



RFID-Driven Smart Border Passing Architecture for Cloud-Integrated Vehicle Authentication

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Abstract

As global trade and tourism continue to expand, cross-border vehicle traffic has significantly increased, demanding more efficient and secure inspection systems. Conventional border checkpoint operations in Thailand rely on manual document verification, which is time-consuming and error-prone. This study proposes the design and implementation of a smart border passing system using Radio Frequency Identification (RFID) to enhance the identification and monitoring of vehicles at border checkpoints. The proposed system integrates three main components: a portable RFID reader, a flexible RFID tag sticker, and a cloud-based database dashboard for data synchronization and tracking. The RFID reader was developed as a compact, battery-powered device capable of reading UHF tags and transmitting data via Wi-Fi in real time. Experimental results demonstrate that the reader achieved 100% detection accuracy within 1.8 meters, with reliable tag readability for 30 days under real outdoor conditions. The web-based dashboard successfully displayed ENTRY, EXIT, and TIMEOUT events, enabling efficient vehicle tracking and administrative reporting. The system offers a practical and cost-effective solution for smart border management, reducing manual workload and supporting proactive detection of unauthorized crossings or vehicle theft. Future enhancements will focus on improving adhesive durability, expanding wireless communication, and integrating predictive analytics for real-time anomaly detection.

Keywords: smart border passing, radio frequency identification: RFID, vehicle identification, cloud database, UHF tag, IoT-based monitoring, real-time authentication

1. Introduction

Globalization has led countries worldwide to expand trade and tourism, resulting in a dramatic increase in cross-border traffic. Vehicle crossings between countries such as the United States and Mexico or among European Union nations continue to rise. In Asia, China's One Belt, One Road initiative has accelerated logistics and tourism routes. Within Southeast Asia, the ASEAN Economic Community (AEC) has

encouraged open-border policies among member nations. According to Thailand's Office of Transport and Traffic Policy and Planning (OTP), annual vehicular border crossings have reached over 14 million, underscoring the need for efficient inspection and monitoring systems [1].

Traditionally, border inspection procedures rely heavily on manual document verification, where immigration officers check passports, driving licenses, and vehicle permits before

granting passage. This manual approach is time-consuming, prone to human error, and inadequate for handling large traffic volumes. To improve operational efficiency, smartcard and Radio Frequency Identification (RFID) technologies have been proposed for automated identity verification at border checkpoints [1].

A smart border passing system using RFID consists of three main components: 1) an RFID reader for scanning tags via radio frequency waves, 2) an RFID tag containing encrypted identification data linked to the vehicle and owner, and 3) a cloud-based database for storing and verifying user information. Numerous studies have demonstrated RFID's usefulness in applications such as access control, electronic toll collection (ETC), public transport fare payment, and logistics management [2-4]. However, most implementations focus primarily on improving traffic flow rather than ensuring secure and traceable vehicle identity verification. To address security concerns, researchers have introduced lightweight authentication protocols and encryption schemes to mitigate cloning and traceability issues [4-11]. These studies have built trust in RFID applications, paving the way for their adoption in security-critical systems.

In addition, recent work has explored the development of RFID tag antennas optimized for UHF operation and sensing applications [12-17]. Yet, most of these antennas are fabricated on rigid FR4 substrates, suitable for card-based systems but

unsuitable for flexible, adhesive-type tags used on vehicles.

Unlike conventional RFID applications, a vehicular border pass system imposes unique mechanical and environmental constraints. The RFID tag must adhere firmly to curved or uneven vehicle surfaces-such as windshields, doors, or hoods-while remaining resistant to heat, moisture, and vibration. Any damage or removal attempt should render the tag unusable, ensuring tamper evidence. Furthermore, the tag must be flexible, low-cost, and easily replaceable [18-20].

