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Top-level smart city traffic management system with radio frequency identification – based road event detection

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ABSTRACT

Smart cities are transforming urban environments by integrating advanced technologies to optimize infrastructure, mobility, and public services. A key part of this transformation is the rise of semi and fully autonomous vehicles, which require seamless interaction with smart city systems to ensure safe, efficient, and adaptive transportation networks. These vehicles must be able to respond not only to static road features, but also to dynamic events that occur in real time. To address this challenge, an RFID-based system was developed that enables real-time information exchange between vehicles and a centralized smart city management platform. Through this communication, vehicles are able to receive timely updates about road conditions, hazards, and regulatory changes, allowing them to adapt dynamically to the evolving traffic environment. To validate the system's effectiveness, a mock-up smart city environment was constructed, replicating common urban traffic scenarios. Various road events, including construction zones, reduced speed areas, intersections, and other critical conditions, were simulated across the layout. RFID transponders embedded within the infrastructure continuously transmit event-specific data to RFID readers installed in vehicles. This system ensures that vehicles are consistently aware of their surroundings beyond what onboard sensors can detect, enhancing overall safety, traffic flow, and the integration of autonomous mobility into future smart cities.

Keywords: RFID, traffic management, dynamic identification, smart city.

INTRODUCTION

Object identification plays a key role in today's world, affecting many aspects of everyday life. Its importance is particularly noticeable in many sectors of the economy, such as industry, wholesale and retail, agriculture, transportation, and even healthcare. In the industrial sector it's fundamental for logistics, such as warehouse services, where it can be combined with machine learning to enhance inventory management [1]. Another way that object identification improves the efficiency of the industry is its broad use in Industry 4.0, where it plays an important role in tool, component, and semifinished product identification [2]. In wholesale and retail, both in the traditional and online formats, product identification enables rapid checkout scanning, facilitates inventory management, and supports the return handling processes [3]. The agriculture sector uses object identification to enhance operational efficiency and resource management by enabling accurate tracking of equipment, livestock, crop yields, and even pest control [4]. Object identification supports data-driven decision-making, improves traceability, and facilitates automation of tasks such as irrigation, and harvesting, thereby promoting productivity and sustainability [5]. Transportation can be divided into freight and passenger services, and while this distinction is important, both branches require identification for effective transport space management, tracking, and transit time estimation [6]. Similar to transportation, healthcare requires two systems. One that identifies people for the purpose of monitoring their health with the goal of proactive medical interventions [7]. And another that identifies items, such as medicine, test samples, etc. improving traceability, financial control, and inventory control [8].

Another important topic plaguing modern society is effective city management. As the global population becomes increasingly urbanized, the number of people living in cities continues to grow steadily [9]. This rapid urban expansion poses numerous challenges for local governments and city planners. One of the most pressing issues resulting from urbanization is the rise in traffic congestion [10]. With more vehicles on the road and limited space for infrastructure expansion, cities often struggle to maintain smooth traffic flow. Another major concern is the environmental pollution that tends to concentrate in urban areas due to industrial activities, transportation emissions, and high population density [11]. In response to these and other complex urban challenges, the concept of a Smart City has emerged as a promising solution. This concept emphasizes the integration of technology and data-driven approaches to enhance urban life and city operations. In urban traffic management, identification plays a key role that spans perception on the vehicle, connectivity with the infrastructure. Identifications based on computer vision or LiDAR quickly degrade under occlusion and adverse weather, which motivates complementary vehicle-to-infrastructure (V2I/V2X) communication [12]. Recent ITS/V2X surveys emphasize that such cooperative cues reduce latency and improve network-wide responsiveness, especially when underpinned by 5G/C-V2X [13].

The purpose of the article is to present the design, implementation, and evaluation of a proof of concept RFID-based traffic management system intended for integration within smart city environments. The system aims to enhance the responsiveness and safety of autonomous and semi-autonomous vehicles by enabling real-time communication between vehicles and road infrastructure. To support this, a physical smart city mock-up was built, measuring six by five meters, as a modular, scaled-down urban environment equipped with various traffic scenarios, including intersections, roundabouts, pedestrian crossings, and restricted zones. What makes this an innovative approach is the use of passive RFID transponders embedded in the road surface, deployed in arrays of 2–3 tags. This setup increases the probability of successful data capture by replicating information across multiple points within the infrastructure, even if the data is limited to a simple UID, the unique serial number of an RFID transponder. As a result, system resilience and reliability are enhanced, particularly under variable environmental conditions. Passive transponders were chosen for two primary reasons. Firstly, the lack of a power supply makes them much more reliable and easier to maintain, mainly by avoiding the necessity of keeping track of the batteries charge and life. Additionally, they are much easier to implement in the infrastructure, again thanks to the fact that they work without a power supply.

To simulate vehicle behaviour and interactions between it and road events, model cars were outfitted with RFID readers. Said events are managed with a unified method, which allows for modification and addition of situations that can happen on a road. Two primary tests were conducted to evaluate system performance: one measured the maximum height at which RFID transponders could be reliably read, and the other assessed the maximum relative speed between the reader and tag that still permitted successful data transmission. Both tests used a controlled experimental setup with repeated measurements to ensure consistent, reliable results and account for mechanical or electromagnetic interference. The novelty of this work lies in combining passive RFID transponder arrays with a modular smart city mock-up, enabling reproducible evaluation of event detection scenarios while maintaining a low-cost, maintenance-free design.

Related work

Currently, identification processes are most commonly carried out using contactless systems, which do not require physical interaction between the device and the object to be identified. Such solutions include graphic code reading techniques, such as barcodes and QR codes, as well as RFID (radio frequency identification) technology. Barcodes are commonly used in retail, logistics, and manufacturing. They hold a small amount of information but are easy to generate and scan. QR codes can store larger amounts of information and are often used in marketing, product identification, and mobile payments. RFID systems are used in automated processes in various sectors. Ongoing research focuses, among others, on Internet of Things (IoT) devices [14]. IoT refers to a network of interconnected physical devices embedded with sensors, software, and other technologies that collect and exchange data over the internet, with the unfortunate caveat of security challenges that come with that [15]. The application of RFID in industrial and manufacturing processes can include logistics of tools, components, and semifinished products in robotics [16]. An interesting and still new technology is additive manufacturing, also known as, 3D-printed, even here RFID found its uses as a measure of quality control [17].

