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

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16. Abstract
This final report summarizes the results of the novel strategy for managing transportation resources, making use of radio-frequency identification (RFID) technology. Through the utilization of RFID's capacity for remote detecting, the system achieves real-time identification of transportation assets, resulting in substantial enhancements in operational effectiveness. The research delves into the arrangement of the system, the RFID devices, the software application, and the database. To facilitate experimentation, open-source Graphical User Interface (GUI) programs are adapted to align with the needs of the proposed solution. Moreover, an illustrative Web GUI is crafted to showcase the viability and feasibility of integrating different RFID readers. Practical tests are carried out to appraise the system's performance and to unveil factors that need thorough consideration for actual implementation.

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Introduction

As emphasized in the US DOT FHWA's Executive Brief [1], effective management of transportation assets is essential for ensuring long-term sustainability, accountability, and performance. This is particularly crucial in addressing public concerns regarding the well-being and safety of these assets. To accomplish these objectives, transportation agencies need a dependable framework that can help them strategically oversee a range of assets, including infrastructure, equipment, and construction tools, in a consistent, automated, and efficient manner [2-3]. Making decisions based on data is vital to striking the right balance between business requirements and service operations.

A significant element of asset management involves accurately documenting attributes for each individual asset. While using barcodes to assign unique identifiers to assets is a straightforward method, it comes with significant limitations. Barcode scanning requires a direct line of sight and can be hindered if the barcode is obscured or contaminated. Moreover, close proximity to the barcode is necessary for successful scanning, which can be labor-intensive and error-prone, especially when dealing with a large number of assets. The lack of data storage on barcode labels further restricts their usefulness for efficient and automated transportation asset maintenance and management.

With the progress in wireless communication, computing, and semiconductor technologies, the Internet of Things (IoT) has emerged as a potent approach for creating intelligent transportation systems [4-8]. In this project, we propose investigating the application of radio-frequency identification (RFID) and other wireless IoT technologies to create an automated solution for efficient transportation asset maintenance and management.

RFID, a wireless tracking technology, enables remote activation, reading, and writing of data between an RFID reader and an RFID tag affixed to or embedded within an object. The technology comprises three main components: an RFID reader, an RFID tag, and firmware. RFID readers send encoded electromagnetic signals to communicate with RFID tags, which respond by transmitting their ID information or other stored data. Compared to barcodes, RFID offers durability, automation, and the absence of a line-of-sight requirement, making it suitable for various applications like asset tracking, supply chain management, security, and access control.

The advantages of RFID technology position it as a critical facilitator for the development of automated transportation maintenance operations and asset management systems. An earlier study suggests the use of RFID technology for managing traffic signs in transportation assets [9-11]. RFID tags are attached to signs, and a reader mounted on a survey vehicle queries these tags while the vehicle is in motion. A handheld reader scans from a close range, while a remote database manages the data, allowing real-time communication. The system adapts well to both rural and urban settings, featuring a flexible mechanical structure for areas with obstacles. It includes a local database to address connectivity issues and allows easy access to cloud services.

In this project, we extend the application of RFID technology to encompass broader transportation asset maintenance and management. RFID tags are affixed to various assets such as vehicles, tools, and other items, and different types of RFID readers—including stationary and handheld readers—are employed to conduct remote or short-distance scans across different environmental conditions and application scenarios. This system accurately traces asset locations and monitors their presence or movement within or outside the garage or facility. It enables real-time access and modification of asset attribute data, significantly enhancing the efficiency of transportation project planning, design, construction, operation, maintenance, and decision-making processes.

This report summarizes all the project development reports, organizing our findings from each quarterly report and providing an integrated final overview of the team's latest discoveries and efforts. It's not presented in chronological order but offers a structured synthesis of the information.

Objectives

This project fulfills the following research objectives:

1. To study the specific features and needs of transportation maintenance operations and asset management, which include asset types, asset attributes, asset locations (e.g., indoor or outdoor), asset storage methods, maintenance operations and asset management requirements (e.g., validation, tracking, safety), management cost constraints, environmental settings, etc.
2. To investigate how RFID and IoT can be used for transportation maintenance operations and asset management and what are the technical challenges for actual deployment and the corresponding solutions.
3. Develop the integrated system and create a test site for technology demonstrations and benchmark, which will be used to assess the feasibility of expanding the technology application to the entire State.

Project Deliverables

Deliverable 1: Transportation maintenance operations and asset management survey report.

Deliverable 2: Comprehensive RFID system specification study report.

Deliverable 3: Laboratory study of RFID readers and antennas and a performance report.

Deliverable 4: Laboratory study of passive, active, and semi-active RFID tags, and a performance report.

Deliverable 5: RFID control program and user-friendly GUI.

Deliverable 6: RFID database.

Deliverable 7: Mechanical structures will be designed for mounting RFID readers and RFID tags on different objects.

Deliverable 8: Integrated RFID system and report.

Deliverable 9: Create a test site on VTrans campus and submit a field test report.

Deliverable 10: Report on the feasibility of employing RFID technology for statewide transportation maintenance operations and asset management.

Deliverable 11: Technology transfer documents.

Deliverable 1: Transportation maintenance operations and asset management survey report.

On November 08, 2021, the VTrans and UVM RFID research team held a Kick-Off Meeting to discuss and review the project scope, objectives, and deliverables in detail. During the meeting, pertinent security issues were also mentioned and addressed. As followed by the meeting, the UVM research team provided a suggested solution for the security issues, which was discussed and agreed upon by the team. Details are in below:

- **Attributes of the transportation assets**

Following the meeting, the UVM team conducted a survey to gather necessary information for the RFID research project. The team reached out to VTrans asset management, IT support team, and other parties involved in the research. Through the survey, the UVM team obtained valuable information about the details and attributes of transportation assets: (1) Portable dynamic message signs, (2) Guardrail ends (in the field), (3) Guardrail inventory/panels (at garage sites) and (4) Trucks.

Table 1. Attributes of portable dynamic message signs

1. Asset Item ID
2. Asset Item Name
3. Corresponding RFID Tag ID
4. Manufacturing or Purchasing Date
5. Vendor
6. Purchasing Price
7. Installation Date
8. Maintenance/Inspection Record
8.1 Inspection Date
8.2 Inspection Result
8.3 Inspector's Name
9. Current Position (storage address and /or GPS coordinates)
10. Current User
11. Comments

Table 2. Attributes of Guardrails (both ends and inventory/panels)

1. Guardrail ID (GID)
2. District
3. Town
4. Route
5. Side
6. BeginFlare
7. BeginTreatment
8. BTCCondition
9. BTPostType
10. BTOffsetBlock
11. RailType
12. RunCondition
13. RunPostType
14. ETOffsetBlock
15. EndFlare
16. Guardrail Height
17. CurbBoard
18. Comment
19. Begin MM
20. End MM
21. Length_ft
22. Last Edit Date

Table 3. Attributes of Trucks

Truck #
License Plate #
Make/Model
Manufacture Year
Driver ID
Acquisition Date
Deployment Date
Inspection History (date/outcome)

For the database access, several recommendations were made regarding the management and access of data in the VTrans database for this project from the survey. Firstly, it was suggested that an integrated database schema be created to cover all the different asset types and data access scenarios supported by the project. Secondly, two options were identified for populating the database tables: SQL queries such as select and insert or bulk updates. Next, to avoid any unintended effects on the VTrans production database, it was suggested that the project data tables be kept separate from the production data tables as much as possible. These two tables can be linked using foreign keys.

- **Security**

For transportation asset management and maintenance operations, system security is of paramount importance. To prevent unauthorized parties from accessing and modifying sensitive data or make other security breaches, in this project we will take the following measures:

1) Select appropriate RFID products

We select RFID products that are compliant with the EPCglobal Hardware Certification program. This is a standard-based compliance and interoperability testing program, developed by the EPCglobal community to provide a neutral and authoritative source for testing hardware products and providing information about certified products and their vendors [12]. Specifically, we will select EPC GEN2-compliant RFID tags and readers. Compared with GEN 1 devices that contain no security features, GEN2 devices have an integrated security mechanism to protect on-chip memory and data from tampering.

2) Secure EPC GEN 2 RFID tags

EPC GEN 2 tags contain two security measures for protecting on-chip data memory.

i. *TID Number:* Each GEN 2 standard RFID tag has a serialized Transponder ID (TID) number for authentication. TID number is locked after being written at the factory and cannot be tampered with.

ii. *GEN2 Tag Passwords:* GEN 2 tag has two password functionalities: access password and kill password. Both passwords are saved in the reserved memory block. See Fig. 1 below.

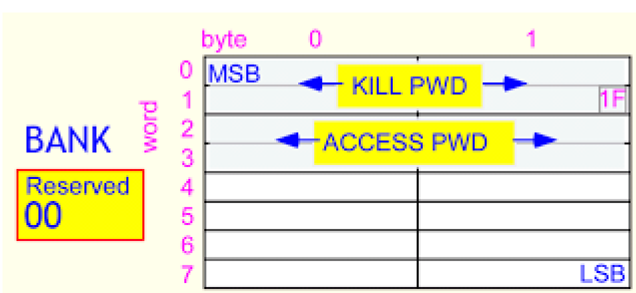


Fig 1: GEN2 tag passwords

<u>Access password.</u> The access code on UHF Gen 2 tags must be written in order to be used. Once written, the access code is stored in the reserved memory bank and is locked along with the kill code and prevents anyone from changing the 'lock'

state without first sending the 32-bit code. To unlock the access code, the user needs to use an RFID reader to send the 32-bit access password first. Once verified, then the access password can be unlocked or changed.

Kill password. The kill code is used to disable the RFID tag. A typical application is for tags at retail stores. When an item is purchased, the cashier can use an RFID reader to send the kill code, which then permanently disables the tag. Using this function, the retailer can validate whether an item has been purchased or not. In transportation asset management, the kill code function can be used to disable a tag under special scenarios --- for instance, when an asset item and/or the tag are not needed in the inventory management.

Deliverable 2: Comprehensive RFID system specification study report.

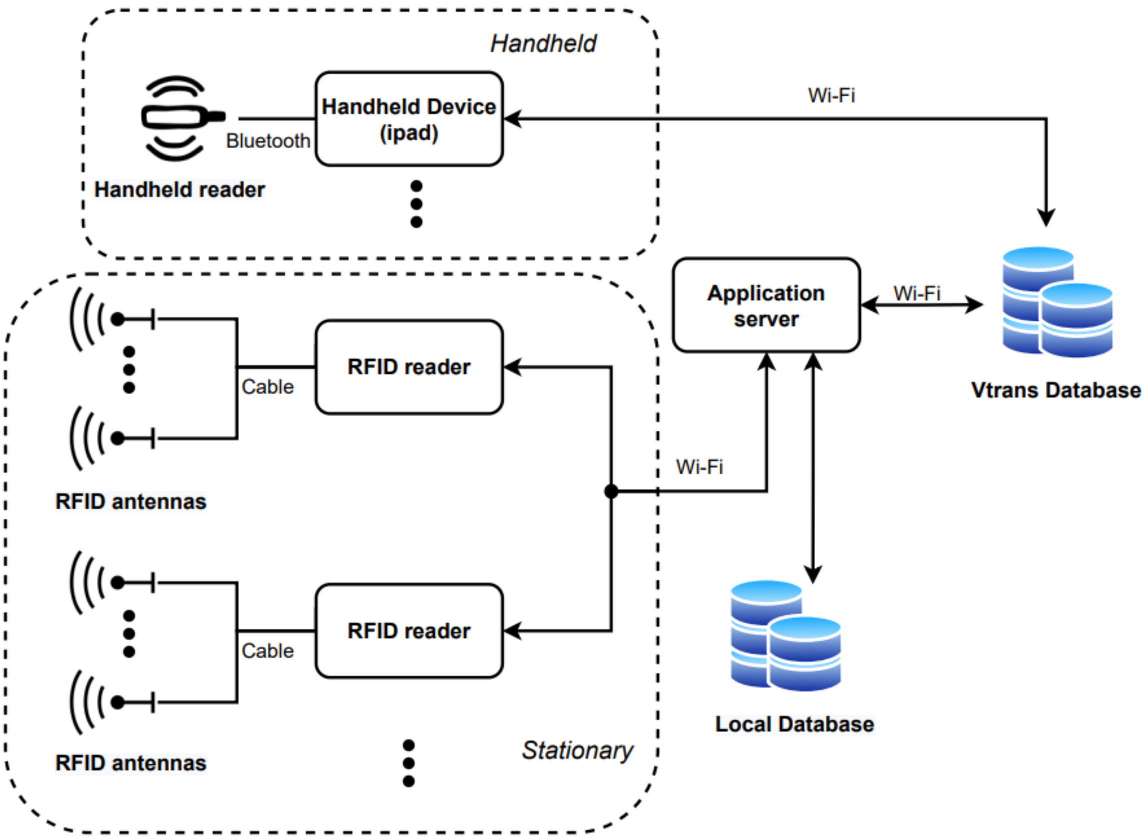


Fig. 2: The system configuration diagram.