While prior studies have demonstrated RFID applications in tolling systems, access control, and livestock monitoring, these works primarily focused on fixed-reading infrastructure and rigid card-based identification. None of them addressed the unique requirements of vehicular border authentication, where temporary permission, return-tracking, and easily removable tags are essential. This research therefore extends those previous concepts by incorporating a handheld reader, a flexible RFID sticker tag, and real-time cloud-based checkpoint validation.

Therefore, this research aims to design and implement a smart border passing system using RFID technology that integrates a compact handheld reader, a flexible RFID sticker tag, and a cloud-based database dashboard. The proposed system targets real-time identification, data synchronization, and operational durability under practical border checkpoint conditions.



Figure 1. System architecture of the proposed RFID-driven smart border passing system.



2. System Architecture

RFID technology was selected over alternatives such as QR codes and automatic license–plate recognition (ALPR) due to its mid-range passive reading capability, low operational cost, and reliability in outdoor environments. QR-based identification requires close proximity and is sensitive to moisture and glare, while ALPR systems involve significantly higher infrastructure costs and are prone to misread plates when vehicles are dusty or obstructed. RFID provides a balanced option suitable for handheld inspection and scalable deployment.

The proposed smart border passing system using RFID, as shown in Fig. 1 is designed to enhance the vehicle verification process at border checkpoints through wireless identification and real-time data management. The overall system integrates RFID-based vehicle tagging, portable reader devices, and a centralized cloud database, enabling automated registration, authentication, and tracking of vehicles crossing the border.

2.1 System Overview

As illustrated in Figure 1, the system comprises three main components:

1. RFID Reader - a handheld reader equipped with an embedded Wi-Fi microcontroller and LCD display. Officers use this device to scan vehicle tags during border entry and exit operations.

2. RFID Tag Sticker - a passive UHF RFID tag attached to the vehicle's surface (e.g., windshield, hood, or door). Each tag contains a unique identification code (UID) linked to the registered vehicle and owner data stored in the cloud database.

3. Cloud Database System - a centralized database that stores, verifies, and updates vehicle records. It communicates with the reader via Wi-Fi, allowing seamless synchronization of data across all checkpoints.

When a vehicle owner applies for a border pass, an officer registers the vehicle and owner information into the database. The RFID tag is issued and attached to the vehicle. During border crossing, the officer uses the reader to authenticate the tag against the stored records. The result is displayed instantly on both the reader's LCD screen and the officer's web-based interface.

If a registered vehicle fails to return within a specified duration (such as 30 days), the system automatically triggers a timeout notification and exports a report in Excel format to alert responsible officials. This feature improves administrative efficiency and ensures reliable monitoring of temporary cross-border traffic. In addition, the timeout function provides an early indication for tracking irregular vehicle movements and supports data traceability for administrative follow-up.

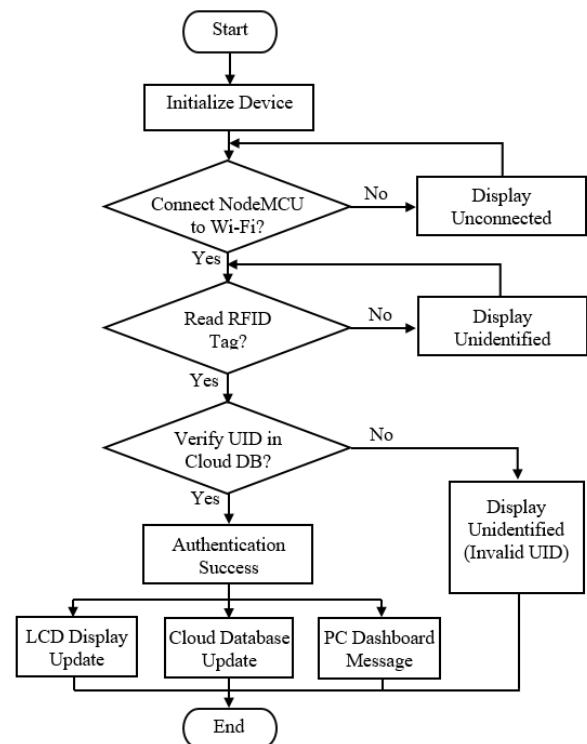


Figure 2 Operational workflow for the proposed RFID-driven smart border passing system.

