RFID and Wireless IoT Technologies for Transportation Maintenance Operations and Asset Management

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ABSTRACT

This paper introduces an innovative transportation asset management approach that harnesses the capabilities of radio-frequency identification (RFID) technology. By utilizing RFID's remote sensing capabilities, real-time detection of transportation assets is achieved, leading to significant improvements in operational efficiency. There exist alternative technologies such as barcode, GPS, and NFC that are used in asset management. However, unlike barcodes, RFID can store data directly on the tag, enhancing information capacity. Moreover, RFID's indoor applicability distinguishes it from GPS; and its broader range sensing surpasses the limitations of NFC, making it a comprehensive and effective tool for asset management across various settings. The study investigates the system configuration, RFID devices, software program and database. In our experiments, vehicles, particularly trucks, are used as the objects to showcase the practicality and viability of the system configuration for asset management using RFID technology. To facilitate experiments, open-source Graphic User Interfaces (GUIs) programs are customized to meet the requirements of the proposed solution. Additionally, a sample Web GUI is developed to demonstrate the feasibility and practicality of integrating various RFID readers. Field tests are conducted to evaluate the system performance and reveal factors that should be carefully considered for actual deployment.

Keywords: Radio-frequency Identification (RFID), Transportation Assets Management System, Stationary RFID Reader, Handheld RFID Reader, Database, REST API

INTRODUCTION

As highlighted in the Executive Brief by the US DOT FHWA [1], effective transportation asset management is crucial for maximizing long-term sustainability, accountability, and performance while addressing public concerns about the health and safety of transportation assets. To achieve these goals, transportation agencies require a reliable framework that allows them to strategically manage diverse assets, including construction tools, equipment, and infrastructure, in an automatic, uniform, and efficient manner [2-3]. Data-driven decision-making is essential to balance various trade-offs between business needs and service operations.

A significant aspect of asset management involves accurately tracking and recording attributes for each individual asset item. While using barcodes to assign unique IDs to assets is a simple approach, it comes with critical drawbacks. Barcode scanning requires a direct line of sight and can be affected if the barcode is contaminated or covered. Additionally, close proximity to the barcode is necessary for scanning, making it labor-intensive and error-prone, especially when dealing with a large asset inventory. The limitations of barcode stickers in automatic and efficient transportation maintenance operations and asset management are exacerbated by the absence of data storage capabilities, which restricts their utility in providing comprehensive data about assets or maintenance needs. RFID, in contrast, allows for the storage of extensive information on a tag, enabling quick and accurate access to data crucial for transportation maintenance and asset management. The absence of data storage in barcode stickers hampers their ability to offer the detailed, real-time insights needed for optimal operational efficiency and management.

With advancements in wireless communication, computing, and semiconductor technologies, the Internet of Things (IoT) has emerged as a powerful method to design intelligent transportation systems [4-8]. In this project, we propose exploring radio-frequency identification (RFID) and other wireless IoT technologies to develop an automated solution for efficient transportation maintenance operations and asset management.

RFID, a wireless tracking technology, enables remote activation, reading, and writing of data between an RFID reader and an RFID tag attached to or embedded in an object. The technology consists of three main functional elements: an RFID reader, an RFID tag, and firmware. RFID readers send encoded electromagnetic signals to interrogate RFID tags, which respond by transmitting their ID information or other stored data. Compared to barcodes, RFID offers robustness, automation, and no line-of-sight requirement, making it suitable for various applications such as asset tracking, supply chain management, security, and access control.

While alternative technologies such as the Global Positioning System (GPS) and Near Field Communication (NFC) are available, RFID stands out for its ability to operate effectively in indoor environments. Unlike GPS, RFID is capable of functioning indoors, making it highly versatile. Additionally, when compared to NFC, RFID offers longer-range sensing capabilities.

In terms of software, while standard business software is increasingly integrating asset management support, there remains a critical gap in fulfilling essential criteria. Particularly, for effective asset management utilizing RFID technology, systems should excel in managing assets individually, facilitating precise location tracking, providing real-time updates on an asset's physical status or quality, allowing the definition of triggers based on specific asset conditions, and maintaining a comprehensive information history for each asset. RFID-enabled asset management systems hold the potential to address these criteria, offering a level of granularity, accuracy, and historical insight that enhances overall operational efficiency and decision-making processes within an organization.[13]

The advantages of RFID technology make it a key enabler for developing automated transportation maintenance operations and asset management systems. A previous study proposes RFID technology for traffic signage inventory management in transportation assets [9-11]. RFID tags are attached to signs, and a mounted reader on a survey vehicle performs tag interrogation while driving. A handheld reader scans at close range, while a remote database manages data, allowing real-time communication. The system is adaptable to rural and urban environments, with an adaptive mechanical structure for obstacle-prone areas. It includes a local database for addressing connectivity issues and easy cloud access.

