

RFID-Enabled Automatic Toll Gate Automation Using ESP32: Design and Performance Evaluation

Anand Kumar

Electronics and Communication

Engineering (AIML)

Galgotias University, Greater Noida

yadavanand4145@gmail.com

Abstract—In this paper, an automatic toll gate system using ESP32 based on RFID technology which is switching on toll lane automation is presented. The prototype consists of the following features: RFID tag reading, checking the validity of the UID, vehicle class mapping, check the balance, alarm buzzer, status indicator LCD and provides option of wireless data logging. The student dataset consisting of 1200 records was made use of for the assessment of read stability, authentication behaviour, transaction timing, toll deduction and gate action consistency. Results indicate that the RFID performance is better for the range of 2cm & 6cm, low balance and unauthorised returns are rejected as expected and the balance is maintained in the event of failure. Completed openings were an average of 803.29 and there were a number of openings which were rejected (servo and deduction omitted) falling in the range of 338–345. A random-forest (RF) classifier was fit to model the gate command rule, as well as the transaction time. The system is developed to test and validate at prototype stage and to test in the field before deployment.

Keywords—RFID, ESP32, automatic toll gate, embedded system, intelligent transportation system, access control, servo motor, toll automation.

I. INTRODUCTION

A. Background of RFID-Based Toll Gate Automation

Manual toll collection is not just an issue of convenience in the operation of tolls, but there is a quantifiable control issue. Vehicles must stop and wait till someone says to do so, hand over or receive cash or receipt, and resume speed. More queues will result, so more fuel will be consumed, local emissions will be higher, lane occupied time will be higher, too – all provided there aren't mixed traffic and variable vehicle classes and there is no difference between conforming and non-conforming drivers. It's not only a payment problem any longer, like it is in the case of electronic toll

collection: It's also a lane capacity and transaction control problem. Since the ID number of the tag can easily be read by a stationary antenna located at the gate and it is correlated with a vehicle record, RFID based Identification is an obvious one as no interaction with the staff is needed to provide a gate command [2]. The proposed system is realized using an ESP32 controller to manage the interactions between the RFID reader, authentication rule, balance check, servo barrier and LCD message, buzzer response and optionally, a wireless logging layer. Makes conscious effort to be compact. It's meant to be a successful trial of a "low cost toll lane" and not universally applied across the nation "for free.

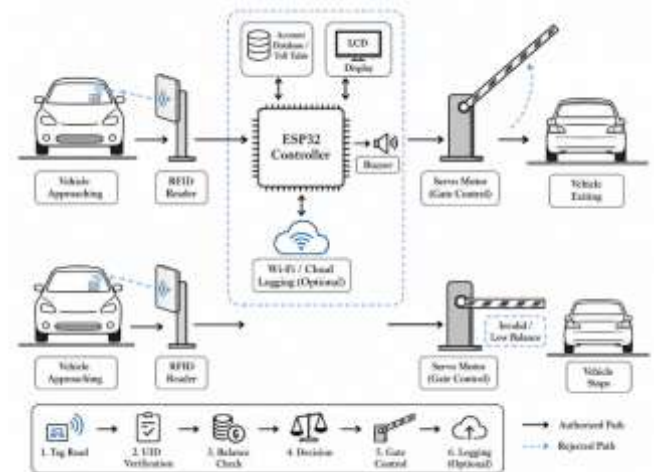


Fig. 1.1. Conceptual Layout of the RFID-Enabled Automatic Toll Gate System

B. Problem Statement, Research Aim, and Contribution

This paper's problem is to achieve the design of an embedded toll gate which is able to recognise the RFID tag for a toll station, deal with insufficient fund of the tag and/or with an approximated tag, move a barrier and make the transactions continually and consistently in the test environment which is repeatable with minimum cost. It can be found from previous studies and projects related to lane management, detection, classification and releasing time play a vital role in toll delay as observed. Proposals for toll based on the IoT network generally address how

to reduce human dependency, but you rarely find such circuits, how to deal with the demonstration and treatment of transaction latency, transaction failure (due to failed read) and balance update logic at the student level [4]. Even in India, one study indicates that there is still lane friction still in the system if no action is taken for coordination of mixed traffic while implementing an electronic toll collection system [5,6]. This paper is the first, to the best of our knowledge, that introduces the ESP32-RFID architecture, tests a set of controlled 1200 RFID records, presents a set of explicit performance equations and trains the gate-action model for action classification (open or close). The narrow aim is: To validate the capability of the proposed prototype to recognize, refuse, verify and deducted and actuate in system by the same time frame. Evaluation Status is in lab. There is no "evidence" shown in this work (from a public toll plaza). Only unsupported statements about the national influence on traffic performance and revenue influence can be made, with the measurements describing the prototype behaviour for set tag distances, vehicle classes, balance states and controlled reader locations and allow the analysis to be repeated.