RFID systems may be susceptible to cloning attacks and unauthorized tag reading in open environments. To mitigate these risks, the proposed system performs cloud-based identity matching and expiration–time validation at the server side, ensuring that duplicated or replayed identifiers cannot gain access. In addition, the security–code mechanism described in our prior work [5] is applicable for advanced protection when deployed at scale.

2.2 System Operational Workflow

The operational workflow of the system is depicted in Figure 2. The process begins when the

RFID reader initializes its components and attempts to connect to the cloud database via Wi-Fi. Once the connection is established, the reader scans for RFID tag signals:

1. If no tag is detected, an “Unidentified” message is displayed.
2. When a valid tag is detected, the reader retrieves the tag’s UID and sends it to the database for verification.
3. If the UID matches a registered record, the database authenticates the vehicle, updates the status log, and displays confirmation messages on both the LCD screen and the officer’s monitoring interface.
4. The updated status is stored in the cloud database, ensuring real-time tracking of vehicle entries and exits.

This workflow supports real-time bidirectional communication between the handheld reader and the cloud database, enabling fast verification even under high traffic conditions at border checkpoints. In cases where a tag cannot be read or the UID does not match an active entry record, the system automatically flags the case on the dashboard and requires manual document-based inspection. Unregistered vehicles are temporarily directed to a secondary inspection lane where identity and permit validation are performed. Once returning vehicles are authenticated, officers may reset their status through the dashboard, after which the tag may be removed by the driver. The process is designed such that a single officer can adequately manage one lane using the handheld device and web-based dashboard.

3. Hardware Reader Development

The hardware reader was developed as a portable RFID-based identification unit for field officers at vehicle border checkpoints. The hardware design emphasizes compactness, low power consumption, and reliable wireless data transmission, suitable for on-site inspection and registration tasks.

The fundamental antenna resonance frequency f_r for a half-wave dipole structure used in the UHF RFID module can be approximated for Equation (1) below

$$f_r = \frac{c}{2L\sqrt{\epsilon_{eff}}} \quad (1)$$

where c the speed of light (3×10^8 m/s), L is the effective length of the antenna, and ϵ_{eff} is the effective dielectric constant of the substrate.

The impedance of the dipole element can be estimated as shown in Equation (2).

$$Z_A = R_A + jX_A \quad (2)$$

where R_A and X_A represent the real and imaginary parts of the input impedance. The impedance matching between the antenna and RFID IC ensures maximum power transfer and reading efficiency within the UHF band (860-960 MHz).

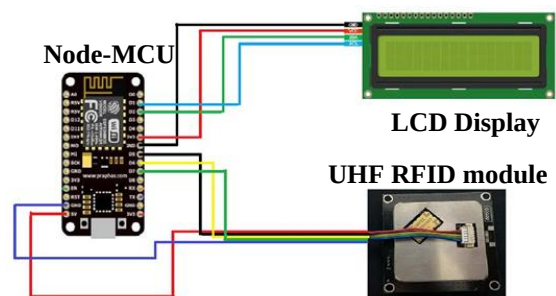


Figure 3 RFID reader diagram showing UHF module, Wi-Fi microcontroller, and LCD display.



Figure 4 Prototype of compact handheld RFID reader for border checkpoint operations.

3.1 Hardware Design

The system circuit, shown in Figure 3, consists of three main components:

1. UHF RFID Reader Module - responsible for generating the interrogation signal and reading the RFID tag’s unique identification code (UID) through electromagnetic coupling.
2. Wi-Fi Microcontroller Unit - serves as the main control processor, handling data communication between the RFID reader, LCD display, and cloud database via wireless protocol.
3. LCD Display Module - displays the system’s operational status and tag identification messages, such as “MODE: REGISTER - Present TAG...” during registration and scanning.