Fig. 2 illustrates the configuration of the RFID system which consists of RFID readers, RFID tags, and an application server with a graphical user interface (GUI), developed by the UVM RFID research team. The system utilizes two types of RFID readers to achieve flexibility of the system: portable handheld readers, located in the top-left corner of the figure, and high-performance stationary readers, located in the bottom-left corner.

The RFID system developed by the UVM RFID research team uses two different graphical user interfaces (GUIs) to manage and retrieve asset data. The GUI used for stationary readers is specifically designed to work with multiple readers, expected to facilitate a statewide data management system. For portable handheld readers, the GUI is accessible through iOS devices such as iPhones and iPads. The iOS GUI enables various data management functions. All data management is performed securely through REST API, ensuring the privacy and confidentiality of the data. This approach to data management through RFID technology demonstrates a significant advancement in the transportation industry and has far-reaching implications for the secure and efficient management of asset data.

Table 4: System components and their key specifications and functions

System Components	Key specifications
Handheld RFID Reader	Scan distance: 10 ~ 15 feet
Stationary RFID Reader	Scan distance: 6 ~ 15 feet Scan angle: ~ [-90^{o}, 90^{o}] azimuth angle Multiple channels: >= 2 channels
Application Server	GUI interface, Wireless connection, Remote and local database access, and management
RFID tags	Unit price range: [$0.3 $5] Scan distance: 3 ~ 15 feet Substrate: metal or non-metal Sustain harsh environmental conditions with minimum maintenance (e.g., no battery recharging need)

Table 4 provides a summary of the specifications for the major components depicted in Fig 2. The system configuration shown in Fig. 2 was designed while considering the specifications listed in Table 4.

Deliverable 3: Laboratory study of RFID reader and antenna and performance report.

Laboratory studies were performed to evaluate two stationary RFID readers and the compatible antennas. A handheld reader was also evaluated.

- **Stationary RFID reader**

Fig. 3: RFID stationary readers (left: sargas, right: izar)

Two stationary RFID readers tested in the laboratory are Sargas and Izar readers. The antennas used are SecureControl Invengo antenna and MTI antenna. In addition, the performance and functionality of linear polarization antennas and circular polarization antennas are also evaluated.

Both readers are compliant with EPC Gen2 standard, and their operating frequencies are all within FCC authorized 902-928 MHz range. They are all 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. Table 5 presents a summary of the specifications for the RFID readers.

Table 5 Stationary RFID readers specifications

Specifications	**IZAR Reader**	**SARGAS Reader**
Air Interface Protocol	EPC Gen 2V2 ISO 18000-63	EPC Gen 2V2 ISO 18000-63
Operating Frequency	Global 865-956 MHz	Global 865-956 MHz
Transmission Power	0 to +31.5 dBm	0 to +30 dBm
# of Channels	4	2
Dimensions	194 x 139 x 33.6 mm (7.6 x 5.5 x 1.3 in)	87 x 80 x 23.8 mm (3.4 x 3.1 x 0.94 in)
Antenna ports	4 RP-TNC Female ports	2 RP-SMA Female ports
OS	Debian Linux kernel version 3.8	Debian Linux kernel version 3.8
Price	$1,643	$1,055
Weight	0.7 kg (1.5 lbs)	0.27 kg (0.60 lbs)

- **Handheld Reader**

Fig. 4: Zebra handheld RFID reader.

The handheld reader is integrated into the system allowing on-site individual tag interrogation to display or modify the relevant tag information (Fig.3). 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 the GUI is for the stationary reader. The database connection and data synchronization has been developed.

In deployment, the handheld reader connects to an iOS device via Bluetooth. When the trigger is pressed, the reader scans the ID of a tag in the close point of view, checks the tag ID, retrieves the pertinent tag data and asset item attributes from the database, and displays the information on the screen of the iOS device. The tag data can be edited and written back to the database server. Any such changes to asset attributes are reflected locally on the reader and remotely in the database on the server.

Table 6: Zebra handheld RFID Reader Specifications

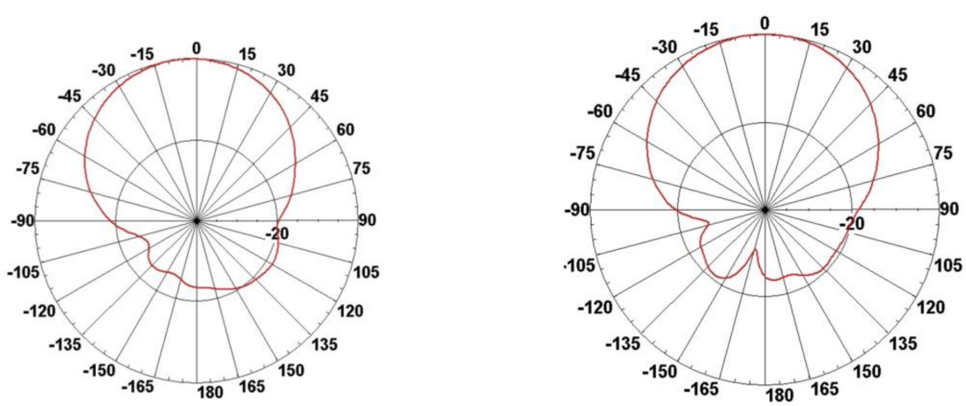
Air Interface Protocol:
EPC Class 1 Gen 2; EPC Gen2 V2
Operating Frequency:
FCC (902-928 MHz)
Max Read Distance:
6+ m (20+ ft)
Operating System:
Devices with Android 4.4 or iOS 8 OS
Data Interface:
USB, Bluetooth
Batch Memory:
Stores 40,000+ RFID Tags, 500 barcode
Dimensions:
130 x 79 x 185 mm (5.1 x 3.1 x 7.3 in)
Weight:
0.43 kg (0.95 lbs)
Operating Temperature:
-10°C to 40°C (14°F to 104°F)

- **RFID Reader Antennas**

Antennas with different polarizations can collectively cover a wider cross-range and longer distance. Antennas show different coverage of cross-range and distance depending on the polarization. Specifically, a linearly polarized antenna radiates energy only in the horizontal or vertical plane, whereas a circularly polarized antenna radiates energy in the sphere. Typically, a linear polarization antenna has a more extended reading distance than a circular polarization antenna due to its higher gain and focused directivity, whereas a circular polarization antenna can cover a wider direction.

Fig.5: MT0682 Antenna

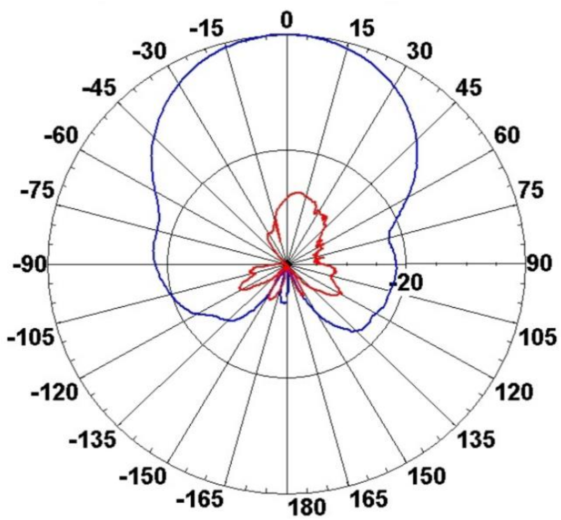
The antennas used are MT0682 series (Fig. 5) antennas. Specifically, they are MT-242043 (circular polarization) and MT-263003 (linear polarization). Fig. 6 shows the radiation patterns of each type of antenna on azimuth and elevated planes, respectively, illustrating the signal strength's angular dependence. For the circular polarization antenna, its maximum gain is 8.5 dBi, and the 3 dB beamwidth is 65◦; whereas for the linear polarization antenna, its maximum gain is 10.5 dBi, and the 3 dB beamwidth is narrower, i.e., approximately 50◦, which indicates a better directivity than the circular polarization antenna.



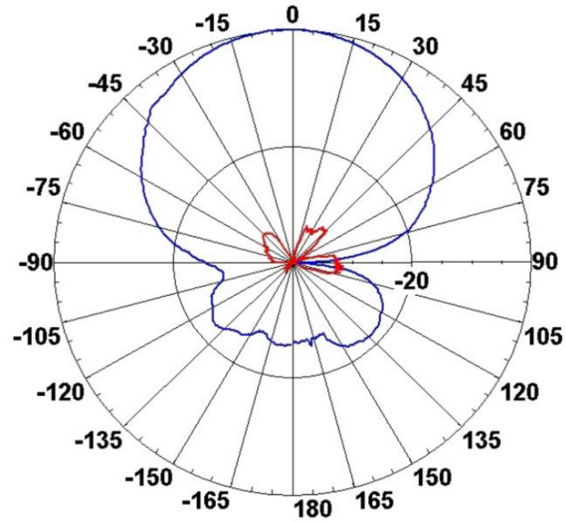
(a) Circular on azimuth plane.

(b) Circular on elevated

Fig.6a: MT0682 Antenna



(c) Linear on azimuth plane.



(d) Linear on elevated plane.

Fig. 6b: Antenna radiation patterns.

Deliverable 4: Laboratory study of passive, active, and semi-active RFID tags and performance reports.

A *passive* tag has no internal power source. It receives energy transmitted by the RFID reader. A passive tag has an internal coiled antenna which is energized upon receiving the radiated energy. It then uses the energy to read the tag data and transmit the data back to the RFID reader using the embedded antenna. Passive tags can havPae different properties and casings depending on the intended use. Some tags are highly durable, some are made for extreme temperatures, some are made for long-distance reads, etc. These tags often cost between $0.25 at the low end and $5 at the very top end.

An *active* tag is internally powered by a battery and is, therefore, more limited in lifespan and far more expensive. However, since it powers its own antenna, it provides a much greater reading distance. Active tags can cost from $20 to $100 depending on the use case – some industries require tags that are both long-distance and highly durable.

A *semi-active* tag has an internal battery. However, the battery does not power an RFID transmitter. Instead, it only powers a small logic circuit board of sensors and memory integrated with the passive RFID tag. Semi-active tags typically store an extra amount of data compared with passive tags. As the battery is not used to power the tag transmitter, the signal transmission distance of the semi-active tag is essentially the same as that of the passive tag.

Fig. 7: RFID tags used in the experiment. (From left to right is tag 1 (Omni-ID Flex 800), tag 2 (Omni-ID Exo 750), tag 3 (Omni-ID IQ 800), and tag 4 (Omni-ID Flex 1200).).

Table 7. Maximum reading distances for different passive tags.

Tag#	**Orientation**	**Substrate**	**Price**	**Reading Distance (feet)**	
				Measured	**Datasheet**
1	Horizontal	Metal	$29 for 10	21.25	26
	Vertical			49	
2	Horizontal	Metal	$49 for 10	55	36.1
	Vertical			50	
	Horizontal	Non-metal		48	
	Vertical			38	
3	Horizontal	Non-metal	$480 for 1000	33	32
	Vertical			55	
4	Horizontal	Metal	$0.86per for 900	15	39
	Vertical			55	

The memory and security of RFID Tag Gen2 protocol

The EPC Class 1 Generation 2 UHF Air Interface Protocol specifies the operation and functionality of passive RFIDs. It also defines the physical and logical requirements for an interrogating data system that operates in the 860-960 MHz frequency range. The RFID tags selected in this project complies with EPC Class 1 Generation 2 UHF Air Interface Protocol.