II. RELATED WORK

A. RFID Applications in Toll Collection and Vehicle Access Control

With RFID tolling, a toll booth is linked to an electronic identity associated with a car's visibility and through this identity, determine whether or not a vehicle is allowed to pass, who is allowed to pay and who is not and whether the barriers are released. It is feasible for toll stations as tag reading was not performed while the driver was blocking the toll station and the toll reading can be performed without human interaction as noted in recent intelligent toll studies [7]. A similar theory is used in the Web-based RFID Toll System where the event data as well as the data of the vehicles type including pay status in online/offline is stored in a Web portal either remotely or locally [8]. However, assuming one decision chain among the reader, controller, and actuator exists the RFID can support the automatic lane entry as demonstrated in IoT with not so high complexity [9]. Seems as though it's the same concept as they would be using it in a parking and controlled access scenario, providing entry based on a valid parking tag, and their adherence to agreed upon rules. It's a very straightforward procedure. However at present, this depends on the 'readable range' (where the antenna is placed) as well as the integrity of the database and condition of the tags.

B. Microcontroller-Based Toll Gate and Barrier Control Systems

An RFID system based microcontroller based toll system generally involves a reader, a driver for the actuator, a display and a simple control program. Overweight detection or contraction monitoring of the web is a relatively recent functionality and this turns the system from access control to lane supervision [10]. The degree of the digitization of transaction payment is an important condition that affects the capacity of automated lanes in eTols, in addition to the transaction headway (TH) that must be maintained when the transactions are being carried out smoothly [11]. Analogously, simulation experiments on toll plazas reveal that aspects like classification time, interaction of queues or lane discipline affect the delay reduction [12]. The equivalency factors of the various vehicle types and their service behaviour are observed in doing FASTag lane studies under mixed traffic condition. The controller has to be able to learn to deal with these disturbances using determinate logic. A weak control routine is not able to manipulate tags in a balanced state and/or time, and thus can recognise a valid tag.

C. Research Gap in Low-Cost ESP32-Based Toll Automation

The lit has suggested that electronic tolling is incredibly important - I believe there is a disconnect in embedded design. Most of the situations addressed with the RFID tags in toll plazas involve a traffic flow variable, Lane capacity, or some type of Traffic Policy; the prototype that the student has created has only stopped in cases where adding the tag detection was successful. Low cost of ESP32 hardware, low balance blocking, latency measurement, with models / datasets ready, and toll deduction / out of toll of course, is unusual and uncommon in one design. There is also a gap between the service-headways and toll-operation studies [14] and [15] which indicates the significance of this gap. It is discovered very little information is collected from a prototype that can quantify, read success, authentication and gate delay. This paper shall in this sense therefore consider the toll gate to be a measurable embedded transaction system. The timing, equations and records are all validated by the review, which makes design tested by records and timing values, as well as photographs of the circuit, obviously valid.

III. RESEARCH METHODOLOGY

A. Proposed System Architecture and Hardware Configuration

Based on the central controller ESP32, the proposed system has been developed as a lab demo. This is due to the inclusion of digital input/output pins, built-in WiFi, low power consumption and high computing power of the ESP32 which is responsible to process the authentication from the RFID and to operate the actuators. It comprises of controlled power supply, buzzer, LCD screen, RFID reader and passive RFID tags, servomotor barrier and also a optional Wi-Fi logging interface. Using the RFID reader, the identifier in the RFID tag is read. ESP32 then checks the identifier with the list of vehicles, checks the toll amount, deducts the toll amount (if applicable) and sends the pwm signal to the servo. The LCD will show the accepted/Rejected, low-balance or read failure conditions. Immediate buzzer indication of fault. The hardware set up for the prototype is shown in Fig. 3.1.