In this project, we broaden the scope of RFID technology to enhance general transportation asset maintenance and management. By utilizing vehicles as sample objects, we showcase the technology's efficiency and accuracy in transportation asset monitoring and maintenance. Different types of RFID readers, including stationary readers and handheld readers, are utilized to perform remote or short-distance scans under diverse environmental settings and application scenarios. This system can accurately track the locations of assets and monitor their presence or movement within or from the garage or facility. It enables real-time access and editing of asset attribute data, which can significantly improve the efficiency of transportation projects' planning, design, fabrication, construction, operation, maintenance, and decision-making processes.

METHODS

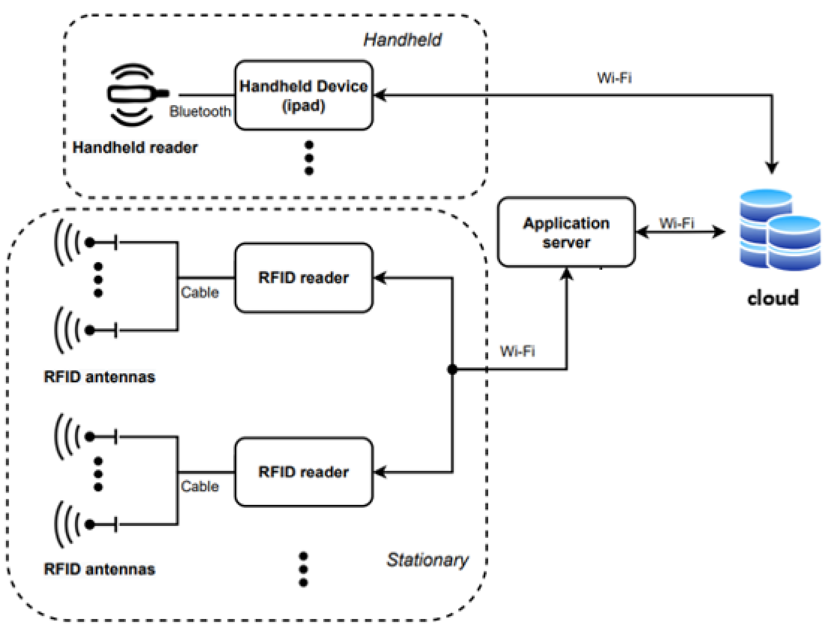
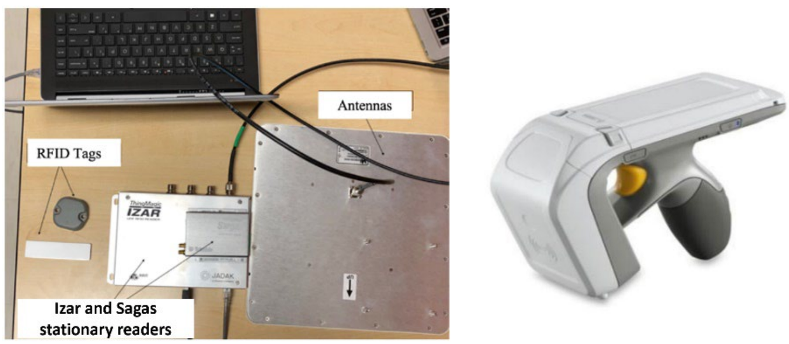


Figure 1. The system diagram of RFID-based asset management system

- *System configuration*

As Figure 1 shows, the system consists of RFID readers, RFID tags, an application server with a graphical user interface (GUI), and the asset database. To achieve application flexibility, two types of RFID readers will be used which include portable handheld readers and high-performance stationary readers. The handheld reader connects to a mobile IOS device (e.g., an iPad or an iPhone), which processes the data, displays the retrieved information from the VTrans database, and accesses the database for editing. The stationary RFID readers will be mounted at the desired positions and equipped with multiple antennas to expand scan direction and coverage. The application server remotely controls all readers and processes the received data, and it also accesses a local database that is synchronized with the VTrans database.