One of the foundational technologies behind Smart Cities is the Internet of Things (IoT), which connects physical devices – such as traffic sensors, public utilities, and vehicles – to the internet, allowing them to communicate and operate intelligently [18]. Building upon this, the Internet of Everything (IoE) extends the connectivity of IoT by bringing together people, processes, data, and things in a cohesive digital environment. This enables smarter decision-making and more personalized services for citizens [19]. Alongside IoT and IoE, Smart Cities also make use of a wide range of other cutting-edge IT technologies, including artificial intelligence, big data analytics, and cloud computing, to improve the efficiency and quality of urban services. To support these interconnected technologies, Smart Cities require robust communication infrastructure. One of the most critical enablers of this infrastructure is the fifth-generation cellular network, commonly known as 5G. This network offers high-speed, low-latency connectivity that allows for real-time data exchange and rapid responsiveness across smart systems [20]. Among the many areas of urban life improved by Smart City technologies, traffic management stands out as a particularly impactful application. Advanced traffic control systems use various identification tools, such as vehicle recognition and GPS tracking, to monitor traffic patterns in real time [21]. These systems are often enhanced by intelligent algorithms that analyse traffic data and make automatic adjustments to reduce congestion and improve traffic flow efficiency [22].

There isn't a great deal of up-to-date research that combines RFID and smart city traffic management. From the existing research, three approaches can be gleaned. The first one places RFID transponders in the signs, traffic lights, and other elements of the road infrastructure [23]. Systems that use road signs as the medium of RFID tags have many advantages, for example, ease of maintenance and upgradability [24]. They do, however, suffer from two major flaws. The detection range for passive transponders is relatively short, as proven in our tests. More importantly, there is only one chance for the vehicle to scan a transponder placed on the sign, unless it is a repeating one, such as railway crossing signs. The second method places RFID transponders on the vehicles and readers on elements of infrastructure, such as signs or traffic lights. This solution is widely used in automatic bar gates that control access to car parks or private driveways [25]. The idea is to use the tried and tested method and build it up for use in, for example, traffic light priority control [26]. The main drawback of this setup is the need to power RFID readers, which limits the places where it can be used. The final approach embeds transponders in the road surface [27]. This synergizes well with short-range RFID data transfer but suffers from high maintenance expenses, as tags can't be simply replaced. Simply put, the pros and cons of the two methods are reversed. The innovative approach proposed in this paper is the use of arrays of tags that hold the same information, which increases the chance of successful data transfer.

THE USE OF RFID IN TOP-LEVEL VEHICLE CONTROL

There is broad recognition of the advantages that RFID technology offers in everyday life. At its current stage of development, RFID is employed in a wide range of tasks associated with retail, goods production, quality control, and item tracking.

A standard RFID system comprises a read/write device (RWD) featuring at least one antenna, alongside at least one identifier equipped with an antenna circuit and microprocessor (Figure 1). The identifier typically stores its unique serial number and additional information about the associated object within its integrated memory. The RWD retrieves this information by reading the identifier's memory and subsequently transmitting the data to host hardware and software systems. In addition, the RWD may also possess the capability to write data to the identifier's memory, thereby allowing for updates to be made at various stages of the object's life cycle. For the purposes of this study, the term "reader" will denote a device capable of both reading from and writing to an RFID identifier.

The most commonly used RFID transponder, referred to as a passive transponder, consists solely of a chip with an antenna circuit. These tags incorporate an energy harvesting mechanism that enables the chip to draw power from ambient sources, thereby extending the operational range for data exchange. The RWD is essential for accessing the stored data. Semi-passive RFID transponders are equipped with an external battery that extends the interrogation zone in which tags can be read, and can be used for additional autonomous functional blocks such as measurement of physical quantities (e.g., humidity, temperature, light intensity, pressure, acceleration, gas, etc.), storage of collected data in memory, and monitoring of activity and power distribution. For the purposes of this study, passive transponders were exclusively used.

Because RWD require a power source, they were mounted on vehicle models, that were used to simulate the behaviour of cars. Passive transponders were chosen to simulate real-world applications where constant battery maintenance is infeasible at city scale where hundreds of thousands of identifiers might be deployed. Semi-passive and active RFID tags are indeed used in domains such as railway logistics [28], but their reliance on regular servicing limits their applicability for city wide embedded road infrastructure.

A conceptual diagram of the RFID transponder reading functionality, implemented within the car model, is shown in Figure 2. An RFID reader mounted in a car model constantly attempts to read RFID tags placed in the road. When it encounters a tag, its ID is read. If the reading is unsuccessful, the vehicle enters alert mode, that slows it down and sends a message

