing idle states, ensuring continuous synchronization, and preventing queue buildup across devices.

This finding aligns with existing literature suggesting that shorter transaction times in digital public services significantly improve user satisfaction and trust, particularly in high-frequency and repetitive service environments [39].

B. Data Accuracy and Validity

The system achieved 100% accuracy in logging license plate numbers, timestamps, and payment status, demonstrating the capability of digital systems to provide reliable, auditable transaction data. This is especially crucial in transitioning from manual parking systems often prone to fraud and data loss to a more transparent, data-driven model [3], [4].

These results reinforce arguments in urban computing literature, which emphasize that CPS implementations capable of capturing structured data can serve as foundational infrastructure for dynamic policymaking, such as time-based tariffs or congestion-aware pricing [10], [37], [40].

C. Human-Machine Interface and User Experience

The application's interface featuring a linear flow, minimal text, and intuitive icons contributed significantly to a smooth user experience. The average satisfaction score of 4.6 (on a 5-point Likert scale) affirms that the system is not only functional but also user-friendly. These findings support prior research showing that simplified UI and reduced cognitive load are critical success factors in mobile-based public service technologies [30], [36], [41]. Nevertheless, user feedback requesting features like audio confirmation and digital receipt storage reflects the evolving nature of user expectations.

D. Technical Resilience

Despite minor setbacks such as occasional Bluetooth disconnections, the system demonstrated strong resilience under fluctuating Wi-Fi conditions. The adoption of a store-and-forward strategy—enabling offline data storage with deferred synchronization—effectively preserved transaction continuity during temporary network disruptions, ensuring data integrity, preventing transaction loss, and supporting reliable recovery once connectivity was restored [38].

In the broader CPS resilience framework, these results illustrate the system's ability to sustain functionality despite uncertainties in the communication layer—one of the key determinants of CPS robustness in dynamic public environments. Such resilience reflects the capacity of the cyber and physical components to adapt, recover, and synchronize autonomously without requiring constant human intervention. This aligns with prior literature emphasizing that CPS resilience depends on fault tolerance, redundancy, and adaptive response mechanisms that allow stable operation under external perturbations [43].

Overall, the system's architecture exhibits the

characteristics of a robust and adaptive CPS, suitable for real-world deployment in high-variability field conditions, which is a critical requirement for digital public infrastructure.

E. *Relevance to Public Sector Digital Transformation*

Beyond its technical success, this system aligns with broader goals of digital transformation in public services. By leveraging widely available Android POS devices and QRIS—a national payment standard—the system is replicable across various municipal contexts, supporting inclusive smart city initiatives [20], [38], [44]. The study also responds to the core challenge of digital public innovation: integrating technology, users, and processes into a cohesive system [39], [44]. The modular, data-driven design of this parking system opens opportunities for further development, such as integration with parking sensors, real-time traffic analysis, and AI-driven tariff policies.

In summary, the integration of digital payment, real-time monitoring, and Android POS automation within a CPS framework has demonstrated measurable improvements in transaction efficiency and system reliability. Compared to conventional manual parking operations which typically require over 60 seconds per transaction and rely on unverified cash handling the proposed digital system reduces processing time by more than half while ensuring complete transaction traceability and transparency. The findings confirm that reliable CPS-based communication and IoT data exchange significantly enhance both operational stability and user experience in public service environments.

From a broader smart city perspective, these results highlight how data-driven, low-cost CPS implementations can strengthen accountability and optimize resource management in urban mobility systems. Lessons learned from this study emphasize the importance of designing resilient architectures capable of maintaining real-time synchronization under variable conditions. Future research will focus on extending this model through multi-node communication, predictive analytics, and adaptive control mechanisms to further enhance scalability and decision-making in smart urban infrastructure.

V.   CONCLUSION

This research confirms that implementing a Cyber-Physical System (CPS) in on-street parking enhances transparency, efficiency, and accountability. By integrating Android POS, QRIS digital payment, and automated receipt printing, the system enables fast transactions (average 22.8 seconds) with 100% data accuracy. User satisfaction further validates the system's usability and effectiveness. The success highlights the value of interdisciplinary collaboration and resilience in system design. Despite challenges like WiFi dependency and printer limitations, the solution proves adaptable and scalable. This work offers a practical model for smart parking aligned with Indonesia's digital transformation goals and opens opportunities for future enhancements such as sensor integration and adaptive pricing, real-time occupancy analytics, interoperability with municipal platforms, and policy-driven data utilization. Moreover, the framework supports auditability, operational monitoring, and evidence-based decision making, strengthening governance and sustainability in urban mobility management while reducing manual intervention and revenue leakage risks.

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