The prototype operates using a rechargeable 6,800 mAh lithium-ion battery pack, which provides sufficient power for continuous field operation throughout a typical working day. The device is designed in a handheld form factor suitable for single-hand use, as illustrated in Section 6, and can be further miniaturized in future development when transitioning to a commercial product. The material cost of the assembled prototype is approximately 4,000 THB, which is significantly lower than that of commercial UHF handheld readers (typically 20,000-50,000 THB), supporting cost-effective deployment.

3.2 Prototype Implementation

The assembled prototype is shown in Figure 4. The unit is enclosed in a durable, lightweight casing designed for handheld use by officers. The internal layout integrates the RFID module, Wi-Fi controller, and power unit efficiently within the limited enclosure space. The LCD interface allows real-time display of operational states, simplifying the verification process.

When the reader detects an RFID tag, it retrieves the UID, verifies it with the cloud database, and updates the authentication result immediately. The combination of hardware and software integration ensures real-time synchronization, reducing manual workload and improving operational speed.

Field evaluation confirmed that the prototype operated reliably under typical field conditions, demonstrating stable wireless connectivity, consistent tag detection, and efficient power management.

4. RFID Tag Sticker

The RFID tag sticker serves as the primary identification element in the proposed smart border passing system. It is designed for attachment to vehicles crossing border checkpoints and provides a unique, tamper-resistant, and weatherproof identifier linked to the owner's registration record in the database.

4.1 Tag Design and Material

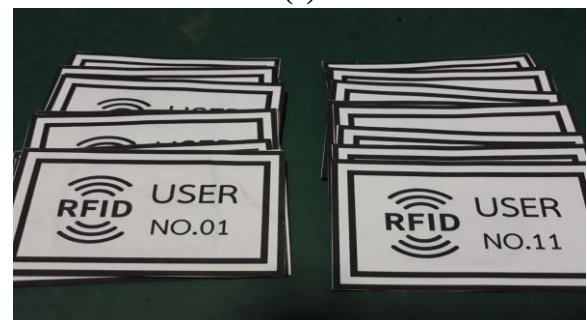
The RFID sticker tag used in this study is a passive UHF EPC-Gen2 (ISO-18000-6C) sticker incorporating a meandered aluminum dipole

antenna ($\approx 70 \times 15$ mm) printed on a PET roll-laminated substrate. The prototype utilized a commercially available tag due to cost and compatibility with the ESP32-UHF reader; however, a custom-designed antenna may be developed in future iterations to improve mounting performance on curved windshields. For large-scale deployment, roll-to-roll PET etching enables cost reduction from approximately 4 THB/unit in prototype quantities to 1.2-1.5 THB/unit when manufactured at $>100,000$ units. Tags may be adhered externally using automotive-grade adhesive or positioned at the inside corner of a windshield using removable low-tack adhesive, supporting quick disposal after vehicle return.

The tag's physical flexibility and small form factor enable installation on various locations such as windshields, doors, or rear panels. Once applied, any attempt to peel or remove the sticker will irreversibly damage its conductive layer, preventing reuse and thus ensuring anti-tampering integrity.



(a)



(b)

Figure 5 RFID tag sticker. (a) Internal structure (IC+antenna). (b) External view with adhesive backing.

4.2 Functional Characteristics

The RFID tag communicates passively with the handheld reader, meaning it does not require an internal power source. Instead, it is energized by

the electromagnetic field emitted from the reader's antenna. The tag's unique identifier (UID) is transmitted wirelessly to the reader, which verifies its authenticity through the cloud database.

The tag exhibits several advantageous characteristics for border checkpoint operations:

1. High durability: resistant to sunlight, dust, and moisture, ensuring long-term performance in outdoor environments.
2. Low cost: suitable for large-scale deployment across border checkpoints.
3. Reliable detection range: optimized for UHF operation, allowing consistent recognition within a few meters.
4. Reusability control: adhesive strength is calibrated to balance secure attachment and ease of replacement during re-registration.