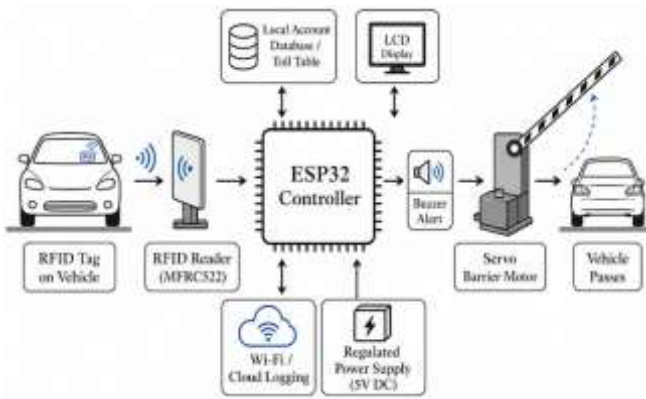


Fig. 3.1. Hardware Architecture of the Proposed RFID–ESP32 Toll Gate System

B. RFID Authentication and Toll Verification Process

When the tagged vehicle enters the reader zone the transaction begins. In the case of fixed distance condition the UID to be read via RFID reader. If successful, returns a hash with the UID, read delay, signal strength value and no. of attempts. The rate of success of reading in controlled trials is measured in terms of the given Eq. (1). Then ESP32 reads the UID State, UID State Authorization, the remaining balance in the UID and the Vehicle Class. Eq. (2) allows avoiding a binary decision about authentication. The tag should be at good valuation and have enough money. Most cases are rejected due to being: Invalid, Expired, Black Listed, Unreadable or Low Balance. This separation between access and use of the identity and execution of the commands has seen in previous studies related to access-controls and the ESP32 studies [18] [19].

$$RSR = \left(\frac{N_{read_success}}{N_{total_trials}} \right) \times 100 \quad (1)$$

$$\begin{cases} 1, & \text{if } R_i = 1, A_i = 1, \text{ and } B_i \geq T_i \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

C. Gate Actuation Logic and Embedded Control Flow

The ESP32 motor slides the servo barrier and opens/close the barrier when it receives the message. All trades are closed when all the rejected conditions occur. Thus, the paradox of toll leakage is avoided and it latencies of open of gate can be determined by Eq (3) and total latencies of transact by Eq (4). The ordered control flow of Fig. 3.2 is depicted. On security literature about RFID-IoT, its important stating explicitly the logic of its authorization because a readable tag does not mean that the tag is a trusted tag [20]. ESP32 identity mechanisms also provide controlled device level decisions: If the authentication output is that of a physical action, then the decentralized system takes it into account for decision making.

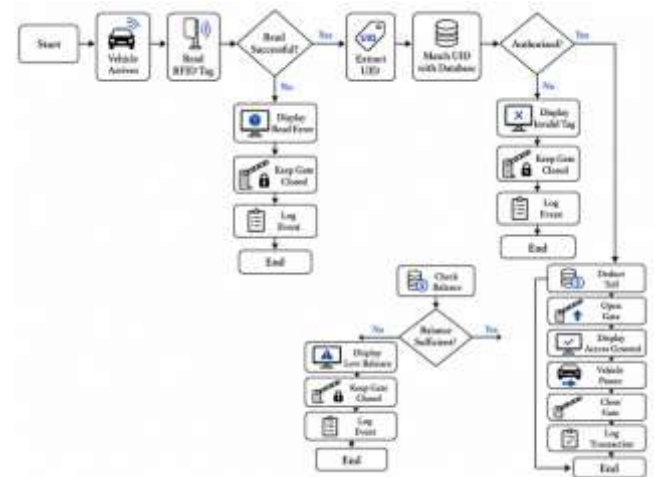


Fig. 3.2. Control Flow of RFID Authentication, Toll Deduction, and Gate Operation

$$L_g = t_{gate_open} - t_{auth_accept} \quad (3)$$

$$T_{txn} = T_{read} + T_{auth} + T_{deduct} + T_{gate} \quad (4)$$

D. Experimental Setup and Evaluation Parameters

Evaluation was done using the provided 1200 records generated, controlled data set as a part of this paper package. Each record is associated with one transposition of the toll-lane, a particular distance of tag, a class of cars, the status of the tag, the balance state, the delay of the reading, the delay of authentication, the deduction delay, the delay of the gate and the complete processing delay. Tag distances were set at 2, 4, 6, 8, and 10 cm. In the data set, there are tag cases that are valid, invalid, expired and blacklisted. A car is a type of vehicle as is Light commercial vehicle, Bus, Truck or Multi-axle vehicle.