In practical use, stationary readers and handheld readers can scan RFID tags and retrieve asset information in real-time. When a tag is detected, its tag ID will be displayed on a reader screen. Then, the reader operator can retrieve information from the database and make modifications if necessary. In addition, the reader will measure the received signal strength (RSSI) which indicates the reading performance, allowing the operator to fine-tune system operation when needed.



(A) (B)

Figure 2. RFID devices: (A) stationary readers, antenna, RFID tags. (B) handheld RFID

- *RFID tags*

In our system, passive RFID tags are selected to use.. Passive RFID tags are powered by the electromagnetic energy emitted by an RFID reader, eliminating the need for an internal battery. This characteristic makes passive tags a cost-effective choice for large-scale deployment due to their lower manufacturing cost. Additionally, the absence of a battery means that passive tags require minimal maintenance, making them easier to deploy and manage over time. On the other hand, active and semi-active RFID tags are equipped with a battery, allowing them to continuously broadcast signals over longer distances compared to passive tags. However, this comes with the drawback of higher cost and the need for battery recharging or replacement. As a result, active and semi-active tags are more suitable for monitoring or tracking applications where battery maintenance is feasible. For our inventory management system, which requires mass deployment of RFID tags and cost-effective maintenance, passive tags are the preferred choice.

In our system, we have specifically selected the Omni-ID Flex 1200 and Omni-ID Exo 750 (Figure 2A) as the passive RFID tags. Both types of tags operate within the same frequency band of 865-956 MHz. The Omni-ID Exo 750 is encased in a hard-plastic package, providing added durability compared to the Omni-ID Flex 1200. This selection allows us to ensure the reliability and longevity of the RFID tags in our transportation asset management system.

- *Stationary Readers*

Two stationary RFID readers tested are Sargas and Izar readers (**Figure 2A**). The antennas used are SecureControl Invengo antenna and MTI antenna. Both readers are compliant with EPC Gen2 standard, and their operating frequencies are within FCC authorized 902-928 MHz range. Both are integrated with a Debian Linux OS making the remote control possible. The difference is that Izar has 4 antenna ports with RF-BNC type connection, while Sargas only has 2 antenna ports with RF-SMA type connection, which means the former can support 4-channel scan while the latter supports 2-channel scan.

- *Handheld Readers*

The handheld reader is integrated into the system allowing for on-site individual tag interrogation to display or modify the relevant tag information **(Figure 2B**). A mobile RFID reader software program has been developed to operate the handheld reader. The program is customized to support filtering, reading, displaying, and saving RFID tag data in the same manner as the stationary reader GUI program. Database connection and data synchronization are also developed.

In deployment, the handheld reader connects to an iOS device via Bluetooth. Upon activation, the reader performs a close-range scan of the RFID tag, checks the tag ID, retrieves the pertinent tag data and attributes of the asset item from the database. This information is then displayed on the screen of the iOS device. The reader allows for the editing of tag data, which can be written back to the database server. Any modifications made to asset attributes are instantly updated both locally on the reader and remotely in the database on the server. This seamless interaction ensures real-time synchronization of asset information between the handheld reader and the central database.

- *Low Cost MFRC 522 RFID Reader for Arduino/ESP 32*

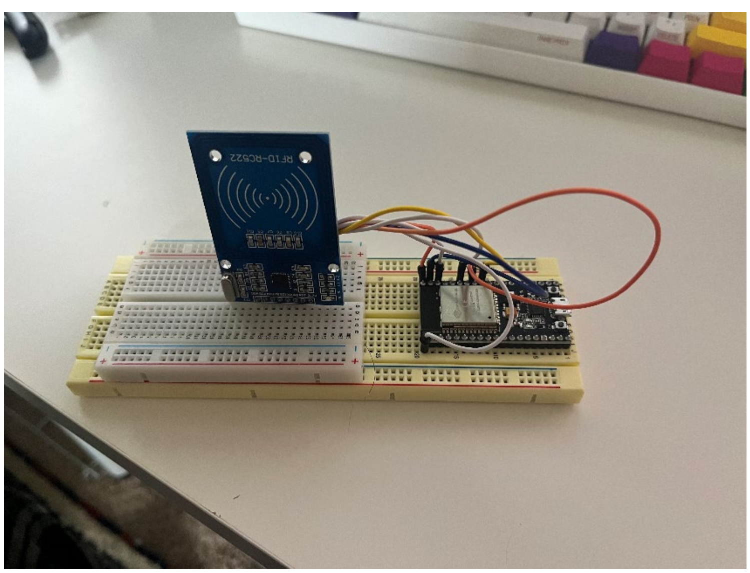
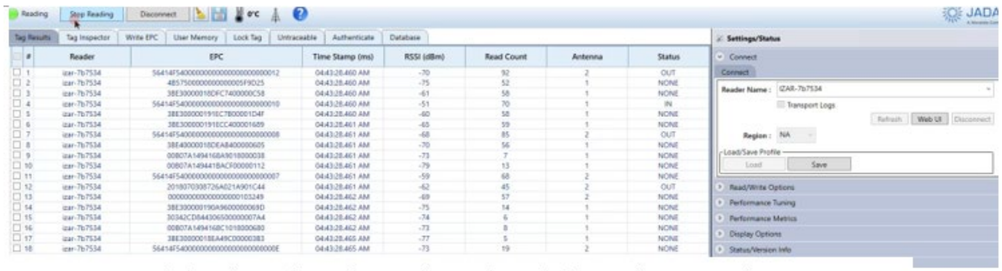