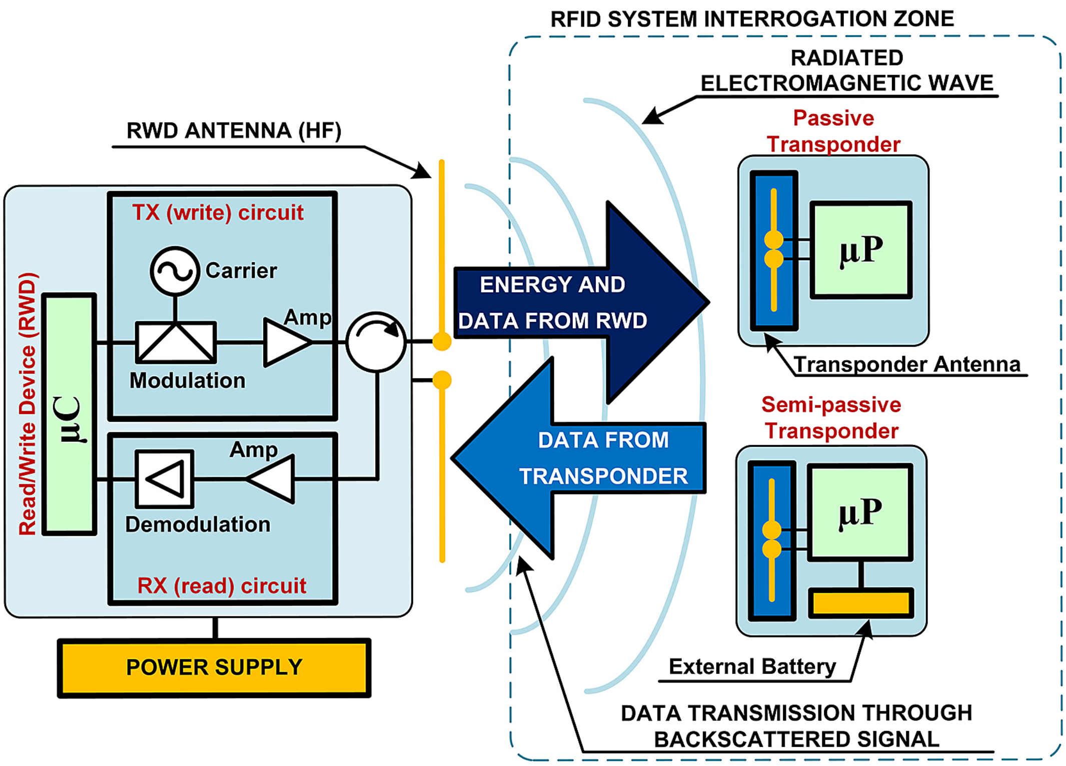

Figure 1. General diagram of an RFID system

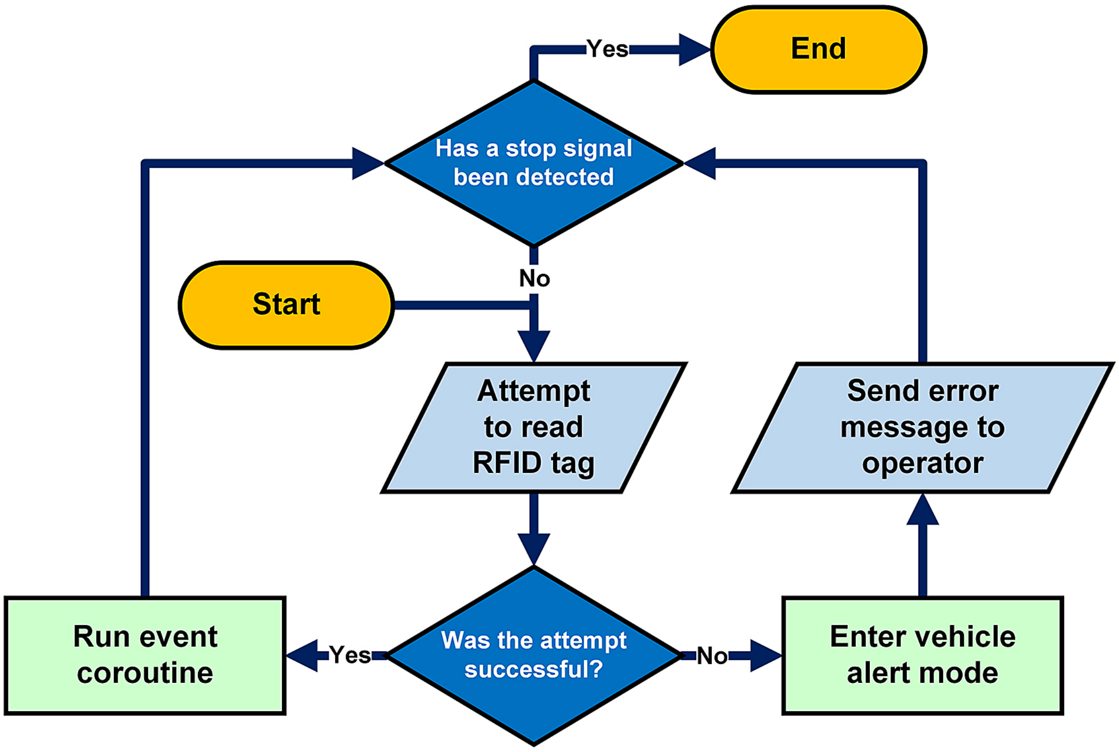

Figure 2. Car RFID handling flowchart

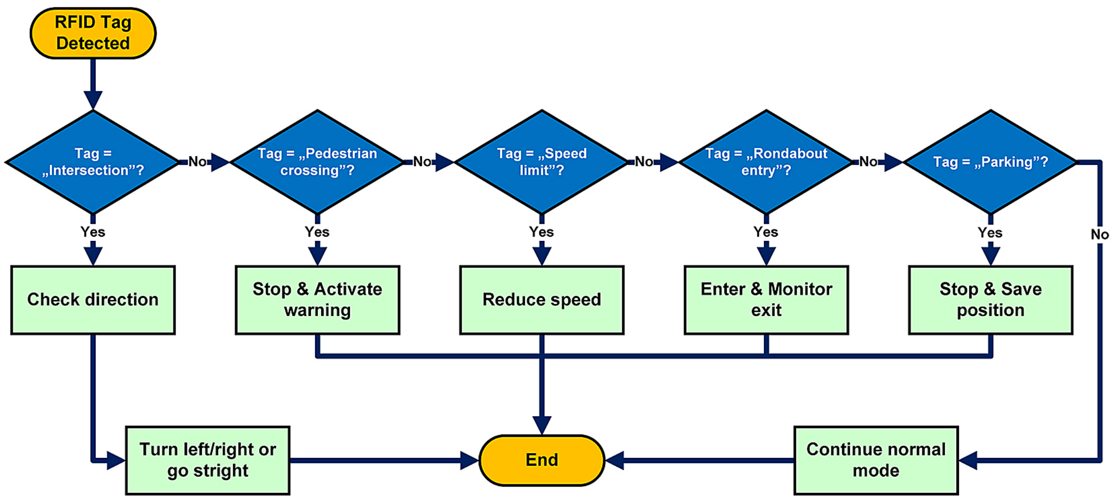

Figure 3. Event handling coroutine

to the operator. If the attempt succeeds, an Event coroutine is called with the tag ID as a parameter.