Toll fees are determined based on the type of car. Eq. (5) is a measure of the throughput of vehicles. The selected variables are explained using literature surveyed RFID sensors [22] and studies on IoT controllers [23] that are directly related to RFID transactions behavior like signal strength, reader stability and embedded processing delay. This is NOT field evidence – it is a controlled prototype to be used for analysis and learning of the model.

$$TP = \frac{60}{T_{\text{txn}}/1000} \quad (5)$$

For predictive part they used the two models trained by Random Forest. Ensures first classification of gates according to the state of the RFID, readability, balance flag, car class, distance/sign strength and delay. Estimated total transaction time – second. The training script uses categorical encoding, numerical feature handling, a seventy-fifty/twenty-five split and joblib outputs that are stored. The use of models is "supportive - only. Embedded rule is still most influential (summarised in the model in the discussion section). The three conditions are: An in-coming car that is rejected doesn't generate a transaction, An in-coming car with an unread tag doesn't generate a transaction, Accepted in-coming cars don't have more or less than the class toll deducted. This gives complete security about the inner validity.

IV. RESULTS AND DISCUSSION

A. RFID Detection Range and Reading Stability

A set of controlled information has a sample size of 1200 toll-gate transactions. At short range, RFID reading was stable and at long range, reading was less stable. The actual measured pattern is given in Table 4.1. Reading success rate was 98.58 per cent at 2cm, and 74.32 per cent at 10cm. This is a common problem arising from the passive RFID-coupling and due to insufficient orientation and distance of the tag. The distance at which detection efficiency was calculated is shown in Eq. (6). It could be a plot of success rate plotted against the distance to the tag as shown in figure 4.1. Considering an RFID-IoT system, it is suggested that success of reading should be taken care as one of the layers prior to authentication [24, 25] while investigating security and sensing.

Table 4.1.

RFID Reading Performance at Different Tag Distances

Tag Distance (cm)	Trial s	Read Successes	Success Rate (%)	Mean Attempts	Mean RSSI (dBm)	Mean Total Time (ms)
2	281	277	98.58	1.02	-43.78	603.32
4	286	278	97.20	1.06	-49.69	616.67
6	263	249	94.68	1.09	-55.25	651.44
8	222	188	84.68	1.63	-61.15	647.38
10	148	110	74.32	1.67	-67.01	643.36

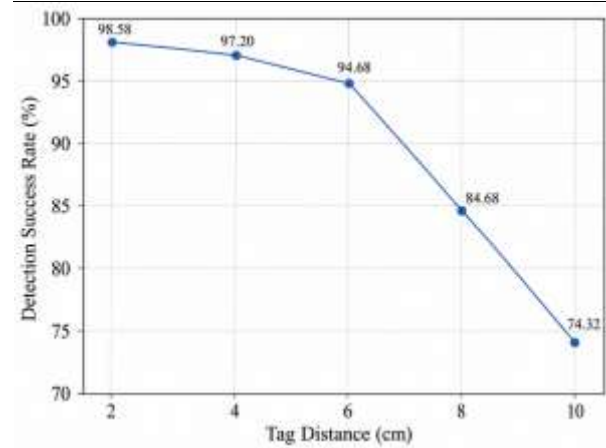


Fig. 4.1. RFID Detection Success Rate Versus Tag Distance

$$DE_d = \left(\frac{N_{\text{success_at_distance}_d}}{N_{\text{trials_at_distance}_d}} \right) \times 100 \quad (6)$$

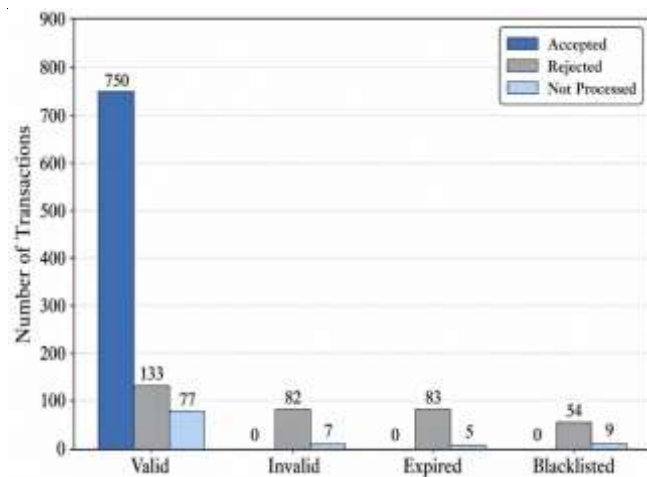
B. Authentication Accuracy and Unauthorized Vehicle Rejection

Post Read - determinant successful. All the tags were invalid (expired or on the blacklist) as shown on table 4.2 the gate will not be unlocked and only valid tags where balance and read had actually been initiated will unlock the gate. The accuracy rate for the program ground-truth rule (decision generation) was 100 percent. The number of cases accepted, ones rejected and ones that have not gone through the process should be visible on Fig. 4.2. The rejection layer is required since RFID can be read and this does not necessarily mean that it is authorized [26, 27].