The selection of UHF passive RFID technology provides an ideal balance between cost-effectiveness, reading distance, and operational stability, making it highly suitable for vehicular identification applications in smart border control environments.

5. Database Development

The database subsystem was developed to manage vehicle registration, verification, and return records associated with the RFID-based border passing process. The system employs MySQL as the primary database engine and phpMyAdmin as the web-based management interface. This configuration enables efficient creation, modification, and retrieval of records while supporting real-time communication with the handheld RFID reader through the cloud.

			id	uid	plate	owner	updated_at
☐				3	E1120209600015525670		2025-10-13 02:14:40
☐				4	E1120206510017355333		2025-10-13 02:14:40
☐				5	E1120206460018422086		2025-10-13 02:14:40
☐				6	E200A1B2C3D4E5F611223344		2025-10-13 02:14:40
☐				7	E2009F8E7D6C5B4A33CCBBAA		2025-10-13 02:14:40
☐				8	E20011223344AABCCDDDEE00		2025-10-13 02:14:40
☐				9	E200DEADBEEF001122334455		2025-10-13 02:14:40
☐				10	E200CAFEBABE010203040506		2025-10-13 02:14:40
☐				11	E2000A1B2C3D4E5F60718293		2025-10-13 02:14:40
☐				12	E20055AA55AA55AA55AA55AA		2025-10-13 02:14:40
☐				13	E200ABCDEF1234567890ABCD		2025-10-13 02:14:40
☐				14	E20013579BDF02468ACE1357		2025-10-13 02:14:40
☐				15	E200F0E1D2C3B4A596877869		2025-10-13 02:14:40
☐				16	E2000F1E2D3C4B5A69788776		2025-10-13 02:14:40
☐				17	E200AAAA5555FFFF00001111		2025-10-13 02:14:40
☐				18	E2001234ABCD5678EF901234		2025-10-13 02:14:40
☐				19	E200FACEFEEDC001D00D1234		2025-10-13 02:14:40
☐				20	E20076AB34CD12EF98BA5432		2025-10-13 02:14:40
☐				21	E20089ABCDEF0123456789AB		2025-10-13 02:14:40

Figure 6. Simulated vehicle user database implemented in MySQL (phpMyAdmin view).



5.1 Database Structure

The database was designed to store and manage essential vehicle and user information for identification and monitoring purposes. As illustrated in Figure 6, each record contains the following key fields:

- *id* - the sequential identifier of each record entry.
- *uid* - the unique RFID code read from the tag attached to a vehicle.
- *plate* - the vehicle's license plate number registered in the system.
- *owner* - the name of the vehicle's owner or driver.
- *updated_at* - the timestamp of the latest system update, automatically refreshed during authentication events.

All records are stored and synchronized in real time to the cloud database, allowing officers to perform registration and verification directly from the handheld RFID reader. The web-based dashboard additionally supports editing, deletion, and CSV/Excel export for administrative reporting. To support multi-location deployment, the database follows a centralized schema that enables simultaneous access from multiple border checkpoints, ensuring consistent information across the monitoring network.

The overall data handling workflow is summarized as follows: the reader transmits a detected *uid* to the server → the database queries the associated record → updates the status and timestamps → and synchronizes the result back to the dashboard. Example screenshots in this paper have been anonymized to prevent exposure of sensitive personal information such as license plates or driver names.

5.2 Operational Features

The system supports three operational functions, consist of registration, verification, and monitoring.

- During registration, officers input vehicle and owner details into the database while associating each record with a unique RFID tag.
- During verification, the reader scans the tag and queries the cloud database. If the UID matches an existing record, the system updates the

updated_at field and confirms successful authentication.

- For monitoring, the system automatically checks the duration of each vehicle's border pass. If the permitted period (e.g., 30 days) expires without a recorded return, the database generates an alert and exports a summary report in Excel format for administrative review.

This database design ensures data integrity, traceability, and easy scalability. It effectively supports the operation of the smart border passing system by providing real-time monitoring, automated record management, and reporting capability for cross-border vehicle control.