As shown in Figure 3, depending on the predefined tag ID ranges, the car responds in one of several predefined ways, such as speed regulation, lane changes, or manoeuvre execution. This structure formalizes the manner in which RFID input influences onboard behaviour and complements perception-based autonomy. All events are presented in the Tag Classification and Event Triggers section.

Construction of the Smart city mock-up and Implementation of RFID-based road event detection

To evaluate the functionality of a high-level traffic management system employing RFID-based road event detection, a physical test bed was developed in the form of a modular smart city model. This setup was intended to facilitate experimentation with real-time interactions between vehicles and events within a controlled urban simulation. The mock-up, designed as a scaled representation of an urban environment, measures six by five meters and is presented in Figure 4 below.

RFID-Based Infrastructure

As previously noted, passive RFID transponders were embedded in the road surface at strategically selected locations. These transponders encode contextual traffic data and are read by RFID readers mounted on vehicles. Tag placement is determined according to the specific type of road event being monitored. A standardized three-tag sequence, comprising early warning, decision trigger, and confirmation tags, ensures robust event detection across a range of vehicle speeds. Placement strategies are outlined in Figure 5, which illustrates tag positioning patterns for intersections, pedestrian crossings, roundabouts, speed zones, parking areas, and temporary detours.

Figure 6 shows a section of the smart city map with transponders marked using red circles. All RFID tags were placed in accordance with the rules presented in Figure 5. As mentioned previously, most transponders are placed in groups of threes. The exception to this rule are parking transponders, which are in a groups of two.

Tag classification and event triggers

A total of 167 RFID tags were placed throughout the mock-up, with each tag type corresponding to specific traffic scenarios and associated behaviour, as detailed in Table 1. Overall, eight different traffic situation categories are simulated, with general warning being the most numerous. Pedestrian crossings, speed limit zones, change in traffic organization and public transport stops were combined as part of the general warning category. Intersections were divided into triple and quadruple types. Similarly, roundabouts were also divided. Additional straight road and curve categories were created.

Simulated traffic scenarios

A series of typical traffic events were simulated on the constructed smart city model. The scenarios were selected based on their considerable influence on the flow and safety of urban traffic. Key events included:

1. Restricted traffic zones / roadwork areas – in these zones, dedicated RFID tags signal for approaching vehicles to reduce their speed to a predefined limit (e.g., 30 km/h). Upon exiting the zone, the system restores the previously applicable speed limit.
2. Intersections and roundabouts – RFID-based vehicle detection at intersections and roundabouts enabled the simulation of scenarios requiring traffic coordination, such as adaptive traffic light phase changes in response to increased vehicle density or the signalling of potential collision risks.
3. Pedestrian crossings – pedestrian presence was simulated through the activation of specific