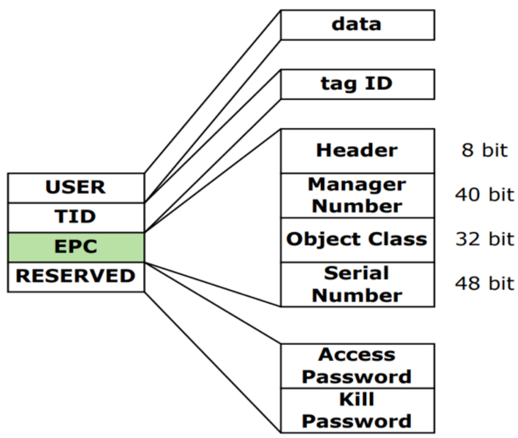


Fig.8: Gen2 memory map

As shown in Fig.8, the RFID gen2 chip contains 4 memory banks: User, TID, EPC, and Reserved. Reserved memory contains the kill and/or access passwords if passwords are set on the Tag. TID memory contains an 8-bit ISO/IEC 15963 allocation class identifier. User memory is an optional memory block for users to store any data.

EPC memory is the primary storage to identify the interrogated RFID tags. The first 6 bytes (48 bits) are reserved for Header and EPC Manager Number, and the remaining 10 bytes (80 bits) are used as the EPC memory space, which consists of an Object Class field and a Serial Number field. To prevent the system from retrieving information from irrelevant RFID tags, we store a prefix code unique to our own use in the Object Class field and store a unique tag ID in the Serial Number field. The prefix code is a 4-byte ASCII code string of the sponsor's name (i.e., "VAOT" for Vermont Agency of Transportation) in a hexadecimal number. With 6 bytes in the Serial Number field to store a tag ID, up to 2^{48} tags can be identified uniquely.

Reserved memory contains the kill and/or access passwords which are for tag security.

- Access password: the default value is zero. An interrogator (RFID reader) may set a non-zero access password in an Access command to enable the tag security state.
- Kill password: the default value is zero. Kill password enables the interrogator (RFID reader) to launch a kill-command sequence to kill a tag and render it nonresponsive thereafter. The killed tags will remain in the killed state under all circumstances and are unusable anymore. Note, killing a tag is an irreversible process. It is usually used to dispose of obsolete tags.

The user can write an access password to an interrogated tag. Once the access password is configured as a non-zero code, the secured state can be set in the URA program which is the graphical user interface (GUI) of the stational RFID reader, as shown in Fig.9. The memories are secured to prevent EPC and passwords from being modified.

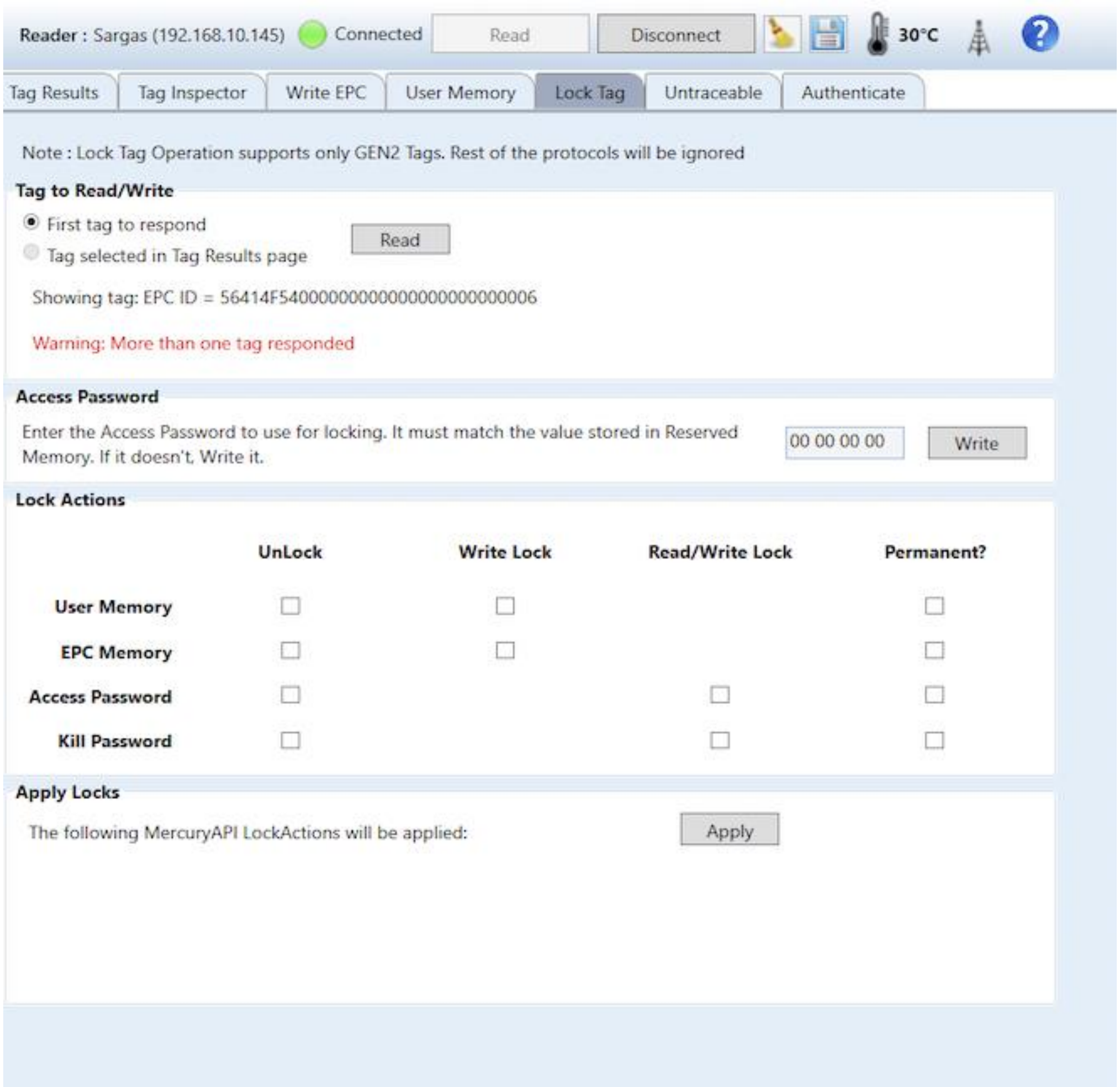


Fig.9: Tag locking interface.

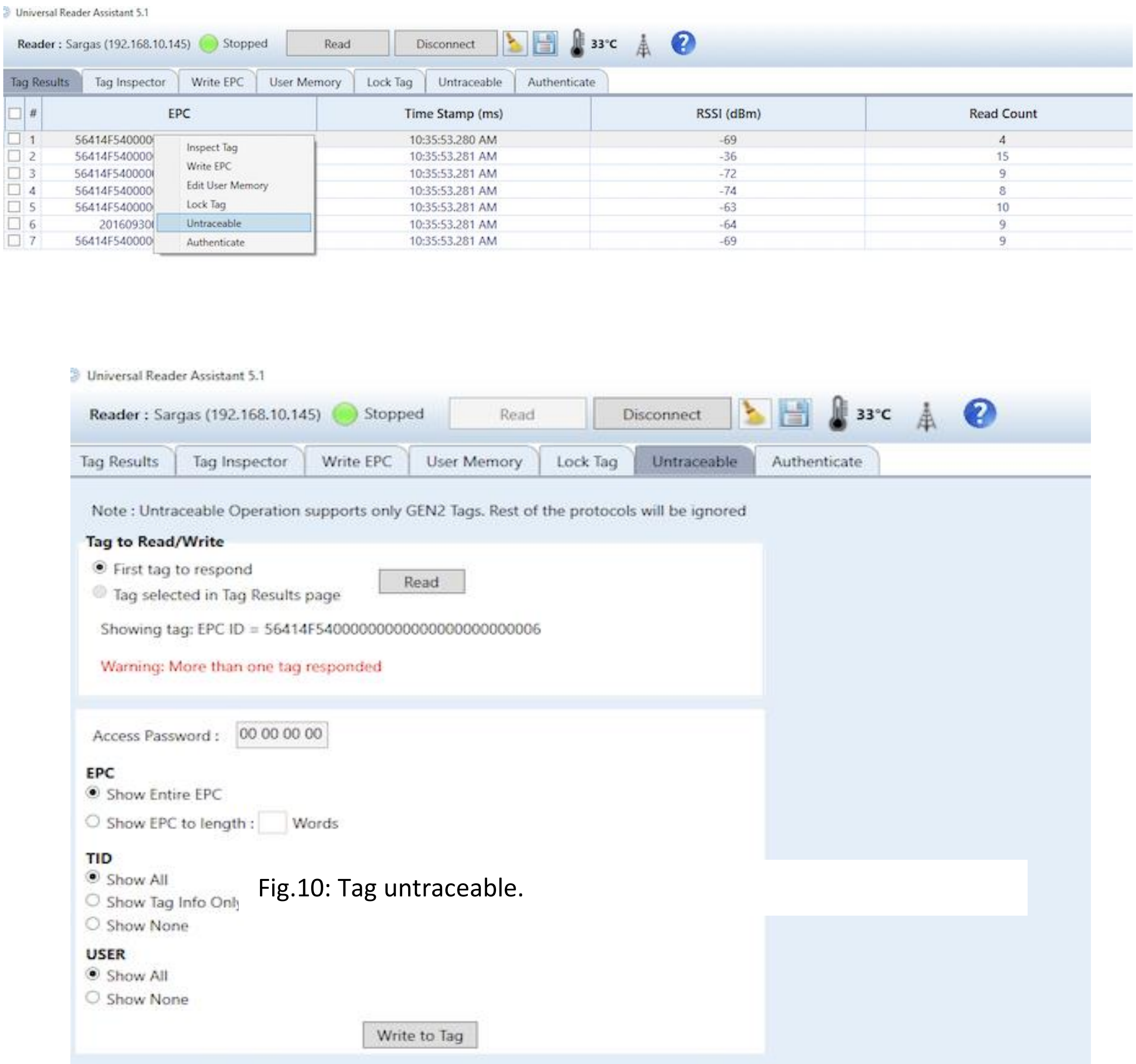


Fig.10: Tag untraceable.

The asset information is retrieved from the database according to the EPC code stored in the tag. The password can only prevent changing the EPC but not reading the EPC. For further protection, the tag can be set to be untraceable (Fig. 10). In this case, the tag is active only when an interrogator (reader) knows its EPC.