6. Experiment and Results

6.1 RFID Reading Accuracy

To evaluate the performance of the developed RFID reader, experiments were conducted to measure the tag detection accuracy at varying distances between the handheld reader and the RFID sticker tag. The purpose of this test was to determine the effective operational range of the device for real-world border checkpoint applications. The evaluation also aimed to verify the stability of wireless communication and the consistency of tag response under controlled environmental conditions.

The detection accuracy *A* of the RFID reader was evaluated using Equation (1) below

$$A = \frac{N_{\text{success}}}{N_{\text{total}}} \times 100\% \quad (3)$$

where N_{success} is the number of successful tag readings and N_{total} is the total number of read attempts at a given distance.

In addition, the standard deviation of the detection rate was calculated to evaluate reading stability across repeated trials, given in Equation (4)

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4)$$

where x_i represents the accuracy at each distance and $\bar{x}$ is the mean accuracy value.

The experimental setup is illustrated in Figure 7. The RFID reader was placed on a flat surface, and a metric tape was used to precisely position the

RFID tag at different distances ranging from 0.1 m to 3.0 m, in 0.3 m increments. Each distance was tested with 100 independent reads to obtain statistically robust detection rates. The results were recorded based on successful detections (SUCCESS) and failed readings (FAIL), and the overall accuracy percentage was calculated accordingly, as reported in Table 1.

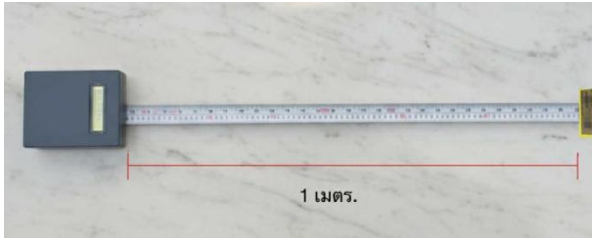


Figure 7 Distance measurement setup for RFID reading-range evaluation.

Table 1 RFID tag detection accuracy at different reading distances (100 reads per distance).

Distance (m)	Number of Tests	SUCCESS	FAIL	Accuracy (%)
0.1	100	100	0	100
0.3	100	100	0	100
0.6	100	100	0	100
0.9	100	100	0	100
1.2	100	100	0	100
1.5	100	100	0	100
1.8	100	100	0	100
2.0	100	92	8	92
2.5	100	66	34	66
3.0	100	0	100	0

The experimental results reveal that the RFID reader achieved 100% detection accuracy within the range of 0.1-1.8 meters. Beyond this distance, the detection rate gradually decreased to 92% at 2.0 meters and 66% at 2.5 meters, while no successful readings were obtained beyond 3.0 meters. The reduction in performance at longer distances is primarily attributed to signal attenuation and the limited gain of the compact antenna used in the handheld reader. Nevertheless, the observed effective range remains well-suited for field operations, ensuring reliable tag recognition without requiring close physical contact with the vehicle.

This indicates that the optimal operational range of the developed RFID reader is approximately 1.8 meters, which is adequate for field deployment at vehicle inspection checkpoints. Such a distance provides officers with sufficient working space and ensures reliable tag detection without requiring close contact with the vehicle. Furthermore, maintaining this range helps minimize signal interference between adjacent readers operating in multi-lane inspection areas. It enhances user safety and convenience by allowing smooth vehicle flow during scanning operations.

Overall, the experiment confirms that the proposed RFID reader delivers high accuracy, stable response, and suitable range for practical applications in smart border passing systems. The obtained results also validate the effectiveness of the hardware design and its readiness for real-world deployment.



Figure 8 Vehicle identification durability test - examples of tag placement on windshields.