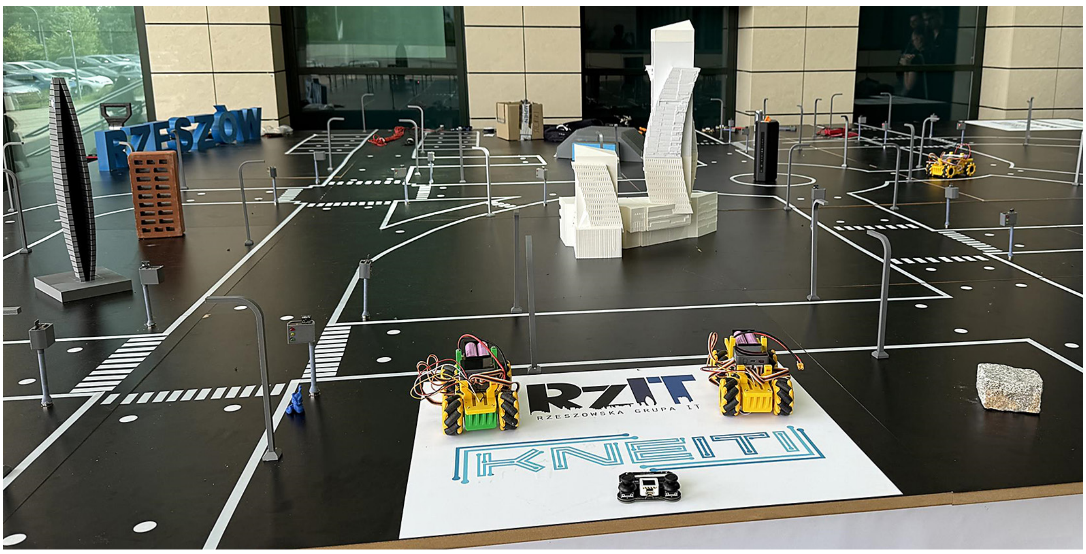

Figure 4. Smart city mock-up for event detection and traffic management

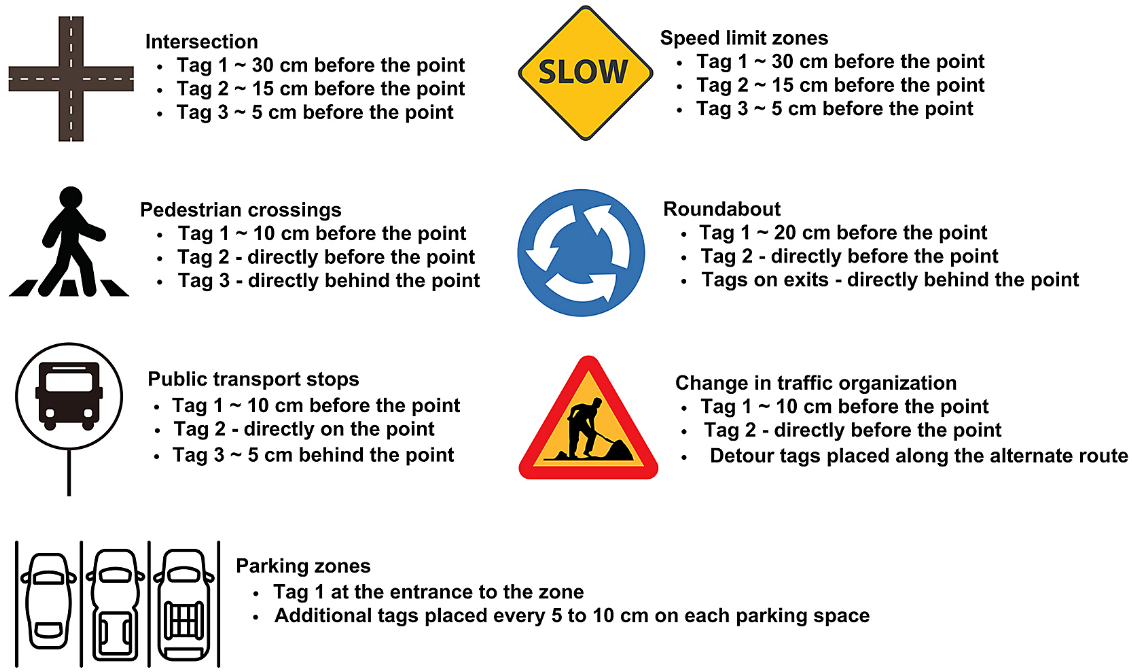

Figure 5. Transponder positioning strategy for various road event types

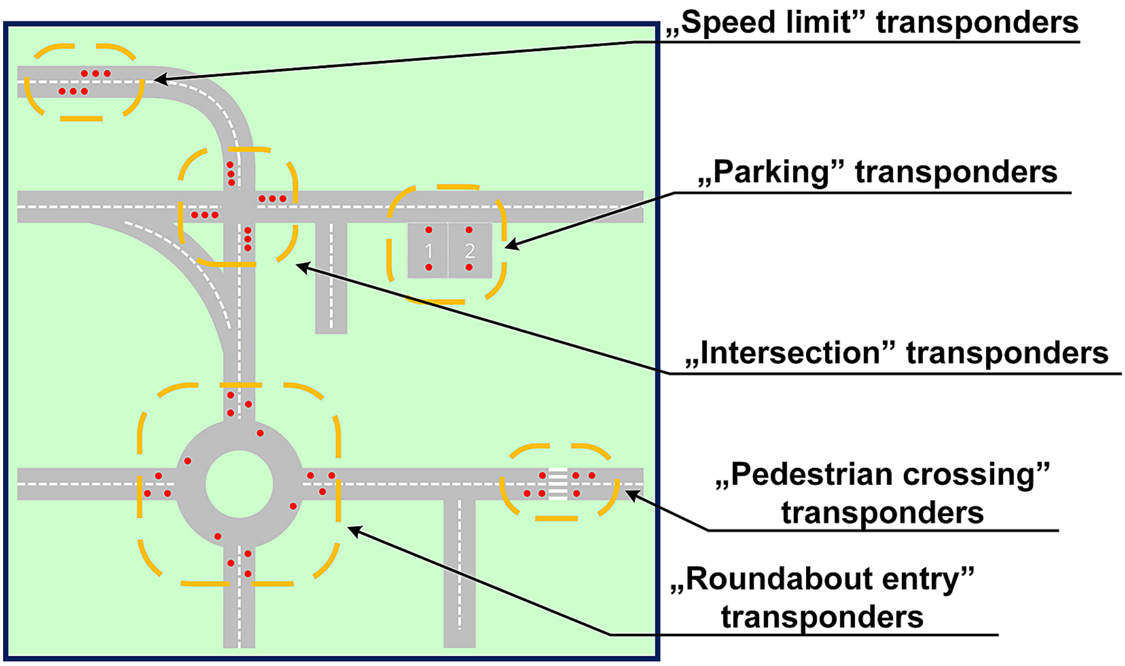

Figure 6. Fragment of smart city map with RFID transponders

RFID tags at designated crossing points. The system responds by alerting approaching vehicles to stop or substantially reduce speed to yield to pedestrians.
4. Traffic jams – sudden traffic congestion was simulated by obstructing traffic flow on selected sections. The system detected these disruptions via RFID tags and dynamically communicated the obstruction, along with potential alternative routes, to vehicles.
5. Emergency stops / damaged vehicles – the presence of immobilized or damaged vehicles was simulated in certain areas of the model. The system was designed to alert nearby vehicles immediately and recommend detours to ensure safety and traffic continuity.

Table 1. Classification of RFID tags and their corresponding triggered events

Traffic situation category	Hex code	Quantity	Triggered action
General warning	0000	60	Activate vehicle alert mode
Straight road	0001	45	Maintain speed and direction
Curve	0002	11	Reduce speed, initiate cornering mode
Triple intersection	0003–0006	21	Path decision (left, right, straight)
Quadruple intersection	0007–000A	12	Adjust based on right-of-way logic
Parking spots (1–10)	000B–0014	10	Stop vehicle, log position
Triple roundabout	0015–0018	4	Initiate rotation logic, check exits
Quadruple roundabout	0019–001C	4	Loop management, path correction

Test platform, measuring method and results

The key questions that had to be answered when evaluating the proposed system were the maximum speed and maximum height at which RFID tags can be read. To facilitate the answer to those questions, a test platform was constructed to allow controlled RFID transponder readouts at set velocities and heights. Figure 7 shows the test platform (a) and its functional diagram (b). Using a motor, RFID tags are spun under a reader. Said reader is attached to an arm that can be lowered or raised, through an interchangeable mount. For the purpose of this experiment, five RFID readers were used, shown in Table 2. All readers used in testing operated on the frequency of 13.56 MHz. PN532 and M5Stack use I2c as a communication interface, SPI522 uses SPI, RDM880C UART and Feig CPR74 uses USB.