Figure 3. MFRC 522 RFID Reader for Arduino/ESP 32

In light of concerns about the cost of RFID readers in the assets management system, we address this challenge by conducting a test using the MFRC 522 RFID Reader for Arduino or ESP 32, shown in Figure 3. Although the MFRC 522 RFID Reader has inferior specifications compared to stationary and handheld readers and operates at a different radio frequency, the test successfully showcases the potential for developing RFID readers independently, without being limited by existing market constraints. Despite its lower cost, the MFRC 522 RFID Reader demonstrated seamless connectivity with the database.

This test highlights the possibility of reducing the overall cost of the RFID asset management system by exploring alternative RFID reader options without compromising its functionality and performance. Thus, we can develop a hybrid system that integrates different RFID devices and specifications holding the potential to strike a balance between cost and performance for managing various types of asset items. By strategically integrating diverse RFID devices and specifications into the asset management system, we can achieve a versatile and adaptable solution that meets the unique demands of different assets while optimizing costs and ensuring effective performance. This flexibility can be a significant advantage in transportation asset management, where assets may vary widely in size, location, and operational requirements.

- *Graphic User Interface (GUI)*



(A) Universal Reader Assistant (URA) for stationary readers

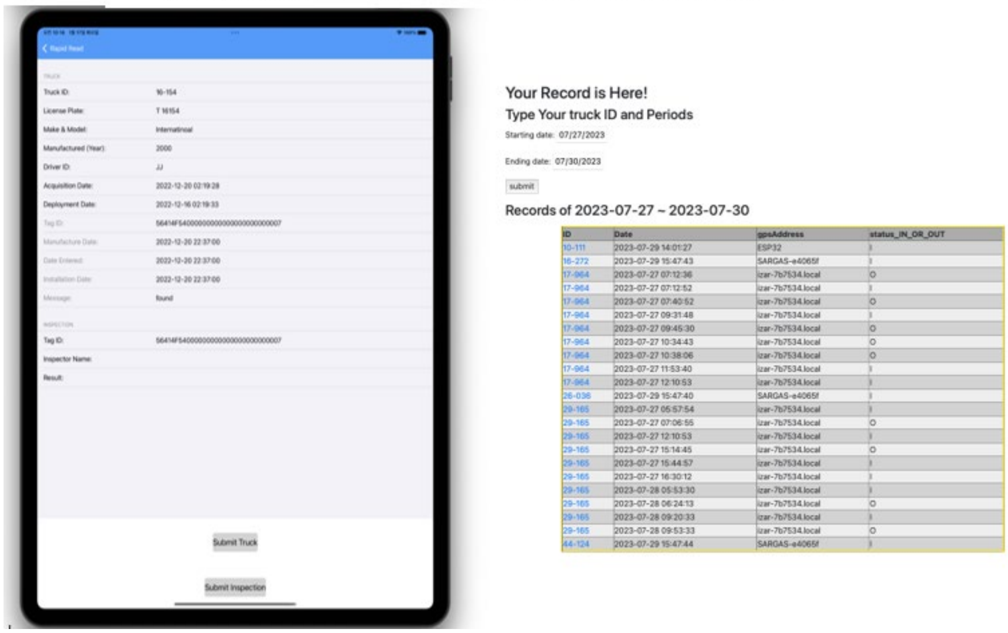


Figure 4. Graphic User Interfaces (GUIs) for RFID asset management

- *Universal Reader Assistant (URA)*

The reader software is developed based on the open-source program of Universal Reader Assistant (URA) provided by the manufacturer Thing Magic/Jadak (**Figure 4A**). The URA is an open-source tag-reading application tool written in C# with the .Net framework. Using the open source codes, we develop customized programs to implement our own user interface functionalities, including (i) reading and displaying tag data (e.g., Electronic Product Code (EPC) (i.e., tag ID), timestamp, source antenna, and received signal strength indication (RSSI)) on screen, (ii) writing custom EPC IDs to tags, (iii) retrieving data from the database and empowering the ability to modify assets's data, and (iv) accepting multiple readers.