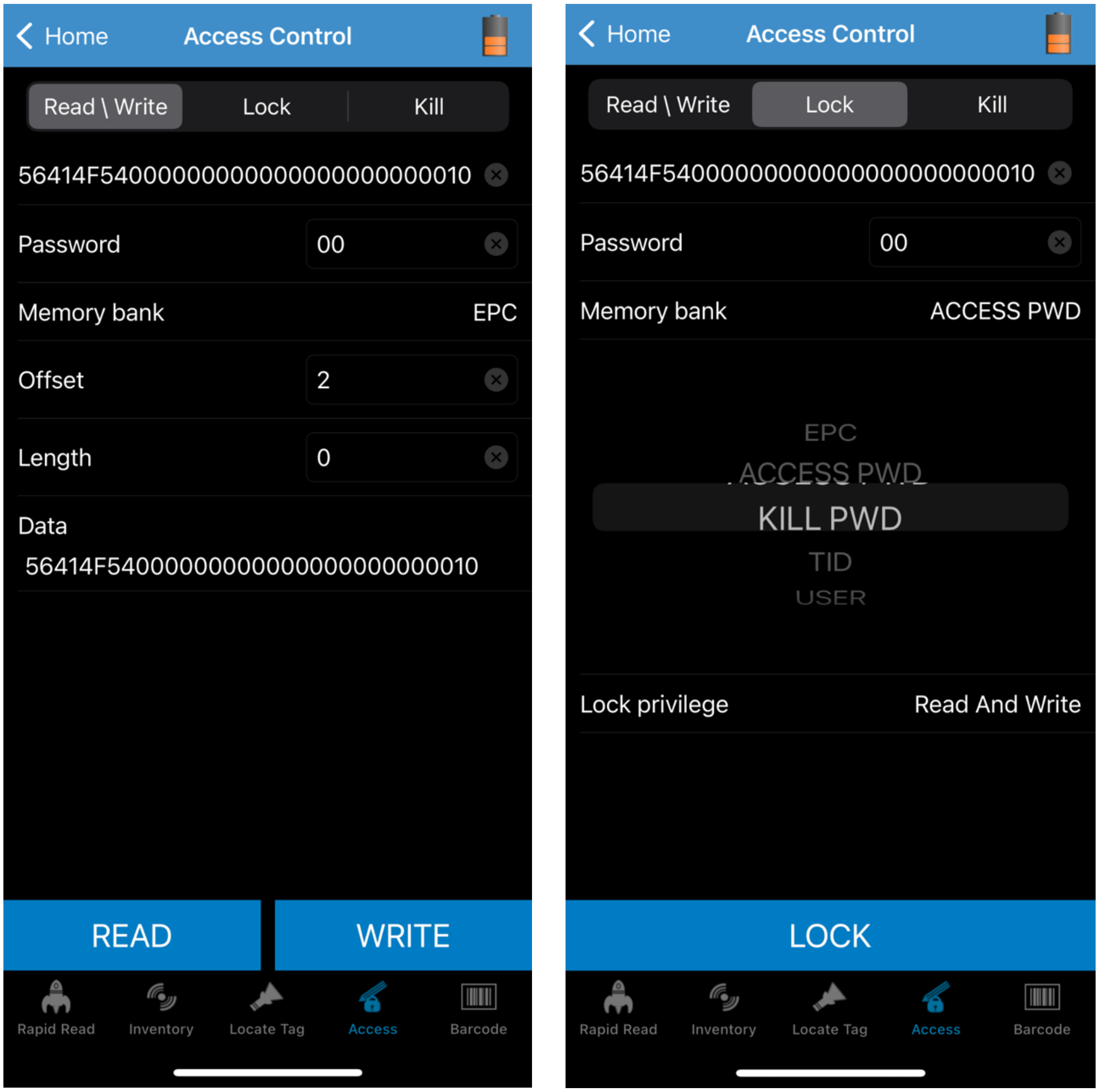


Fig.11: Write to tag and lock tag functionality on the handheld reader app.

Similarly, the tag-security state and password can also be configured on the held-hand reader (Fig. 11).

Deliverable 5: RFID control program and user-friendly GUI

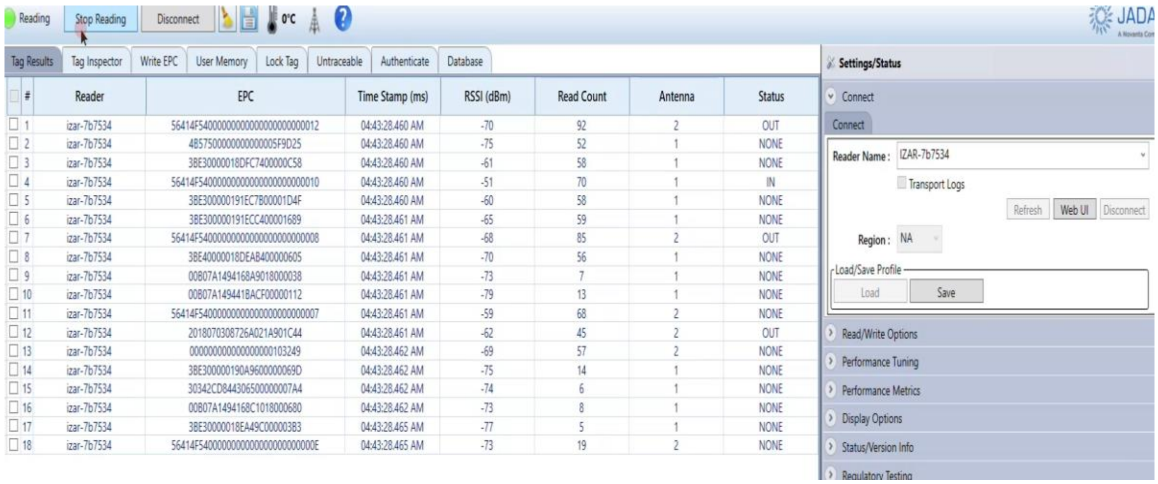


Fig.12: URA displaying multiple tag reading results.

The GUI for stationary readers is programmed using the open-source code of Universal Reader Assistant (URA). We customize the source code design to achieve our user interface functionalities, including (i) filtering tag IDs based on a designed criterion (i.e., a prefix field indicating that a tag belongs to AOT (e.g., Vermont Agency of Transportation) (see Figure 12), (ii) reading and displaying on the screen the tag data (e.g., EPC (tag ID), timestamp, in-and-out state), (iii) saving the tag data to a txt file (auto-save), (iv) inspecting the tag information in detail (e.g., corresponding asset name, location, and other information), (v) communicating the database (e.g., modifying tag information in the database or synchronizing with the database in could), (vi) writing custom EPC IDs to tags, and (vii) displaying tags from multiple readers. To achieve in-and-out state in (ii), we used the time difference of the detection of two different antennas. For example, suppose antenna 1, facing the garage, read the tag prior to antenna 2. Since antenna 1 responded to the tag prior to antenna 2, it is going out from the garage. For function (iii), a txt file is a temporary copy of the data. It is to prevent data loss from the loss of internet connection when uploading to the database. Once the internet connection is established, data will be automatically saved to the database via REST API. Functionalities (iv) and (v) are done in the Database tab in URA as indicated in Figure 13. If the data of the detected tag exists in the database, it will display the information. This enables the modification of the tag data.

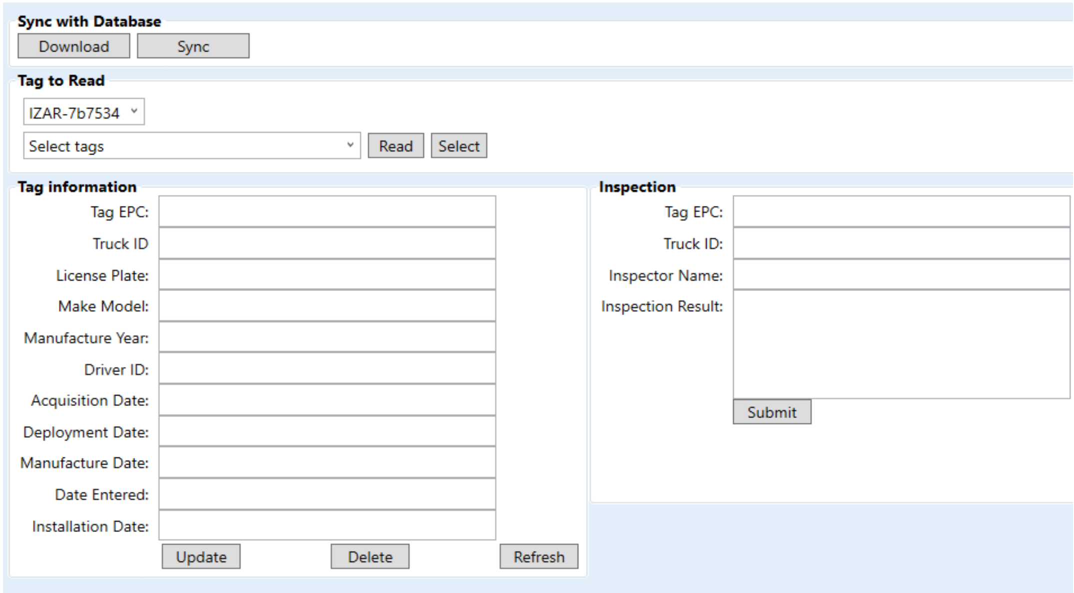


Fig.13: URA Database Tab Configuration

In addition to the stationary reader, GUI for handheld readers is also programmed using the open-source code of ZebraRFID app. We customize the source code design to enable database interaction, such as (i) retrieving tag data and information from the database, (ii) updating tag information and syncing it with the database (See Fig. 14.)

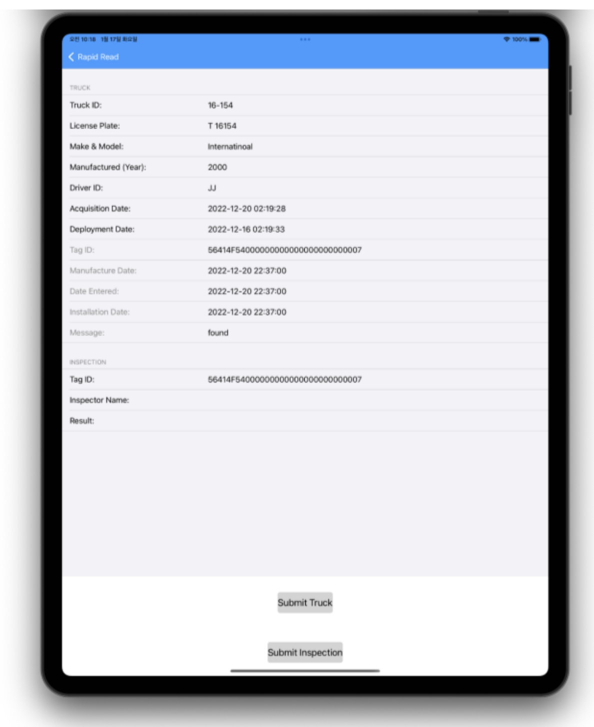


Fig.14: ZebraRFIDApp with Database interaction

- **Deliverable 6: RFID database.**

  Both the in-vehicle and handheld RFID readers can save data locally or to a remote database server. The database design schema is shown in Fig. 15. The project sponsor uses Microsoft SQL Server to manage their large transportation assets. We accordingly integrate our reader software with Microsoft SQL Server. In the current database design, each RFID tag is associated with exactly one traffic asset (i.e., sign, guardrail). A temporary loss of internet connectivity should not stop the system from operating. To address this issue, tag data are saved locally on the reader and are synchronized with a remote database when and while the internet connection is re-established. A web-based data access (connectivity and synchronization) is added to the sponsor's remote server via ArcGIS REST API. To connect the application to the remote server, the application's various functionalities need to be connected to the respective REST API calls using the HTTP protocol.