6.2 Vehicle Identification Durability Test

A long-term field experiment was conducted to evaluate the durability and stability of RFID tag identification when installed on real vehicles. As illustrated in Figure 8, ten vehicles were equipped with RFID sticker tags, each installed at ten different points on their windshields. This experimental setup was chosen due to its practical feasibility-testing with a large number of vehicles (e.g., 100) would be logistically challenging for



both installation and continuous monitoring. The vehicles remained outdoors in standard roadside parking conditions and were naturally exposed to sunlight, heat (approximately 32-35 °C daytime

temperature), dust accumulation, and intermittent rainfall throughout the observation period. These real environmental conditions provide practical stress factors similar to those expected at border checkpoint deployments.

Table 2 Vehicle identification results per period (10 vehicles × 10 tags each).

Vehicle No.	Period (Day)								
	Day1	Day2	Day3	Day5	Day7	Day10	Day15	Day20	Day30
Vehicle No.1	10	10	10	10	10	10	10	10	10
Vehicle No.2	10	10	10	10	10	10	10	10	10
Vehicle No.3	10	10	10	10	10	10	10	9	9
Vehicle No.4	10	10	10	10	10	10	10	10	10
Vehicle No.5	10	10	10	10	10	10	10	10	10
Vehicle No.6	10	10	10	10	10	10	10	10	10
Vehicle No.7	10	10	10	10	10	9	9	9	9
Vehicle No.8	10	10	10	10	10	10	10	10	10
Vehicle No.9	10	10	10	10	10	9	9	9	9
Vehicle No.10	10	10	10	10	10	10	10	10	10
Total	100	100	100	100	100	98	98	97	97
% of success	100	100	100	100	100	98	98	97	97

The RFID reader was used to scan each vehicle's tag periodically on Day 1, 2, 3, 5, 7, 10, 15, 20, and 30 after installation to determine whether the tag could still be identified successfully. The summarized results are shown in Table 2.

6.3 Result Discussion

The experimental results show that during the first seven days, all RFID sticker tags were successfully detected with a 100% identification rate, confirming excellent initial adhesion and signal stability. After Day 10, a slight reduction in the success rate to 98-97% was observed toward the end of the 30-day test period.

Importantly, further inspection revealed that all unreadable cases were caused by sticker detachment, not by device malfunction. For the stickers that remained properly attached to the vehicle surfaces, the RFID reader maintained 100% reading accuracy throughout the entire period. This finding verifies the high reliability and consistent performance of the developed RFID reader hardware.

However, the experiment also highlights a practical consideration regarding adhesive selection for tag assembly. If the adhesive layer is too weak, the tag may detach under outdoor

conditions such as heat, rain, or car washing. Conversely, using an overly strong adhesive can make sticker removal difficult and may damage the vehicle surface when the tag is replaced or reissued. Therefore, selecting a balanced adhesive formulation-strong enough to resist environmental effects but still removable without residue-is critical for long-term deployment in smart border passing systems. As an alternative installation method, the tag may also be applied at an inside corner of the vehicle windshield, where a lighter, removable adhesive can be used without risking detachment. This allows users to peel off the sticker conveniently after authentication and database reset are completed.

Overall, these findings confirm that the proposed RFID reader and tag combination provides 100% functional reliability, while future optimization should focus on improving adhesive durability and environmental resistance for extended field use. In addition, further refinement of material composition and protective coating could enhance long-term tag performance under varying climatic and operational conditions.

6.4 Dashboard System Demonstration

A demonstration test was conducted to verify the functionality of the cloud-based dashboard used in the smart border passing system. As shown in Figure 9, the web interface displays real-time

vehicle transaction data within a 30-day observation period. Each record includes the RFID tag UID, vehicle plate number, owner name, and status log consisting of ENTRY, EXIT, and TIMEOUT events.