- *Zebra Mobile Application*

GUI for handheld readers is also programmed using the open-source code of ZebraRFID app (**Figure 4B**). We customize the source code design to enable database interaction, such as (i) retrieving tag data and information from the database, and (ii) updating tag information and synchronizing it with the database.

- *Database Connectivity and Synchronization*

Both stationary readers and handheld RFID readers can save data locally or on a remote database server. The database design schema is shown in **Figure 5**. In the current database design, each

RFID tag is associated with exactly one traffic asset, such as a truck. One of the key considerations in our system is to ensure uninterrupted operation even in the event of a temporary loss of internet connectivity. To address this concern, the tag data is stored locally on the reader, allowing the system to continue functioning even without internet access. Once the internet connection is re-established, the locally saved data is synchronized with the remote database, ensuring seamless data transfer and continuity of operations. To facilitate communication between the application and the remote database server, we have established REST API calls using the HTTP protocol. This enables the various functionalities of the application to connect and interact with the remote database as needed, ensuring efficient and reliable data management.

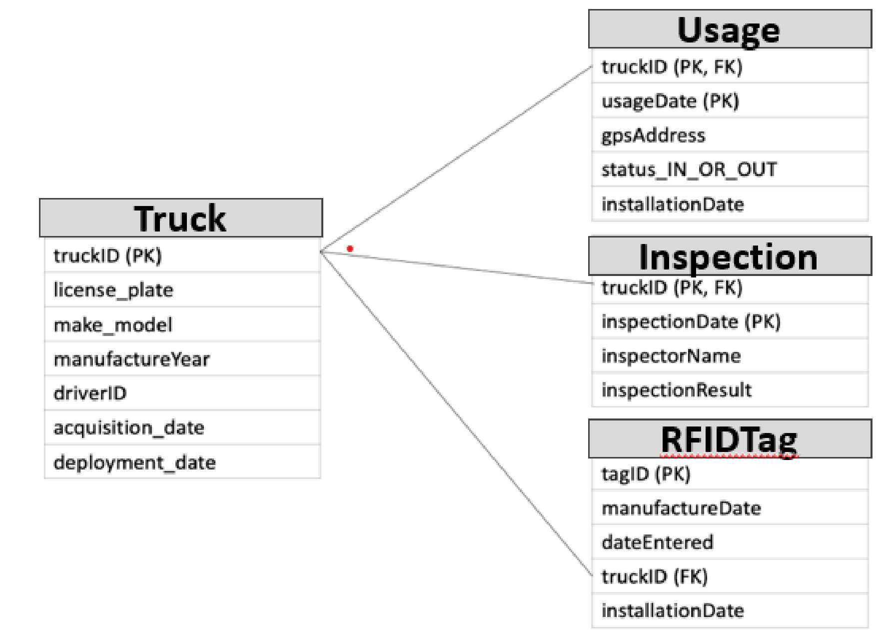


Figure 5. RFID asset management database scheme

The asset management database is designed using MySQL. For demonstration purpose, Figure 5 illustrates four tables created for specifically for managing trucks. These tables include: Truck, Usage, Inspection, and RFIDtag. The Truck table contains crucial information about the trucks such as the license plate number, model, and driver details. Whenever an RFID reader detects a tag mounted on the truck, the relevant information is automatically recorded and saved in the UsageLog table. For stationary readers mounted at the garage entrance, the 'status_IN_OR_OUT' field is used to keep track of the truck’s movement status, indicating whether it is entering or leaving the garage. The Inspection table is responsible for storing the inspection history of the trucks. Its attributes can be updated using either handheld readers or stationary readers. Lastly, the RFIDtag table serves as a repository for storing the unique tag Electronic Product Code (EPC) assigned to each tag mounted on the asset item. This table ensures the accurate association of RFID tags with their respective asset items in the system.