The procedure for testing the maximum reading height has been designed to ensure reliable and repeatable results and is shown as a flowchart diagram in Figure 8. The measurement process begins by setting the reader at a distance of 4 mm from the rotating disc on which the RFID transponder is located. Ten attempts to read the stored data are made, successful ones are stored as 1, and unsuccessful ones as 0. When ten readings are completed, the distance between the reader and the transponder is increased by 2 mm and the readings are repeated. The test is finished when the series of measurements at the height of 50 mm is completed.

Table 2. Tested RFID readers

Name	Frequency [MHz]	Communication interface
PN532	13.56	I2C
SPI522	13.56	SPI
RDM880C	13.56	UART
M5Stack (WS1850S)	13.56	I2C
Feig CPR74	13.56	USB

Owing to the use of interchangeable mounts for RFID readers, multiple types of devices could be easily tested and compared. For the purpose of this study, five configurations were chosen, for each height, ten independent measurements were made, which allowed for elimination of the influence of temporary disturbances and random deviations resulting from various factors, such as temporary blockage of moving parts of the system or fluctuations in the electromagnetic field. The results of said measurements as a graph in Figure 9.

The conducted measurements demonstrated that the majority of the tested RFID readers achieved high identification efficiency for RFID transponders positioned at distances up to 20 mm from the reader. Within the range of 4 to 20 mm, none of the readers exhibited an identification efficiency below 80%, and half of the evaluated devices maintained performance levels close to 100%. Among all tested readers, the Feig reader showed the highest performance in terms of operational range, significantly outperforming the remaining devices. The CPR74 reader consistently achieved 100% identification efficiency throughout the 4 to 38 mm range. Only beyond a distance of 40 mm between the reader and the transponder did the identification performance begin to decline gradually.

The second critical experiment was conducted to ascertain the maximum relative velocity of the transponder and reader at which the system could accurately read data (Figure 10). The optimal reading distance of 10 mm that was previously established in the first test was used. Initially, the disc's rotational speed is set to 1 km/h. Just as