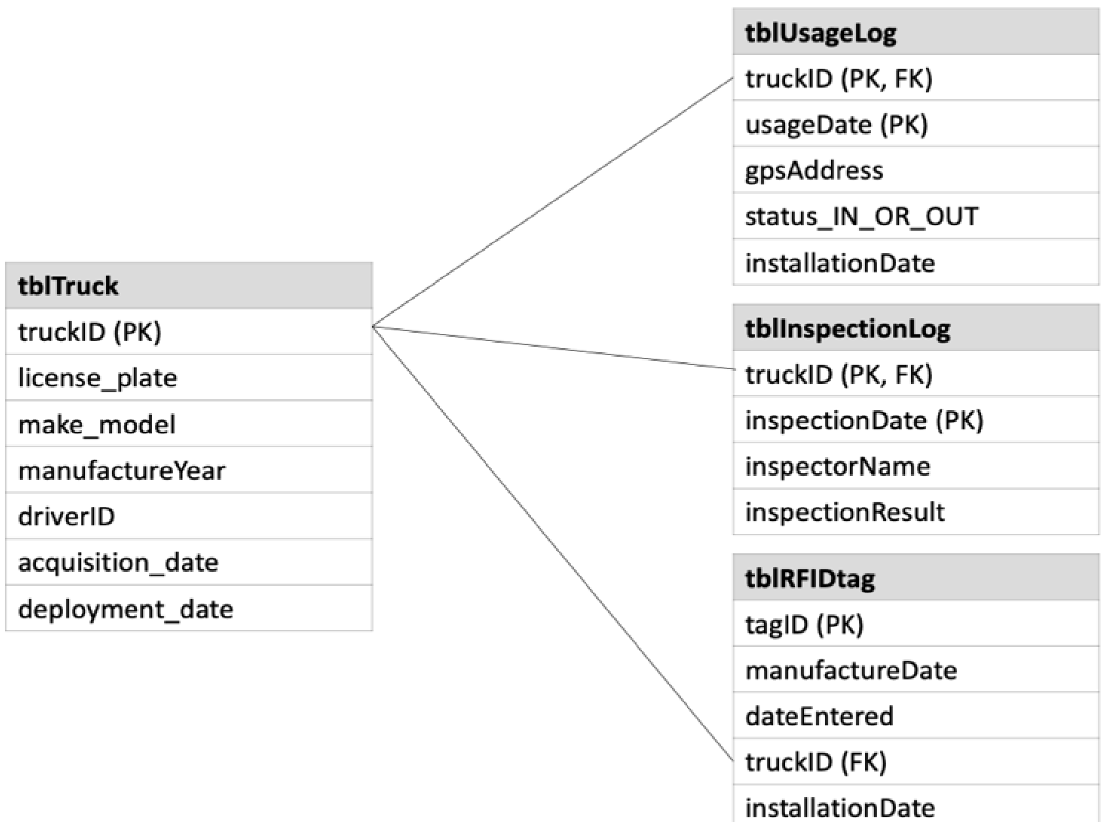


Fig.15: the Normalized Database Table Scheme

As part of our asset management efforts, the UVM team has designed a MySQL-based database consisting of four tables: tblTruck, tblUsageLog, tblInspectionLog, and tblRFIDtag, as illustrated in Fig 15. The tblTruck table contains important truck information, such as the license plate number, model, and driver details. Whenever RFID readers detect tags, the corresponding information is automatically saved in the tblUsageLog table. For stationary readers, the 'status_IN_OR_OUT' field is used to keep track of the asset's status. The tblInspectionLog table stores the inspection history and can be modified or inserted using handheld readers or the URA for stationary readers. Lastly, the tblRFIDtag table stores the unique tag EPC assigned to the assets.

To facilitate secure and efficient database interaction, the UVM team has implemented a REST API protocol. This protocol allows for seamless communication between the database and other software applications. It is noteworthy that the REST API protocol is both secure and fast, ensuring that data transfer between the database and the system is efficient and safe. As mentioned in the Quarter 01 section, due to concerns regarding security when directly accessing the VTrans database, the UVM team built a MySQL-based test database. All tests were conducted on the UVM silk server, and there were no conflicts with VTrans data.

Deliverable 7: Mechanical structure designed for mounting RFID readers and RFID tags

To prepare for the field test, the functional components and mounting mechanical structures are obtained and assembled.

Solar panel and mounting structure

Since at the garage gate, there is no power source, we prepare the solar panel that can be used to charge the battery to provide power to the RFID system. The solar panel part number is Solon Blue 220/01. The dimensions are 64.57 × 39.37 × 1.65 in, and the weight is 51.8 lbs. BougeRV 41in adjustable solar panel tilt mount brackets with foldable tilt legs were ordered and assembled.

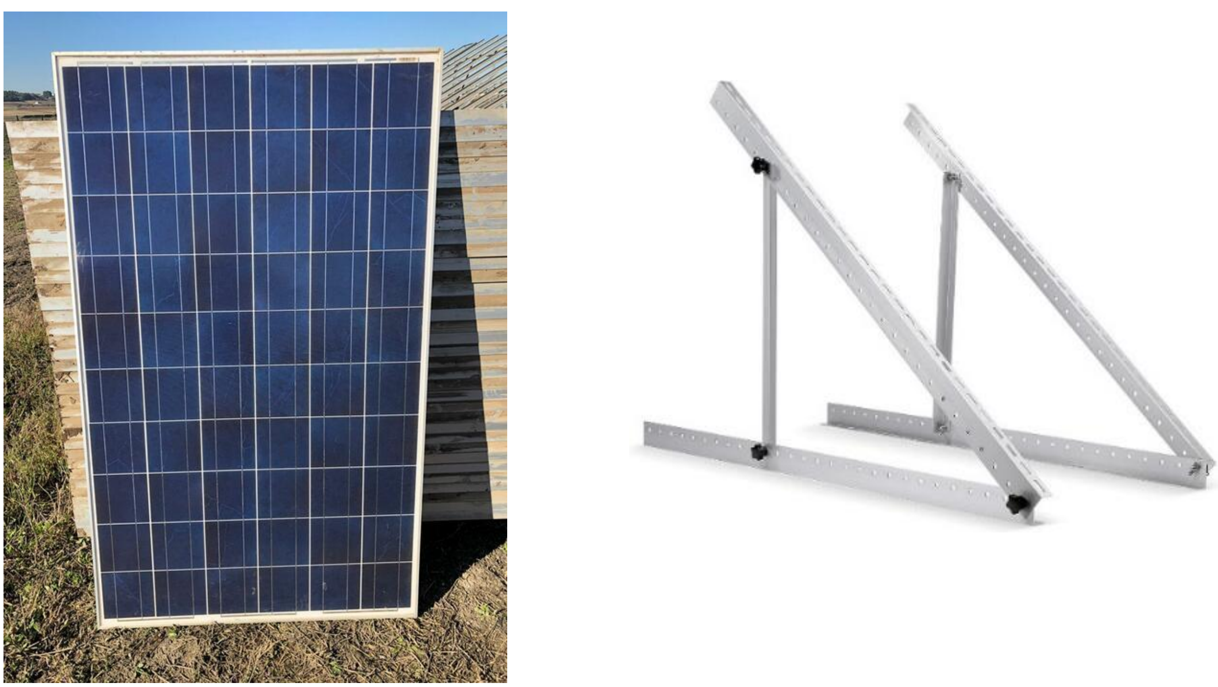


Fig. 16: Solar panel and Adjustable legs

Rechargeable battery

The battery selected is CHINS Bluetooth LiFePO4 Battery Smart 12V 100AH Lithium Battery, which spports Low Temperature Charging (-4℉/-20°C) with built-in 100A battery management system (BMS).

Battery Charge Controller

Renogy Voyager 20A 12V/24V PWM waterproof solar charge controller with LCD display.

Battery Charger

ExpertPower 12V 5A Smart Charger for Lithium LiFePO4 Deep Cycle Rechargeable Batteries.

Fig. 17: Battery, Controller, and Charger

EAP225-Outdoor AC1200 Wireless MU-MIMO Gigabit Indoor/Outdoor Access Point

EAP225-Outdoor AC1200 wireless signal extender is obtained which can extend the wifi signal to 60 meters for outdoor applications. We use this device to connect the RFID reader at the garage gate to the wifi network inside the garage.

Amazon EERO Mesh Wifi Router

As the wifi signal in Randolph garage was not stable, we used eero mesh wifi router to set up a mesh network which greatly improved wifi signal quality for RFID system.

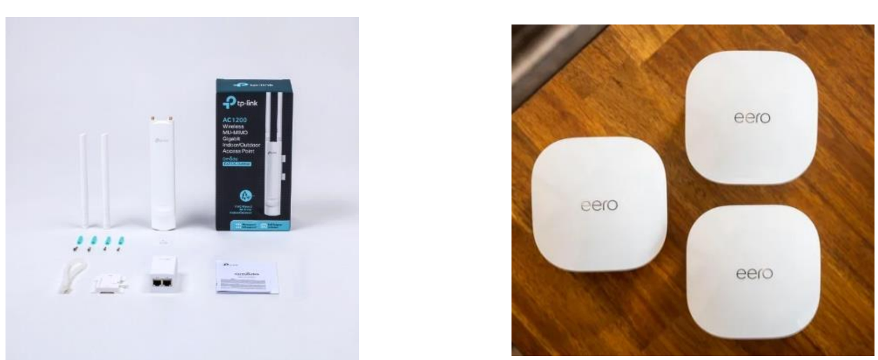


Fig. 18: WiFi extender and eero mesh wifi router

Storage Box

A 64 Qt. storage box width lead is ordered to host RFID reader, battery, and charge controller. The box is sealed using duct tape to make it waterproof.

Metal poles

Two metal poles are planted at the garage entrance which will be used to install RFID antennas.

Fig. 19: storage box and two poles for mounting antennas

Deliverable 8 – Integrated RFID system

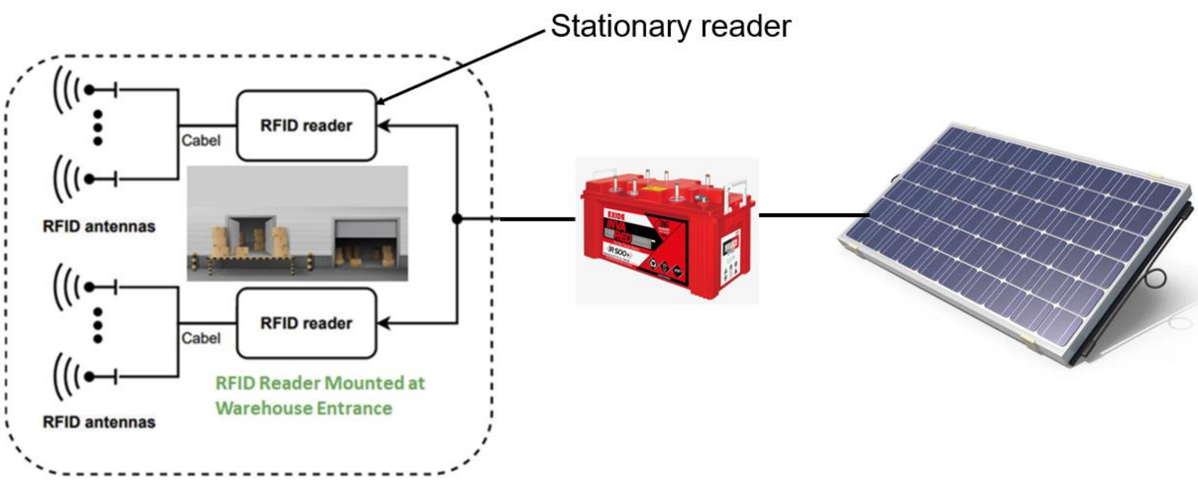


Fig. 20: Integrated system diagram

As there is no power source available at the garage gate, we prepared a solar panel to charge a battery to provide power to the RFID system. The solar panel we selected is the Solon Blue 220/01, which had dimensions of 64.57 × 39.37 × 1.65 inches and weighs 51.8 lbs. Additionally, we used BougeRV 41-inch Adjustable Solar Panel Tilt Mount Brackets with Foldable Tilt Legs (as shown in Fig 8) to install the solar panel.

Fig 11 shows the battery components, including a rechargeable battery, a controller, and a battery charger. We have chosen the CHINS Bluetooth LiFePO4 Battery Smart 12V 100AH Lithium Battery, which supports Low Temperature Charging (-4℉/-20°C) and comes with a built-in 100A battery management system (BMS). For the controller, we have used the Renogy Voyager 20A 12V/24V PWM waterproof solar charge controller with an LCD display. And for the battery charger, we have used the ExpertPower 12V 5A Smart Charger for Lithium LiFePO4 Deep Cycle Rechargeable Batteries.

To ensure that the Wi-Fi signal reaches the RFID readers, we have used a Wi-Fi extender. Since Wi-Fi connectivity is essential to the RFID system, we have designed (as shown in Fig 12) and installed a Wi-Fi extender (as shown in Fig 12). We have tested the EAP225-Outdoor AC1200 Wireless MU-MIMO Gigabit Indoor/Outdoor Access Point and Amazon eero devices, both of which facilitate the creation of a local network for the RFID system.

For outdoor usage, we used storage boxes for battery and two metal poles as shown in Fig 13.