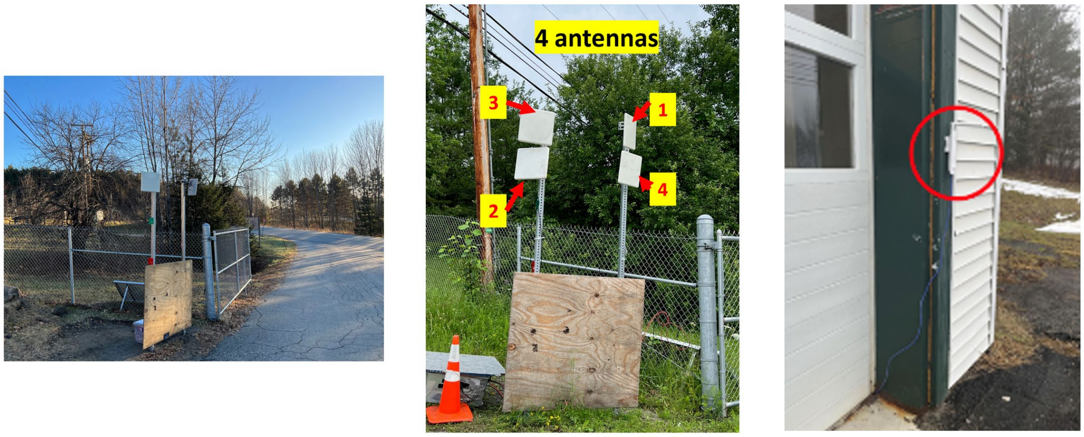
To facilitate secure and efficient database interaction, we have implemented a REST API protocol. This protocol enables seamless communication between the database and other software applications. The REST API ensures that data transfer between the database and the system is both efficient and secure. By using the REST API, authorized software applications can easily access and manipulate data stored in the database. This allows for real-time updates and retrieval of information, enhancing the overall performance of the asset management system. Moreover, the REST API's security features ensure that only authenticated and authorized users can access sensitive data, safeguarding the confidentiality and integrity of the information. Additionally, the REST API's speed and efficiency enable rapid data transfer and processing, optimizing the system's performance and responsiveness.

RESULTS

For performance evaluation and validation, we have set up the RFID system (**Figure 6A**) in the Randolph Garage, which is owned by the Vermont Agency of Transportation and located in Randolph, Vermont. This real-world test environment provides us with the opportunity to assess the system's capabilities in a practical and operational setting.

In the experimental setup, a stationary RFID reader is installed at the entrance of the garage to monitor the status of trucks – entering or departing the garage. In each truck, an RFID is attached to the windshield. To ensure efficient detection of the trucks moving at different speeds and in different directions, a 4-channel IZAR RFID reader is employed and configured with high emission power (**Figure 6B**). The reader's antennas are strategically positioned. Antennas 1 and 4 are oriented outward, facing outside the gate, while Antennas 2 and 3 are directed towards inside of the garage. In this configuration, when Antenna 1 or 4 detects RFID tags before Antenna 2 or 3, it indicates the truck is entering the garage, denoted as "IN" or “I”. Conversely, if Antenna 2 or 3 detects RFID tags before Antenna 1 or 4, it indicates that the truck is exiting the garage, referred to as "OUT" or “O”. This systematic arrangement enables assets tracking based on the sequence of RFID tag detections by the respective antennas.

Additionally, for the RFID readers to synchronize information with the central database, they need to be connected to the internet. This connection can be established either through Wi-Fi or an Ethernet cable. During the testing, a Wi-Fi extender is installed (**Figure 6C**) to ensure reliable internet connectivity for the readers, thereby facilitating seamless data transmission to the database.



A B C

Figure 6. RFID system set up at the entrance of Randolph garage
A. Garage entrance B. RFID reader with 4 antennas C. a Wi-Fi extender

Experimental Results

The system configuration, depicted in Figure 1, is successfully deployed in the field tests. This configuration featured the modified Universal Reader Assistant (URA) operating under the purview of the application server, which managed the incoming assets' information, regardless of internet connectivity. When the application server is online, it promptly transmits the antenna number that detects the RFID tag. In cases where internet connectivity is unavailable, the data is securely stored in the local database and transmitted later when the internet connection is restored. For enhanced RFID tag detection, the stationary Izar reader is employed with four antennas. These antennas operate asynchronously to detect RFID tags, and the gathered data is then forwarded to the application server for further processing.