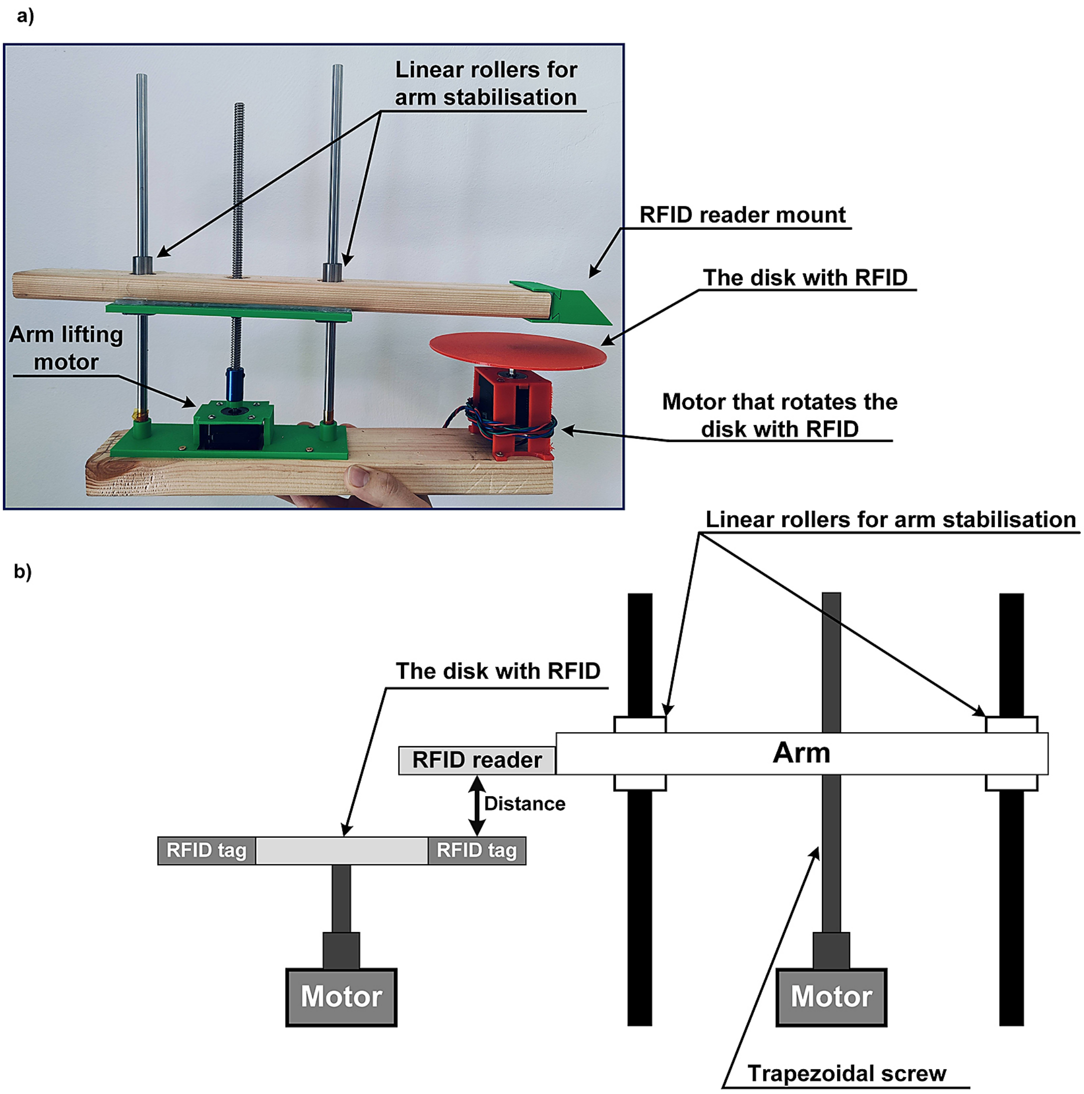

Figure 7. a) Test platform photo, b) Test platform diagram

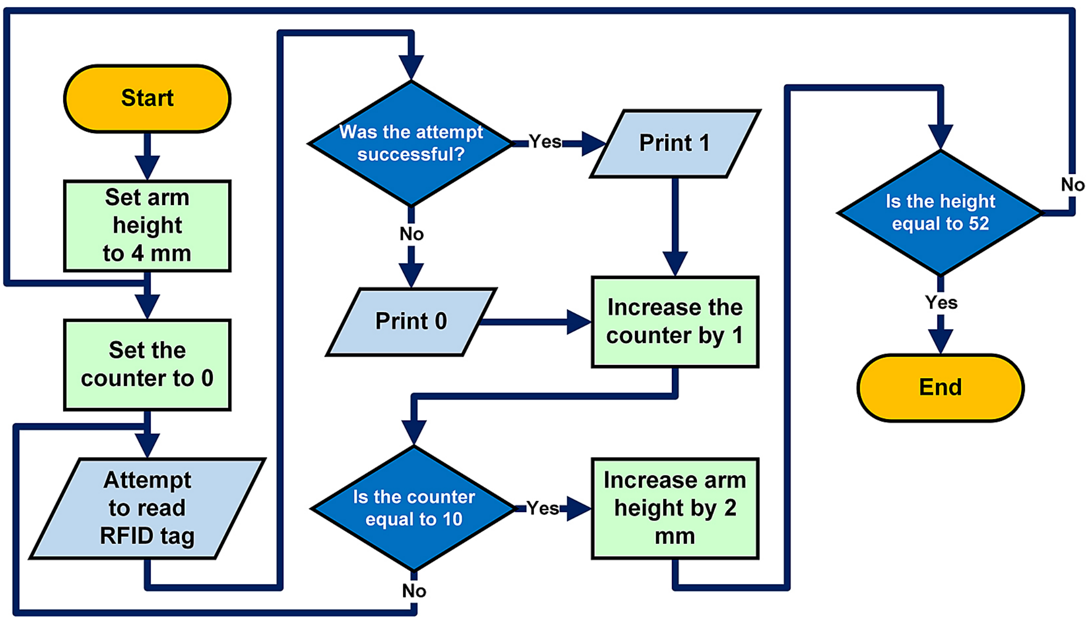

Figure 8. Maximum RFID transponder reading height test algorithm

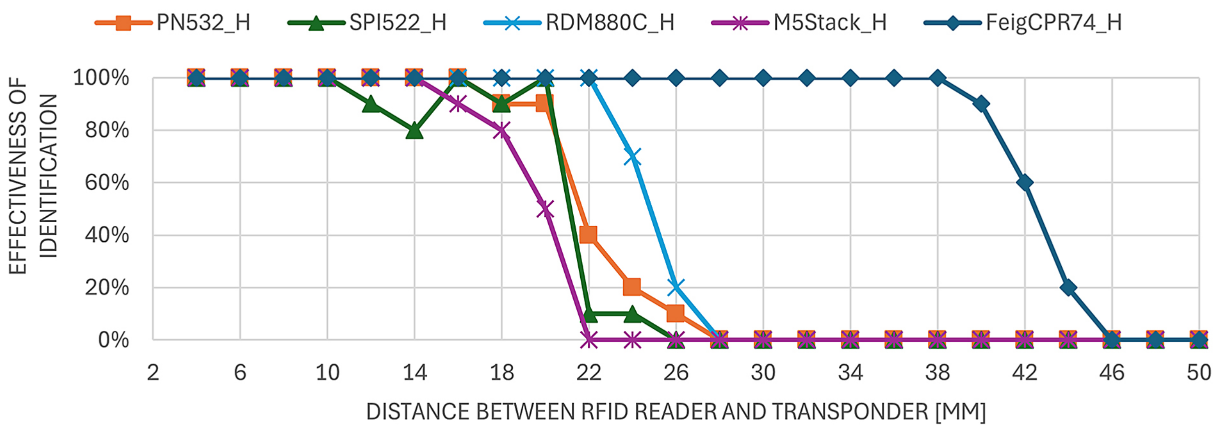

Figure 9. Readers height test measurements

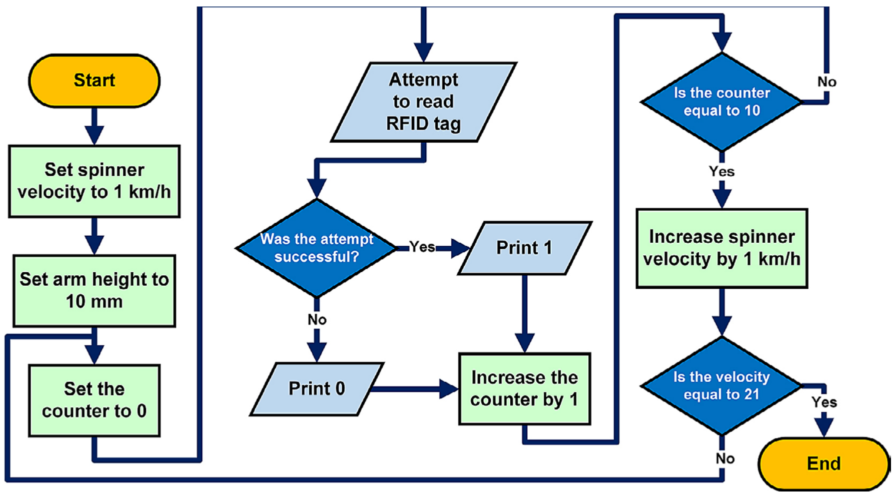

Figure 10. Maximum RFID transponder reading velocity test algorithm

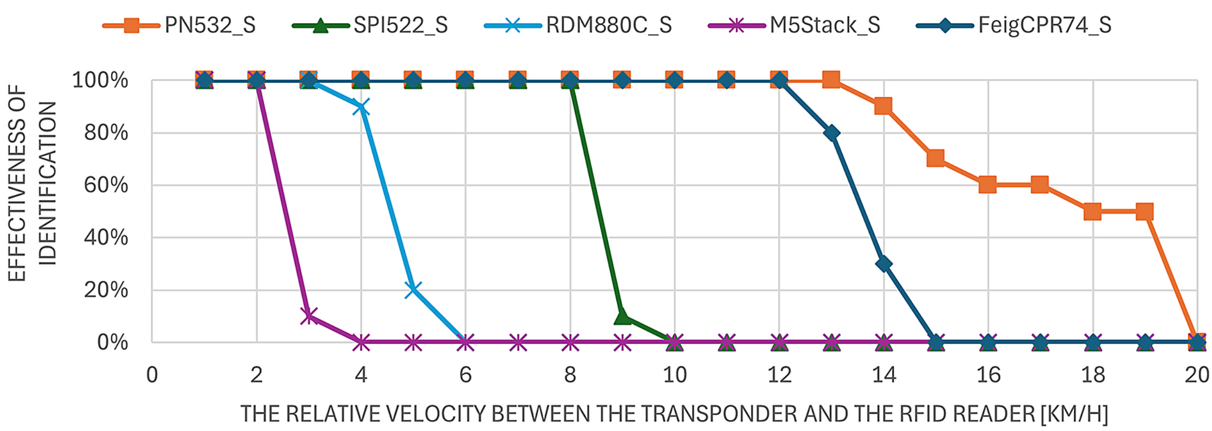

Figure 11. Readers velocity test measurements

with the first test, ten attempts to read the RFID tag are made. When the attempts are completed, either by failing or succeeding, the rotation speed of the spinner is incrementally increased by precisely 1 km/h. Before the next reading, the system allows the spinner to accelerate to the set velocity. Similarly to the first test, successful reading attempts are saved as 1, and unsuccessful ones as 0.

The second test was also conducted for five different RFID readers. Again, ten independent measurements for each set velocity were made, with the aim of removing random deviations. The results of the test are shown as a graph in Figure 11.

The identification efficiency measurements, conducted in the context of varying relative speeds between the reader and the transponder, clearly demonstrated how the readers responded to changes in speed. The M5Stack reader showed a decrease in efficiency at just 3 km/h, which is a relatively low speed. Similarly, the SPI 522 and RDM 880C readers exhibited 0% identification efficiency before reaching 10 km/h. The most resilient readers to the increase in relative speed between the reader and the transponder were the CPR74 and PN532, which maintained 100% identification efficiency up to 13 km/h. The PN532 reader, at speeds above 15 km/h, was still able to identify objects with low efficiency, while the Feig reader was unable to identify any objects.

It must be noted that the tests were conducted under controlled laboratory conditions. This ensured reproducibility but excluded external disturbances such as weather, tag wear, or urban electromagnetic noise. Future field trials are planned to address these factors and validate scalability in real traffic environments.

CONCLUSIONS

This paper demonstrates the potential of integrating RFID-based technology into smart city traffic management systems, aimed at enhancing the safety, efficiency, and adaptability of autonomous and semi-autonomous vehicles. The proposed proof-of-concept system allows real-time data exchange between vehicles and road infrastructure, enabling dynamic responses to road events such as traffic congestion, pedestrian crossings, and speed restrictions. The