Deliverable 9: Create a test site on VTrans campus and submit a field test report.

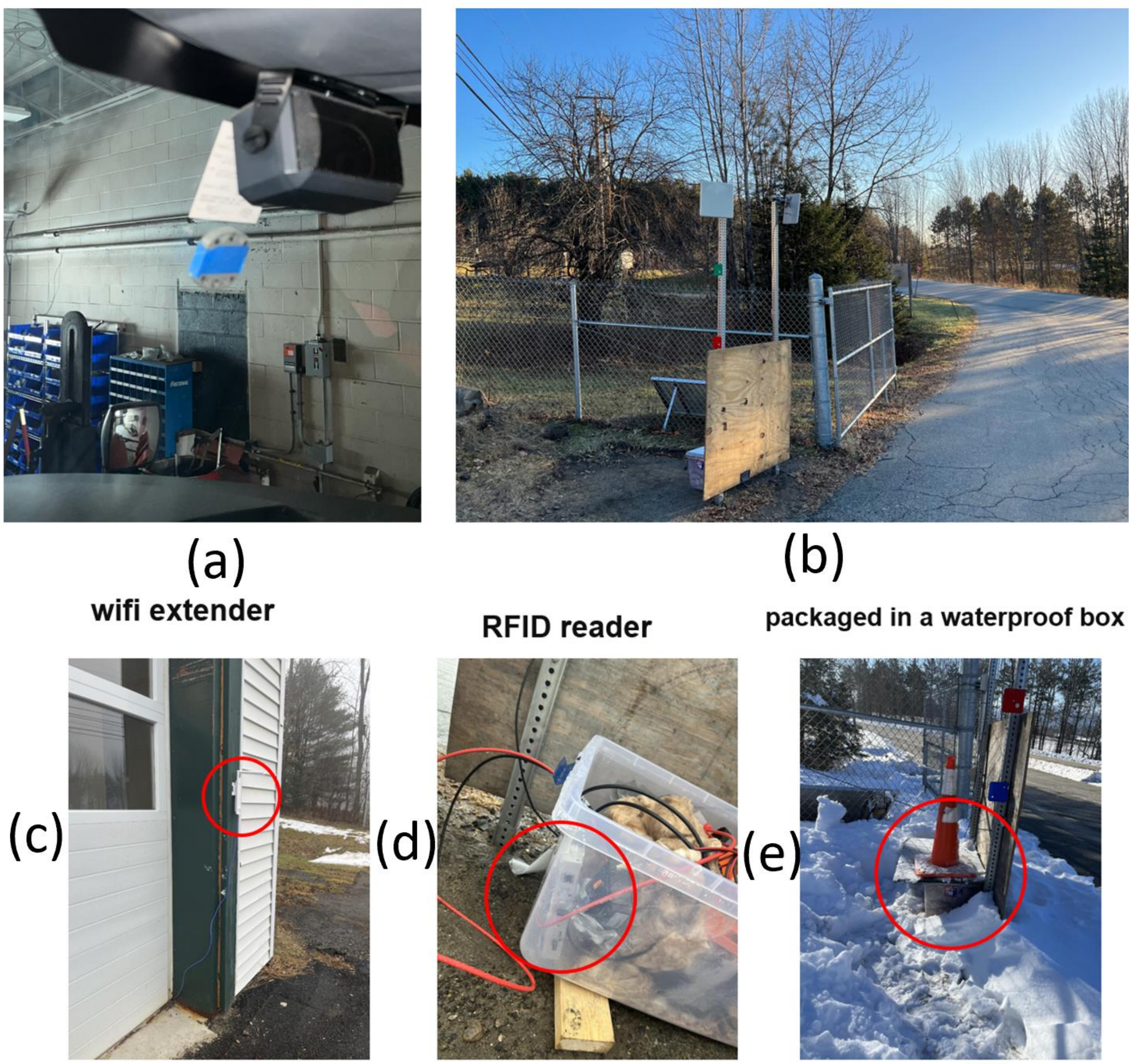


Fig. 21: Mechanical structure to place the RFID readers and related accessories

The UVM team and VTrans collaborators selected VTrans' Randolph garage as the test site for system performance evaluation. The goal was to use RFID technology to monitor garage's trucks movement state (entering or existing the garage), movement time and other information. To achieve this goal, the team and VTrans collaborators decided to install the system at the gate of the garage (shown in Fig. 21) which was about 20 meters from the garage building. As it was an outdoor environment, the system set up consisted of several steps:

- Mounting RFID tag on the windshield inside each truck (Fig. 21a)
- Mounting RFID reader antennas on two poles next to the garage door (Fig. 21b)
- Installing a wifi extender to extend indoor wifi signal coverage to the garage door (Fig. 21c)
- Putting RFID reader and battery inside a waterproof storage box (Fig. 21d)
- Setting cable connections for RFID reader, battery, solar panel and antennas (Fig. 21e)

The UVM team conducted the 1st field test in Randolph's garage on a winter day, December 11th, 2022. Since then, the UVM team have been continuing system development, defect diagnosis and debugging to improve system performance and reliability. During the field tests, the team identified a number of issues and developed the corresponding solutions.

Power Supply Issue:

The system was able to detect truck movement and update database record correctly. However, the test revealed a major issue regarding the power supply due to two factors: (1) excessive power consumption and (2) Weather conditions.

(1) excessive poser consumption was observed during the operations. It was noted that the power generated by the solar panel was not sufficient to meet the power requirements of the IZAR RFID reader. The reader consumed 20 watts of power at 12 volts, which was translated to around 1.6 A of current. Although the solar panel generated a peak current of about 2 A at noon, it only produced about 0.5 A of current at other times, considering the weather conditions in the winter season. Additionally, the solar panel generated little to zero power in the evening when the RFID reader was still running and consuming 20 watts of power. This power shortage was the main reason that the battery was exhausted after just three days of operation.

(2) The harsh weather conditions in Randolph during the field test period had a significant impact on the battery's capacity. The LiFePO4 battery we chose can only be charged when the temperature is above 0°C, and its capacity decreases significantly at low temperatures. In December, the weather in Vermont was icy cold, and there was snow on the ground, which further worsened the situation. The solar panel's ability to generate power was also hindered by the unfavorable light conditions. To address this, we chose a battery with a self-heating function that uses the battery's self-power to maintain the battery temperature above 0°C for charging. However, this self-heating function increased power consumption speed and further exacerbates the battery charging and discharging issue associated with limited solar panel capacity.

Subsequently, a temporary solution was discussed during a meeting with VTrans on January 18th, 2023. The UVM team proposed a resolution centered around a battery-swapping approach to address the power supply problem. Specifically, this strategy involves the use of two rechargeable batteries: one actively powers the system while the other undergoes recharging. Every 4 days, a collaborator from VTrans will swap the operational battery and the recharged one. This method ensures the power supply is maintained to fully support system operations without interruption. The approach was put into action on February 16th, 2023, when the UVM team returned to Randolph's garage and implemented the new system.

Missed Detection Issue

In the initial experimental setup, a stationary RFID reader with two antennas was installed at the entrance of the garage to monitor the status of trucks – entering or departing the garage. In each truck, an RFID tag was attached to the windshield. It was noticed that sometimes the RFID tag could not be detected. In other words, a missed detection occurred. The team studied the problem and found the reason that caused this problem.

The RFID antennas were mounted on the poles beside the garage gate. One antenna faced outward while the other faced inward to monitor the truck entering or existing the garage. It was observed that during the truck's motion, occasional instances arose where the vehicle did not align optimally with the antenna, leading to the substantial angle between the antenna and the RFID tag. This misalignment resulted in the tag falling beyond the purview of the reader antenna's coverage area, consequently leading to instances of undetected activity.

To solve this problem, a remedial approach was adopted, involving the addition of two supplementary antennas. This augmentation effectively broadened the scope of detection coverage, effectively mitigating the problem at hand. Illustrated in Figure 22 is a comprehensive 4-antenna arrangement: Antennas 1 and 4 have been strategically positioned to face outward, thus capturing the area outside the gate. The orientations of these antennas have been finely adjusted to optimize coverage expansion. Additionally, Antennas 2 and 3 have been meticulously directed towards the interior of the garage, each set at slightly distinct angles.

This configuration operates on a specific principle: when either Antenna 1 or 4 detects RFID tags prior to Antenna 2 or 3, this signifies the entry of a truck into the garage. This state is aptly marked as "IN" or “I”. Conversely, if Antenna 2 or 3 identifies RFID tags preceding Antenna 1 or 4, it conveys the truck's exit from the garage, denoted as "OUT" or “O”. This deliberate arrangement establishes a methodical framework for proficiently tracking movement based on the precise sequence of RFID tag detections facilitated by the respective antennas.

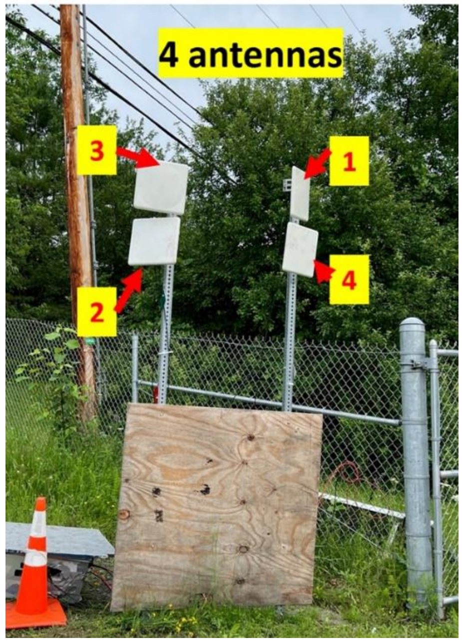


Fig. 22: 4-channel configuration

Multi-detection Issue

While the incorporation of four antennas effectively alleviated the concern of missed detections, it inadvertently introduced a new challenge—namely, the occurrence of multiple detections. As illustrated in Figure 22, antennas 1 and 4 are oriented outward, while antennas 2 and 3 are directed inward. To enhance clarity, these antennas are grouped: antennas 1 and 4 constitute Group 1, whereas antennas 2 and 3 constitute Group 2. As per the intended design, when a truck enters the garage, only the antennas in Group 1 should register a detection, and conversely, when a truck exits the garage, only the antennas in Group 2 should trigger detection.

However, during actual testing, a notable observation emerged: periodically, both antenna groups exhibited detection reporting. In essence, during the movement of a truck, the varying orientation of the vehicle led to the RFID tag affixed to the windshield intersecting the coverage areas of both antenna groups. Consequently, a situation of simultaneous detection arose, engendering what can be termed a "multi-detection issue." This circumstance introduced confusion in the determination of the truck's movement direction or the accurate recording of its state.

To address this issue, the UVM team employed a simple approach. We assigned weighting factors to the two groups: weighting factor‘100’ for group 1, and weighting factor ‘1’ for group 2. Each time multiple detection occurred, we calculated the average values for the first and second halves of the sequence.

An illustrative instance is depicted in Figure 23. Presented therein is a sequence of digit strings, namely 11112112222112, which corresponds to the recorded RFID scan outcomes. In this context, the digit 1 signifies a detection from antennas within group 1, whereas the digit 2 denotes detection emanating from antennas within group 2. Notably, this digit string is divided into two equal parts at its midpoint.

Subsequently, the mean values of both halves are calculated for comparison. In the specific case of this digital string, the average score of the first half amounts to 86, while the second half yields an average score of 29. Notably, the disparity between the averages of these two halves carries significance. In instances where the average score of the first half surpasses that of the second half, this implies a predominance of group 1 detections during the initial sensing phase. Consequently, the inference drawn is that the truck is indeed detected as being in motion into the garage. Conversely, when the average score of the first half is inferior to that of the second half, the determination indicates the truck's movement occurring outward from the garage.