29-165	2023-07-26 05:53:39	izar-7b7534.local	O
29-165	2023-07-26 06:52:02	izar-7b7534.local	O
29-165	2023-07-26 10:40:34	izar-7b7534.local	I
29-165	2023-07-26 12:04:31	izar-7b7534.local	O
29-165	2023-07-26 12:38:26	izar-7b7534.local	I
29-165	2023-07-26 16:32:33	izar-7b7534.local	O
29-165	2023-07-27 05:57:54	izar-7b7534.local	I
29-165	2023-07-27 07:06:55	izar-7b7534.local	O
29-165	2023-07-27 12:10:53	izar-7b7534.local	I
29-165	2023-07-27 15:14:45	izar-7b7534.local	O
29-165	2023-07-27 15:44:57	izar-7b7534.local	I
29-165	2023-07-27 16:30:12	izar-7b7534.local	I

Figure 7. A 2-day record of Truck 29-165 (dates: 07/26/2023-07/27/2023)

The results depicted in Figure 7 illustrate the dynamic status changes captured by the reader in two days test (07/26/2023-07/27/2023). Within the GUI interface, one can easily view the truck ID, corresponding timestamps, reader's name, and the status denoted by 'O' for 'Out' and 'I' for 'In'.

Truck 29-165 Information

License Plate	Make Model	Manufacture Year	Driver ID	Acquisition Date	Deployment Date
[redacted]	GMC 2500 HD	2019	[redacted]	2019-02-04 00:00:00	2019-04-01 00:00:00

Figure 8. Truck 29-165's information

The data in Figure 7 highlights the notable activity of trucks 29-165, which stands as the most frequently tracked asset on the site. Clicking on the first column (29-165 in Figure 7) will lead to the page that shows the truck information as shown in Figure 8. Additionally, the final column in Figure 7 shows the repeated alternation between 'I' and 'O', clearly indicating the truck's consistent pattern of arrival and departure. Based on a two-day record, the system successfully identified the time of truck's arrival at the garage (indicated by a red square) and departure from the garage (indicated by a blue square) (Figure 8).

Nevertheless, it is worth noting that the system occasionally exhibits outliers, as shown by the two rows marked with a yellow star on the right side of Figure 7. These outliers could be attributed to various factors. For instance, in the case of the row with the first star, if multiple assets or trucks approach the reader in close-proximity, interference within that range might occur, leading to certain vehicles not being detected by the reader. Such occasional incidents can be expected in complex scenarios with dense asset movement, and they underscore the need to consider potential interference issues when analyzing the data obtained from the system. We will do further investigations into this issue.

Handheld RFID reader

truckID	inspectionDate	inspectorName	inspectionResult
16-154	2023-07-29 17:54:17	Jay Hwasung Jung	RFID asset management handheld reader testing

Figure 9. Inspection example

As previously mentioned, the Handheld RFID reader fulfills essential functions, such as conducting inspections or adding new assets to the database. For demonstrative purposes, inspections were performed on one of the RFID tags, and the corresponding results are shown in Figure 9, presented as a database table named *Inspection*.

To account for potential internet connectivity issues in the field, a practical functionality is integrated which allows the GUI to store the assets' information in the local database and allows the asset manager to modify or input inspection information even without an internet connection (Figure 10). Subsequently, the "Sync" option facilitates seamless synchronization with the central database once an internet connection is re-established.