constructed smart city mock-up proved to be an effective testing environment, enabling the simulation of various traffic scenarios and providing valuable insights into the system's operational capabilities. Similarly to other research presented in the related works section, RFID was proven to be a viable choice for vehicle detection and management in smart cities. The transponder array used in the proposed system is an innovative setup compared to standard one tag systems, that allows for data redundancy and increases the success rate of data transfer.

The conducted measurements of RFID transponder identification efficiency, considering both distance and relative speed between the reader and the transponder, identified two top-performing readers. These are the Feig CPR74 reader and the more commonly used PN532 reader. Both devices demonstrated good parameters, both in terms of the effective identification range and their resistance to high relative speeds during reading. The PN532 reader showed better object detection at higher speeds; however, it only provided information about the detection of an object. In contrast, the CPR74 reader, under similar conditions, attempted to read all the data stored on the RFID transponder in addition to detecting the transponder itself. If the reading attempt failed, the reader immediately returned an error, resulting in the transponder no longer being detected within the reader's range. As a result, the identification efficiency for the Feig reader dropped to 0% for speeds above 15 km/h. In terms of the maximum distance between the RFID reader and the transponder that guarantees effective object identification, the CPR74 reader turned out to be the superior choice. This device outperforms the others, maintaining a 100% identification efficiency up to a distance of 40 mm, compared to a maximum of 20 mm for the other readers.

The unique contribution of this work lies in demonstrating that arrays of passive RFID transponders can be effectively embedded in road infrastructure to signal events in a low-cost and maintenance-free manner. While the system currently employs a deterministic architecture, it has been designed with scalability in mind, enabling future integration with machine learning, sensor fusion (GPS, V2X, cameras), and AI-based traffic optimization.

Further research will explore the scalability and real-life applicability of this system in larger urban environments and its integration with other technologies, such as 5G, IoE, sensor fusion, artificial intelligence and cloud computing for more comprehensive smart city solutions.

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