Home User Data Registration Read Tag ID Dashboard

Dashboard (30 วันล่าสุด)

UID: กรณ UID เพื่อกรอง		ช่วงเวลา: 30	Filter					
ID	UID	ทะเบียน	เจ้าของ	Status	Entry	Due	Exit	นาที
57	E1120206510017355333			ENTRY	2025-10-29 04:52:50	2025-10-29 05:07:50		
56	TEST12345			TIMEOUT	2025-10-20 01:21:21	2025-10-20 01:24:21	2025-10-20 01:27:11	5.00
55	E1120209600015525670			EXIT	2025-10-20 00:39:03	2025-10-20 00:49:03	2025-10-20 00:39:03	0.00
54	E1120209600015525670			EXIT	2025-10-19 19:29:20	2025-10-19 19:39:20	2025-10-19 19:29:20	0.00
53	E1120209600015525670			EXIT	2025-10-19 19:20:52	2025-10-19 21:20:52	2025-10-19 19:20:52	0.00
52					2025-10-19 19:04:48	2025-10-19 21:04:48		
51	E1120206460018422086			ENTRY	2025-10-19 23:29:23			
50	E20011223344AABCCDDE00			TIMEOUT	2025-10-19 23:21:52		2025-10-19 23:24:47	120.00
49	E1120206460018422086			TIMEOUT	2025-10-13 22:25:27		2025-10-14 02:33:30	248.05
48	E1120206510017355333			TIMEOUT	2025-10-13 22:25:21		2025-10-14 02:33:41	120.00
47	E1120209600015525670			TIMEOUT	2025-10-13 22:25:16		2025-10-14 02:33:50	248.57

Figure 9. Example of system testing via the web-based dashboard showing ENTRY, EXIT, and TIMEOUT events.

When a vehicle passes through the checkpoint, the system automatically records an ENTRY event. Upon return within the authorized period, an EXIT event is logged, updating the database and resetting the record status. Conversely, if a vehicle does not return before the specified due date, the system generates a TIMEOUT alert, which is displayed in red on the dashboard and prompts administrative review.

This feature is particularly valuable for monitoring cross-border traffic behavior, such as identifying potential unauthorized crossings or preventing vehicle theft across national boundaries. Furthermore, the dashboard allows officers to filter transactions by UID or date range and export detailed reports for further analysis.

7. Conclusion and Future Work

This research presented the RFID-driven smart border passing architecture, integrating hardware, software, and cloud-based data management to enhance the efficiency and security of vehicle inspection at border checkpoints. The developed framework demonstrates how IoT-enabled identification and centralized data sharing can streamline operations and reduce verification errors.

The system architecture was composed of three main components: a portable RFID reader, a UHF RFID tag sticker, and a cloud database with a web-based dashboard. The prototype reader demonstrated 100% tag detection accuracy within an operational range of up to 1.8 meters, providing



a suitable working distance for field officers. In addition, the long-term durability test confirmed that all RFID tags that remained properly attached maintained 100% identification success throughout 30 days, with failed readings attributed solely to sticker detachment rather than hardware malfunction.

The developed dashboard interface successfully displayed real-time vehicle entry, exit, and timeout events, serving as an effective administrative tool for tracking cross-border movements. This capability supports not only faster verification at checkpoints but also enhances monitoring and enforcement against unauthorized crossings or vehicle trafficking incidents.

Furthermore, the low-cost nature of the prototype-approximately 4,000 THB for the handheld reader and around 4 THB per sticker tag-indicates strong cost-effectiveness and practical scalability for regional or nationwide deployment, especially in resource-constrained border provinces.

Future development of the system will focus on several directions:

1. Improving tag adhesion materials-optimizing adhesive formulations to balance long-term durability and ease of removal.
2. Expanding communication reliability-integrating LTE or 5G connectivity to extend coverage beyond local Wi-Fi range.
3. Enhancing data analytics - implementing anomaly detection algorithms to automatically flag suspicious traffic behavior.
4. Integrating biometric or QR-based verification for dual authentication, improving the identity assurance of both driver and vehicle.

In conclusion, the proposed smart border passing system demonstrates a practical, cost-effective, and scalable solution for modern border management. With continued refinement and field testing, it has strong potential to be deployed across regional checkpoints as part of a national intelligent transportation and security infrastructure. The outcomes of this study also provide a foundation for future integration with advanced analytics and AI-driven decision support

to enhance operational efficiency and situational awareness.

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