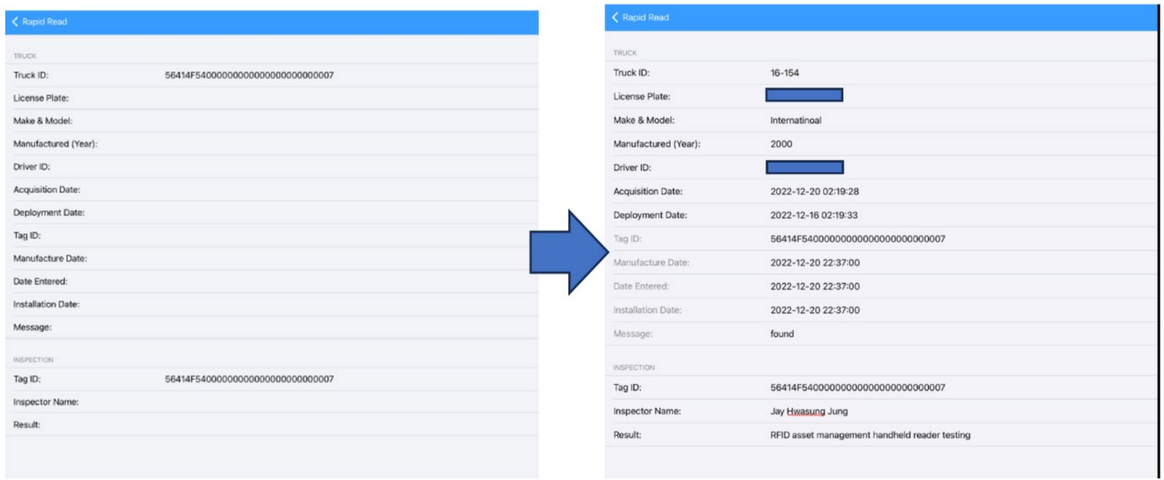


Figure 10. Results of sync the database on local device and the remote database server

MFRC 522 RFID reader

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Connected to WiFi network with IP Address: 10.0.0.3
Read personal data on a MIFARE PICC:
**Card Detected:**
Card UID: 8A 4A 8A 80
Card SAK: 08
PICC type: MIFARE 1KB
8A4A8A808a4a8a80
Name: □□□□□□□□□□□□□□□□ □□□□□□□□□□□□□□□□
**End Reading**
```

Figure 11. MFRC 522 RFID reader result

num	truckID	usageDate ▼ 1	gpsAddress	status_IN_OR_OUT
11345	10-111	2023-07-29 14:01:27	ESP32	1

Figure 12. Records of tag detection in Usage by MFRC 522

The practicality of the proposed systems using different RFID readers, along with the viability of a low-cost RFID reader, is examined through testing with the MFRC 522 RFID reader. Figure 11 depicts the process of the second proposed configuration (Figure 1B). Initially, the ESP 32 establishes a connection with the MFRC 522 RFID reader, which is then connected to the internet. Subsequently, an RFID tag with a unique identifier (UID) of "8A4A8A80" is successfully detected. Leveraging the REST API developed for this purpose, the detected information is seamlessly stored in the database, as shown in Figure 12. This experimentation validates the adaptability of the proposed systems across different RFID readers and reinforces the potential for being independent of constraints, such as cost.

DISCUSSION

The system configuration proposed in this paper have a fundamental difference from the previously suggested configurations [10]. Unlike the earlier ones, our configuration allows for the deployment of multiple readers that can be managed within a single graphic user interface (GUI). This capability of controlling multiple readers is crucial because it enables us to expand the system to a state-wide level, efficiently managing assets across thousands of facilities. This scalability makes our proposed configurations highly advantageous for large-scale asset management applications.

The results of the proposed RFID asset management system offer valuable insights into its viability, and reveal several factors that need to be considered for actual deployment: a) Internet connectivity. The RFID readers need to establish connections with remote database server. It is important to ensure the availability of internet connectivity where the RFID readers will be deployed. This may involve setting up Wi-Fi network or utilizing other communication services, such as cellular networks. b) Power Supply. The RFID system requires a constant and uninterrupted power supply to maintain its operations. In the test scenario, the RFID reader was mounted next to the outdoor garage gate, which was far from an indoor power supply. As a temporary solution, we used two rechargeable batteries that needed frequent swapping for recharging. For long-term deployment, a more sustainable solution is to connect the system to the power grid or utilize large solar panels to provide a reliable and continuous power source.

CONCLUSIONS

In conclusion, this research demonstrated how RFID and wireless IoT technologies can be used for efficient transportation asset management. Unlike traditional barcodes, RFID offers automation and no need for direct visibility, making it a robust option for asset tracking. The experiments are conducted for design validation. However, challenges like limited internet access in rural areas and power supply need to be considered for practical implementation. Despite the challenges encountered during the validation process, the proposed RFID asset management system demonstrated its viability in real-time asset tracking and management, offering valuable insights for transportation projects to make informed decisions. Future work in this area can concentrate on further enhancing accuracy through the implementation of advanced methods such as Machine Learning. Additionally, efforts can be made to increase the system's resilience in challenging environmental conditions.

By leveraging the potential of emerging technologies like RFID and IoT, this research paves the way for significant improvements in transportation asset management practices. The integration of RFID technology into transportation operations has the potential to enhance overall sustainability and performance.. This research serves as a foundational stepping-stone towards the adoption of innovative solutions for asset management in the transportation sector.

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AUTHOR CONTRIBUTIONS

Tian Xia and Byung Lee lead the project as primary investigators making substantial contributions to conception and design of the research. Jay Hwasung Jung and Wenzhe Chen are student research assistants developing system hardware and software programs and conducting laboratory and field tests.

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