Table 4.2.

Authentication Accuracy for Valid and Invalid RFID Tags

RFID Tag Status	Trial s	Accepted	Rejected	Not Processed	Gate Opened	Decision Accuracy (%)
Valid	960	750	133	77	750	100.00
Invalid	89	0	82	7	0	100.00
Expired	88	0	83	5	0	100.00
Blacklisted	63	0	54	9	0	100.00


Fig. 4.2. Authentication Outcome Distribution for Tested RFID Tags

$$A_{\text{auth}} = \left(\frac{TP + TN}{TP + TN + FP + FN} \right) \times 100 \quad (7)$$

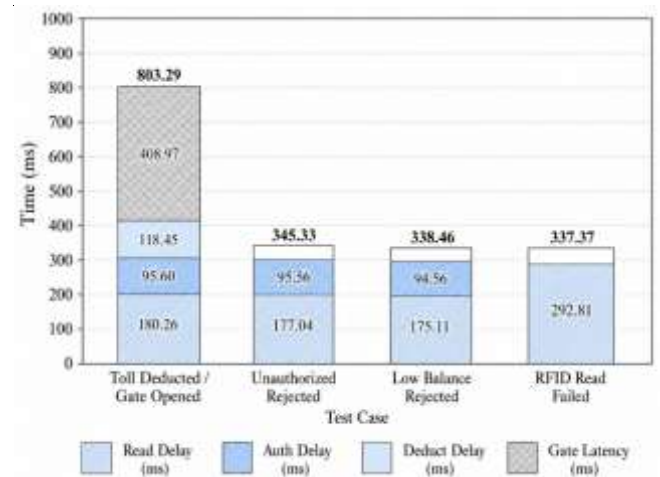
C. Gate Response Time and Transaction Processing Performance

Transaction timings are used to make the difference between accepted traffic and rejected traffic. The total time (deduction + servo movement) of accepted transactions, as seen in Table 4.3, were longer. Cases rejected were quicker as the barrier would be closed. From (8), the mean gate transaction time for completed transaction is 803.29 msec while the mean gate transaction time for cases that did not complete successfully is 345.33 msec. Times taken in this test should be compared with times given in fig.4.3.

Table 4.3.

Transaction Time Measurement for Toll Gate Operation

Transaction Result	Records	Read Delay (ms)	Auth Delay (ms)	Deduct Delay (ms)	Gate Latency (ms)	Total Time (ms)	Throughput (veh/min)
Toll Deducted / Gate Opened	750	180.26	95.60	118.45	408.97	803.29	75.33
Unauthorized Rejected	219	177.04	95.56	0.00	0.00	345.33	178.45
Low Balance Rejected	133	175.11	94.56	0.00	0.00	338.46	181.83
RFID Read Failed	98	292.81	0.00	0.00	0.00	337.37	181.67


Fig. 4.3. Average Transaction Processing Time Across Test Cases

$$AGTD = \left(\frac{1}{N_{\text{open}}} \right) \sum_{i=1}^{N_{\text{open}}} T_{\text{txn},i} \quad (8)$$

D. Toll Deduction and Balance Update Reliability

Balance logic is congruent 100%. In Table 4.4, it is indicated that only completed transactions led to a decrease in the balance, and that on average the toll value was seven times the value by which the balance decreased. No climb/drop in number of rejected and failed cases. Briefly tell the story of the prototype. A known problem in demonstration systems – improper opening of the gate without an approved decision and decreasing the total balance upon an declined decision – is prevented [28] [29].

Table 4.4.