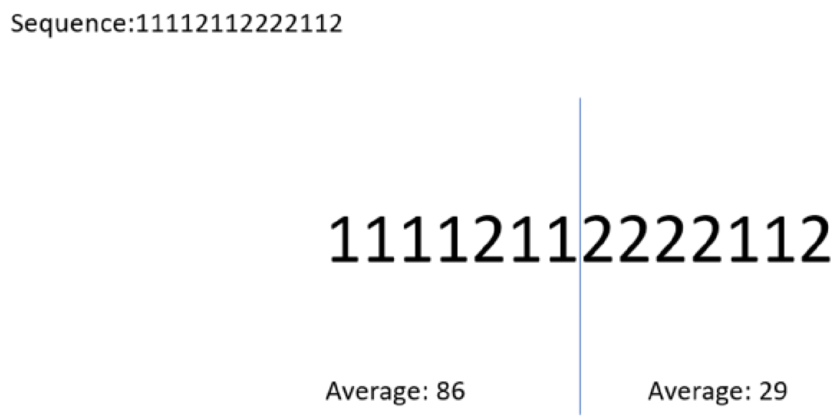


Fig 23. Methodology of determining the status

Throughout the course of the experiments, the UVM team additionally noted instances wherein specific conditions, such as scenarios involving high-speed or low-speed truck movements, perturbed the anticipated sequence of antenna readings. This unpredictability posed a notable obstacle in confidently ascertaining the status solely based on the sequence of detections. In response to this intricate challenge, the team implemented a strategy involving the incorporation of both preceding and subsequent statuses into the analysis. In this method, the previous state value recorded in the database is utilized to help determine the current track moving state. Importantly, this particular methodology comes into play exclusively when faced with non-deterministic outcomes stemming from digit sequence calculations.

Field Test Results

Fig. 24 illustrates the status information of truck 29-165 (depicted in Figure 24-A) as presented in the Web GUI, in accordance with the three core principles mentioned above. As depicted in Figure 24-B, the final column highlights the truck's traceability utilizing the RFID transportation maintenance system, indicated by the transitions between 'IN' and 'OUT'. For instance, the vehicle consistently enters the garage at approximately 5:55 AM each day, with active activities throughout, and concludes its operations around 4:30 PM.

Truck 29-165

License Plate	Make Model	Manufacture Year	Driver ID	Acquisition Date	Deployment Date
T 29165	GMC 2500 HD	2019	JA	2019-02-04 00:00:00	2019-04-01 00:00:00

Fig. 24-A. Truck (ID 29-165) information

29-165	2023-07-26 05:53:39.000000	izar-7b7534.local	IN
29-165	2023-07-26 06:52:02.000000	izar-7b7534.local	OUT
29-165	2023-07-26 10:40:34.000000	izar-7b7534.local	IN
29-165	2023-07-26 12:04:31.000000	izar-7b7534.local	OUT
29-165	2023-07-26 12:38:26.000000	izar-7b7534.local	IN
29-165	2023-07-26 16:32:33.000000	izar-7b7534.local	OUT
29-165	2023-07-27 05:57:54.000000	izar-7b7534.local	IN
29-165	2023-07-27 07:06:55.000000	izar-7b7534.local	OUT
29-165	2023-07-27 12:10:53.000000	izar-7b7534.local	IN
29-165	2023-07-27 15:14:45.000000	izar-7b7534.local	OUT
29-165	2023-07-27 15:44:57.000000	izar-7b7534.local	IN
29-165	2023-07-27 16:30:12.000000	izar-7b7534.local	OUT
29-165	2023-07-28 05:53:30.000000	izar-7b7534.local	IN
29-165	2023-07-28 06:24:13.000000	izar-7b7534.local	OUT
29-165	2023-07-28 09:20:33.000000	izar-7b7534.local	IN
29-165	2023-07-28 09:53:33.000000	izar-7b7534.local	OUT

Fig. 24-B. Records of truck (ID 29-165) movement on July 26^{th}-28^{th}

Truck 27-964

License Plate	Make Model	Manufacture Year	Driver ID	Acquisition Date	Deployment Date
T 17964	International HV507	2019	CM	2019-09-04 00:00:00	2021-06-01 00:00:00

Fig 24-C. Truck (ID 17-964) information

17-964	2023-07-27 07:12:36.000000	izar-7b7534.local	IN
17-964	2023-07-27 07:12:52.000000	izar-7b7534.local	IN
17-964	2023-07-27 07:40:52.000000	izar-7b7534.local	OUT
17-964	2023-07-27 09:31:48.000000	izar-7b7534.local	IN
17-964	2023-07-27 09:45:30.000000	izar-7b7534.local	OUT
17-964	2023-07-27 10:34:43.000000	izar-7b7534.local	IN
17-964	2023-07-27 10:38:06.000000	izar-7b7534.local	OUT
17-964	2023-07-27 11:53:40.000000	izar-7b7534.local	IN

Fig 24-D. Records of truck ID 17-964 on July 27th

Fig. 24 illustrates the status information of Truck 29-165. In general, the RFID system can track and monitor truck movement correctly. However, there is an odd case highlighted in Fig. 24-D. On July 27th, 2023, at the time instances of 7:12:36 and 7:12:52, two detections were reported within 16 seconds, both indicated 'IN' (entering) state. The 16-second time gap was longer than these in typical multiple detection phenomena. By using the prior state record in the database, we were able to confirm that the detected ‘entering’ state was correct. The team suspected this 16-second time gap might be caused by the truck’s very slow moving speed, or other interference factors, which would be further investigated.

Deliverable 10: Report on the feasibility of employing RFID technology for statewide transportation maintenance operations and asset management.

Participating in this project has proven to be a transformative experience for the team, greatly augmenting their comprehension of the intricate realms of RFID and IoT systems. Moreover, this engagement has afforded team the invaluable opportunity to cultivate practical skills through active involvement in multifaceted tasks, including the intricate domains of system development, the art of optimization, and the demanding rigor of validation processes.

To expand the system application to encompass statewide transportation maintenance operations and asset management, there are a number of factors that should be carefully considered:

- ***System architecture***

Our existing system is built upon the architectural framework illustrated in Figure 2, wherein an application server plays a pivotal role in orchestrating the synchronized operations of numerous stationary RFID readers. However, through extensive experimental testing, a noteworthy revelation has emerged: the application server is not essential. Each RFID reader has the potential to directly interface with the remote database server on the cloud. This revised approach, as depicted in Figure 25, holds the promise of streamlining system intricacies significantly by eliminating the intermediary application server. This, in turn, holds the potential to yield manifold benefits including reduced complexity, lowered costs, and heightened operational dependability.

For the development of a comprehensive statewide RFID system, an innovative hybrid network structure can be developed, amalgamating the architectural frameworks of both Figure 2 and Figure 25. In certain regions where stationary RFID readers necessitate specialized coordinating activities, the deployment of an application server can foster the development of localized regional RFID networks. Here, the application server serves as a bridge connecting to the remote database server. Conversely, in other regions where stationary RFID readers fulfill general tracking functions, the direct

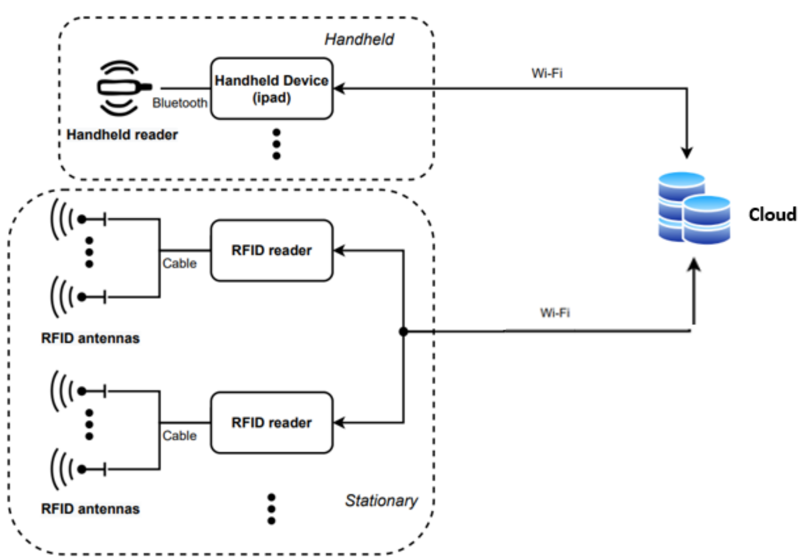


Fig 25. System architecture of RFID direct access to remote database server

database-accessing architecture can be harnessed to great effect. This multifaceted approach ensures that the system is tailored to the specific needs of diverse areas, fostering optimal efficiency and efficacy.

Hybrid RFID Readers and Tags

In our current system implementation, we adopt two stationary RFID readers (Sargas and Izar readers, Fig. 3) and a handheld RFID reader (Zebra reader, Fig. 4). These readers have sophisticated functions. We have conducted extensive tests to evaluate and validate their performance. However, one major limitation is the cost. For each of these readers, the unit price is within the $1000 ~ 2000 range. For statewide deployment with a large number of such readers, the cost will be significantly high. For some application scenarios that uses short distance scan, low cost RFID readers and tags can be adopted. The team has developed and tested an MFRC 522 RFID reader in conjunction with an ESP 32 microcontroller, shown in Fig. 26.

(a) (b) (c)

Fig 26. Low-cost MFRC 522 RFID reader, RFID tag and the configuration with an ESP 32 microcontroller

While this reader has lower specs, e.g. short distance, compared to other RFID readers and uses a different radio frequency (13.56 MHz), our tests demonstrate its functionality and effectiveness. In spite of its low price, $6.00, the MFRC 522 RFID Reader can be connected smoothly with the database. Fig. 27 shows a test result. In the test, 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. 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.

```
.....
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**
```

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

Fig 27. Low-cost RFID reader MFRC 522 experiments operations and results shown in the database

This test highlights the possibility of reducing the overall cost of the RFID asset management system by exploring alternative and more cost-effective 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.

- **Power Supply**

Ensuring a reliable power supply is of paramount importance for the seamless operation of an RFID system, particularly when it involves stationary RFID readers. In scenarios where the system is installed within a building, such as a warehouse or garage, or positioned at the entrance of a structure, a steady power supply is typically readily available. However, the challenge arises when deploying stationary RFID readers in outdoor environments, where providing a consistent power source becomes a critical factor.

In such outdoor settings, devising a sustainable power solution for stationary RFID readers is essential for uninterrupted operation. One compelling option is harnessing solar energy through the utilization of solar panels. When considering the implementation of solar panels, several key factors come into play, demanding careful consideration:

Solar Panel Size: The size of the solar panel must align with the power requirements of the stationary RFID reader. Larger panels can capture more sunlight and generate more energy, but they also occupy more space and can be less practical in certain installations. Finding the right balance between size and power output is crucial.

Efficiency: The efficiency of the solar panel refers to its ability to convert sunlight into electricity. Higher efficiency panels are more effective at generating power from limited sunlight, which is especially important in areas with varying weather conditions. Opting for efficient solar panels maximizes energy production.

Sunlight Conditions: Assessing the sunlight conditions is fundamental. Factors like the average daily sunlight hours, seasonal variations, and potential obstructions (e.g., snow) must be carefully evaluated.

Energy Storage: The integration of an energy storage system, notably utilizing batteries, becomes imperative to store excess energy generated during sunlit periods, subsequently ensuring uninterrupted operation during cloudy days or nighttime. When selecting batteries, careful consideration must be given to both their capacity and type to adeptly fulfill the power requirements of the RFID reader. In addition to these considerations, one must account for the unique challenge posed by Vermont's cold winters. The frigid temperatures prevalent during this season have a notable impact on battery capacity and overall usability. Therefore, opting for rechargeable batteries equipped with a self-heating function becomes essential to mitigate the adverse effects of low temperatures, guaranteeing the longevity and reliability of the RFID system in the region's harsh winter conditions.

- **Wireless Communication**

In order to facilitate effective communication between the RFID readers and the remote database server, it is paramount to maintain a consistently strong and reliable wireless connection. There are several methods that can be implmeneted to leverage wifi signal quality and coverage, and maintain data synchronization between RFID readers and the remote database.