Toll Deduction and Balance Update Validation

Transaction Result	Records	Mean Toll (INR)	Mean Balance Before (INR)	Mean Balance After (INR)	Mean Balance Change (INR)	Consistency (%)
Toll Deducted	750	131.47	544.57	413.11	131.47	100.00
Gate Opened						
Unauthorized	219	138.08	137.31	137.31	0.00	100.00
Rejected						
Low Balance	133	160.30	72.80	72.80	0.00	100.00
Rejected						
RFID Read Failed	98	137.14	359.98	359.98	0.00	100.00

E. Comparative Discussion and Practical Feasibility

In comparison with manual tolling, the proposed work ESP32-RFID gets rid of necessities for a manual cash exchange machine to process tolls, manual identity check at dispatch or stop by place, and inconsistent releasing of the barriers. It gives a distance behaviour report and doesn't deny state, equilibrium, times of transactions and performance of the model in comparison to simple demonstrations of RFID. As the gate rule was deterministic, in the test it was able to classify 100 per cent accurately. The result obtained in the case of transaction-time regressor using the training database is mean absolute error is 44.68ms and R2 is 0.9409 which indicate consistent transaction timings. Other types of product in this prototype may not be applicable to the following. These can still be used for validation in a laboratory. In Fig. 4.4, it would be helpful to compare the cost of tolling by hand and the default computer RFID system against that of the measured system. Studies on IoT Packet Filtering, based on communications behaviors and IoT Integration of RFIDs, which is the case of embeddedness, show that IoT reliability depends on the behavior of communications and the execution of rules [30,31].

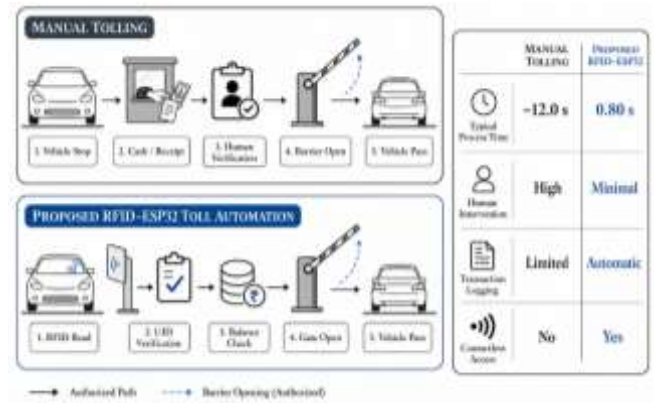


Fig. 4.4. Comparative Analysis of Manual Tolling and Proposed RFID-ESP32 Toll Automation

There are 750 gated result sets (open) and 450 closed result sets. This split is NOT a traffic demand, it's distribution to a test-bench for testing the states valid, invalid, expired, blacklisted, low balance, unreadable. Then the meaning of the number of "successes" over the greater distance has more meaning than the number; and it gives the reader an increasing tolerance. The installation should be as close to windshield/chute area as possible NOT at end of the lane. Thus anything below the limits of 2cm or above the limits of 6cm in this prototype will be at risk of continually returning a result that is outside of the range. This design still will work, but discipline in placement will come in handy.

V. CONCLUSION AND FUTURE WORK

In the proposed automatic toll gate using RFID communication, everything from identification to deduction of toll to actuation of barrier can be performed by using low cost embedded controller (ESP32 microcontroller) under lab test environment. The design on purpose is narrow. It doesn't mention any toll plaza is a public one. It has a very strong attribute of having a disciplined presence of all those RFID sensing and deterministic authentication, checking of the account state, servo control, logging and measurable performance-testing attributes.

The stability of the inner dynamics of a set of 1200 data records in the prototype was measured. As for the read success of RFID the closer the RFID approach to the surface the better was the read success, as it was removed, the success of the read also dropped. The accepted trans (deduction & servo) had a larger time per accepted/operation. Not a fault. Generally, the amount of money that can be typically expected to complete a valid transaction. Unauthorized, expired, blacklisted, low balance and unreadable cases didn't cause the stored balance to be deducted along with the gate remaining

shut, as was the case previously. The accounting rule was thus constant through all of the test cases.

The determinants property of the control policy was verified by the trained gate-action classifier and transaction-time regressor made a good approximation for the timing variation that can be used for prototype analysis. These models are not meant to be used in place of the Integrated Rule. They see that variable patterns of operation can be produced that have stable patterns and can be used for later optimisation.

Future work would aim to achieve a hardware-in-loop testing and also scale up to more tags within the testbed as well as do more testing with environmental stresses including heat, vibration, fluctuation in power supplies etc. To consider: implement a database on a secured cloud, encrypted use of the UIDs, audit logs, and vehicle verification camera and mobile recharge prior to deployment. Could be offline operations using solar – cache could be helpful in low network connectivity. More versions of the timing protocols are also to be added in the future once comparing the performance of ESP32 and Industrial controllers. The final test shall be a field trial. Until then the claims shall remain in the prototype phase, and experimental bounds.

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