- Wifi extender or mesh network: In the pursuit of expanding the Wi-Fi network coverage and enhancing signal strength, there are two viable approaches. Firstly, deploying a Wi-Fi extender is a cost-effective solution. It offers immediate and efficient coverage extension. Secondly, to obtain broader and more robust coverage, the implementation of a mesh network, featuring multiple strategically placed Wi-Fi nodes, provide a scalable and comprehensive solution.
- 4G or 5G network: For the handheld reader, if wifi signal is not available, when a Wi-Fi signal is not accessible, it possesses the capability to establish connectivity with the remote database via either a dedicated 4G or 5G hotspot device or through a hotspot generated by a 4G or 5G cell phone. This versatile feature significantly extends the operational range of the handheld reader, even when operating in remote or geographically challenging areas.
- Local database: In areas devoid of Wi-Fi, 4G/5G, or any other communication signals, a viable solution is to maintain a local database copy on a computer or smartphone, which can be connected to the handheld reader. This setup enables the scanning operation to continue seamlessly using the local database. Subsequently, when communication signals become accessible, an automatic synchronization process will initiate, bridging the data gap between the local database and the remote database hosted on the server.

- **RFID Security**

RFID tag security involves tag locking through the utilization of the access password and kill password so that the operations on memory are restricted. It should be clarified that setting a non-zero access password does mean the RFID tags become locked and no memory sections are accessible, i.e., readable, or writable. Here we will clarify RFID authentication operations for a focus on explaining access password functions, as the kill password serves to dispose RFID tags which is not commonly used.

As introduced in Deliverable 1, RFID tag has four types of memory bank:

- Reserve memory bank: storing access password and kill password.
- EPC memory: stores the Electronic Product Code (EPC). It allows the unique identification of items to which the RFID tag is attached to.
- TID memory: to store the unique tag ID number by the manufacturer when the IC is manufactured.
- User memory: It can store user defined data.

An RFID chip implements a set of LOCK Action bits for every memory bank. Each memory bank's Lock status is described by two bits. One for the pwd-write (or pwd-read/write) and a second one for permalock. Using EPC memory bank as the example, if locked (using a non-zero access password) or if permalocked, you can read it but cannot write it. Depending on the value of these two bits, it sets the following functions [14]:

	Pwd-write=0	**Pwd-write=1**
Permalock=0	You can read and write the EPC memory and you can change the protection status. This is not recommended.	You can read the EPC memory but in order to write it you must know the access password[1]. This means that the EPC memory is password write protected[2]. You can also change the protection status. This is the preferred way to reversibly lock the EPC memory.
Permalock=1	Under this condition the EPC memory will be always writeable (and readable) and this status cannot ever be changed. There is no way to write-protect the EPC memory.	You can read the EPC memory, but you can never write it whatever the state. You will never be able to change the protection status. This is the preferred way to permalock the EPC memory.

https://www.gs1us.org/content/dam/gs1us/documents/industries-insights/by-industry/apparel-general-merchandise/guideline-toolkit/GS1-US-EPC-Write-Protection-Recommendation.pdf

Note: The reserved memory bank, which encompasses access and kill passwords, can be locked for both writing and reading purposes. In contrast, all other memory banks, including EPC, TID, and User, are only capable of being write-locked. It's worth noting that, as a standard practice, the Tag Identification (TID) memory bank is typically permanently locked during the manufacturing process [13].

During the routine scanning process, RFID readers emit power signals to activate the RFID tag and retrieve its EPC code. If the EPC code is accurately defined in accordance with the application protocol, the reader will acknowledge it, granting access to the associated database. In the event of an incorrect or non-conforming EPC code, the reader will simply disregard the tag. The verification of access passwords is exclusively employed during write operations, particularly when there is a requirement to modify the EPC or User memory banks. In standard read operations, the examination of access passwords is omitted, and as a result, it does not impact the performance of the read operation.

- **RFID Devices Considerations**

- RFID Tag Types: When dealing with higher-cost, robust RFID tags, it's crucial to consider their suitability for affixing to large equipment or valuable assets exposed to challenging environmental conditions. These tags are designed to withstand harsh outdoor elements, such as extreme temperatures, moisture, and physical impacts, making them suitable for applications like tracking trucks, signage boards, cranes or other large asset items. Moreover, large equipment and valuable assets are frequently not conveniently accessible for short-range scanning. Utilizing larger tags that facilitate longer-distance scanning confers significant advantages in such scenarios. For low cost and small tags, they can be used on small asset items, such as tools, computers, etc.

- Mounting Considerations: Affixing robust RFID tags to these assets may require specialized mounting techniques, such as bolting, or adhesive bonding, depending on the asset's material and design. For low cost tags, there are many different packaging types, such as wire tags, wet inlay tags, hang tags, etc. The choice of mounting method should be carefully evaluated to ensure the tag remains securely attached over the asset's lifecycle.
- Indoor Assets: Conversely, assets predominantly stored indoors, such as small tools or computers, can benefit from the use of inexpensive, compact RFID tags and readers. These tags are cost-effective and space-efficient, making them suitable for tracking smaller items without significantly increasing operational expenses.
- Tag Size and Form Factor: Compact RFID tags are typically smaller and more discreet, making them easy to attach to smaller assets. Their form factors, such as adhesive labels or embeddable chips, enable straightforward mounting options, reducing installation complexity.
- Reader Infrastructure: Deploying RFID readers for indoor asset tracking is relatively straightforward due to the controlled environment. Inexpensive RFID readers can be strategically placed within indoor facilities to ensure comprehensive coverage. In addition, handheld RFID reader provides flexibility for operators to scan asset items located at different places. For the more expensive stationary RFID readers, they have stronger radiation power for longer distance scanning, they can be placed at the entrance of the garage to monitor objects of relatively far distance, 10~ 30 feet. Multiple antennas might be needed to increase scanning coverage.
- Cost-Effectiveness: The choice between robust and inexpensive RFID tags should be based on a cost-benefit analysis. For high-value assets or those exposed to challenging conditions, investing in robust tags can provide long-term reliability and data integrity. In contrast, for smaller, indoor assets, cost-effective solutions can offer efficient tracking without incurring unnecessary expenses.
- Data Integration: Regardless of the RFID tag type chosen, integrating RFID data into an existing asset management or inventory system is essential.

- **Handheld RFID Reader**

The handheld RFID reader serves as a versatile tool in the realm of inventory management. Its primary function is to detect and catalog inventory items within its proximity, effectively streamlining the inventory checking process. This detection mechanism allows for the tagging and automated tracking of a diverse array of items, offering efficiency in managing stock and assets.

One of the notable advantages of the handheld RFID reader is its inherent scalability. Unlike stationary readers, which are typically fixed in place, the handheld scanner's portability liberates it from any physical constraints. Consequently, it can be effortlessly employed in various locations and scenarios, adapting seamlessly to the ever-changing inventory landscape. This adaptability makes it a suitable tool in diverse environments.

Scalability in the context of the handheld RFID reader extends not only to the number of items being tracked but also to the number of handheld readers employed. The key to achieving scalability lies in the system architecture. A well-structured system can effortlessly accommodate an expanding network of handheld readers, ensuring smooth and efficient operation for multi-site applications. In this regard, opting for a server-less (no application server located between the handheld reader and the database server) architecture is a more scalable approach. This architecture distributes the processing and data management responsibilities across the network of handheld readers, eliminating the bottleneck of a centralized server. As a result, the system can readily handle increased loads at different sites without compromising performance or responsiveness, making it a highly adaptable and scalable solution for inventory management.

One of the inherent limitations of the handheld RFID reader is its reliance on manual operation, rendering it less than ideal for applications necessitating automated scanning. This drawback becomes particularly evident in scenarios where the objective is to autonomously register asset items as they enter or exit a facility, a task that mandates seamless automation without human intervention. Therefore, integrating both handheld and stationary RFID readers can offer a more comprehensive solution to enhance the efficiency of the asset management system.

- **Mounting of RFID Reader and Tags**

When utilizing a handheld RFID reader, the positioning of the RFID tag is of minimal concern, as it is easily adjustable to accommodate various reader scanning positions and orientations. However, for stationary RFID readers, meticulous mounting becomes a crucial factor demanding careful consideration. The optimal placement for a stationary RFID reader is at the entrance gate or a strategic point that vehicles consistently pass through when entering or exiting the garage. In general, installing the reader at the midpoint of the overhead entrance gate can provide optimal alignment for scanning the RFID tag inside the vehicle. The stationary RFID reader can be equipped with two antennas: one directed outward towards the gate and another oriented inward, allowing for scanning vehicles moving in different directions. In cases where overhead mounting is not practical, the stationary reader and antennas can be installed on one side or both sides of the garage door. It is essential to meticulously adjust the angles of the antennas to effectively cover the area where the truck moves.

When considering the placement of RFID tags in vehicles, there are two viable options. The first is to position a single tag at the center inside the front windshield, adhered to the glass surface. Alternatively, we can opt to use two tags, with one affixed to each side of the vehicle. Employing two tags in this manner simplifies the scanning process, particularly for the readers located on the sides of the garage gate.

- **Multisite Deployment**

Deploying RFID for asset management across multiple sites involves a range of considerations beyond equipment duplication and database connections. Here are some additional factors that should be carefully considered:

- Site-Specific Needs: Each site may have unique requirements and challenges. Conduct a thorough assessment of each location to understand its specific needs and constraints, such as environmental conditions, layout, and access points.
- RFID Tag Selection: Choose RFID tags that are suitable for the assets and environment at each site. Consider factors like tag durability, attachment methods, and whether active or passive tags are more appropriate.
- Data Standardization: Ensure consistent data standards and naming conventions across all sites to maintain data integrity and facilitate centralized management.
- Integration with Existing Systems: Evaluate the integration requirements with existing systems like asset management software, security systems, and other databases. Seamless integration is essential for efficient operations.
- RFID Reader Placement: Optimize the placement of RFID readers and antennas for each site's layout to ensure comprehensive coverage and minimize blind spots.
- Power Supply and Backup: Ensure reliable power sources and consider backup power solutions like uninterruptible power supplies (UPS) to prevent system downtime during power outages.
- Communication Network: Implement robust network connections to ensure continuous data communication and develop local database backup in the event of network failures.
- User Training: Provide comprehensive training to staff at each site to ensure they understand how to use the RFID system effectively and follow best practices.
- Security: Implement robust security measures to protect the RFID system against unauthorized access, data breaches, and cyber threats.
- Maintenance and Support: Establish a maintenance and support plan for each site, including regular equipment checks, software updates, and a process for reporting and addressing issues promptly.
- Cost Analysis: Conduct a thorough cost-benefit analysis to evaluate the financial feasibility of deploying the RFID system across multiple sites. Consider not only initial deployment costs but also ongoing operational expenses.
- Project Management: Assign a dedicated project manager or team to oversee the deployment at each site and ensure that timelines and objectives are met.

Deliverable 11: Technology transfer documents.

The project report package includes the consolidation of all developed software programs. Additionally, the package encompasses a comprehensive user manual, providing VTrans personnel with clear and detailed instructions for effective system utilization.

Conclusions

The potential benefits of RFID technology are indeed highly promising for the creation of an automated system catering to transportation maintenance operations and asset management. Our comprehensive study has meticulously assessed and substantiated the technology's efficacy in real-time tracking of asset movements and concurrent recording of diverse attributes. Through the strategic amalgamation of varying RFID tag types and readers—ranging from fixed, handheld, to vehicle-mounted—our study facilitates the execution of both extensive range and short-distance scans, whether in indoor or outdoor environments, stationary or in motion. This adaptability holds immense potential in significantly enhancing transportation maintenance operations and elevating asset management practices.

Additionally, our investigation has unveiled a series of pivotal considerations imperative for the seamless deployment of this technology. Factors encompassing system architecture, cost efficiency, reliable power supply, and communication network availability warrant meticulous attention. Despite the complexity posed by these challenges, it is essential to emphasize that our team perceives the technology as being mature and poised for practical application. These challenges, while noteworthy, are not insurmountable barriers that impede the actual deployment of the technology. On the contrary, they present opportunities for strategic solutions and innovative adaptations that can facilitate its effective implementation in real-world scenarios.

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