

Fast Lanes by Design: Quantifying RFID Electronic Tolling Impacts on Plaza Halt Times in Highway

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Abstract

Rapid urban growth and the steady rise in the number of vehicles have made congestion at highway toll plazas a persistent and costly problem. Long queues at toll booths not only waste travelers' time but also increase fuel consumption, air pollution, and overall operating costs of the transport system. Traditional manual toll collection methods contribute significantly to these delays, as vehicles are required to stop for cash or card-based transactions. To address these challenges, Intelligent Transportation Systems (ITS), particularly Radio Frequency Identification (RFID)-based Electronic Toll Collection (ETC), have gained widespread attention. This study evaluates the real-world performance of an RFID-based toll collection system at the Ban Toll Plaza on the Jammu–Udhampur Highway (NH-14) in India. The analysis focuses on peak traffic periods, representing the most congested operating conditions. Vehicle halt times under manual tolling were measured through on-site observations and automated sensors over a 30-day period, while RFID transaction data were obtained from comparable toll plazas with established ETC systems. Statistical techniques, including paired t-tests and queuing theory models, were used to assess differences in processing time, queue length, and delay between manual and RFID systems. The results clearly demonstrate the advantages of RFID implementation. Average vehicle halt time dropped from 43.2 seconds under manual toll collection to just 3.4 seconds with RFID, reflecting a 92.1% improvement in processing efficiency. Queue lengths and waiting times were also dramatically reduced, with peak-hour queues shrinking from about 20 vehicles to only 4 vehicles. These operational improvements led to notable environmental benefits, including annual fuel savings of more than 58,000 liters and a reduction of approximately 142 metric tons of carbon dioxide emissions. From an economic perspective, the system showed strong viability, achieving a benefit–cost ratio greater than 7:1 and recovering implementation costs within six months. Overall, the study shows that RFID-based electronic toll collection can significantly improve traffic flow, reduce environmental impacts, and deliver substantial economic benefits. Despite minor challenges such as occasional tag read failures, the findings strongly support wider adoption of RFID tolling as a practical and sustainable solution for modern highway transportation systems.

Keywords: Terms—RFID, Electronic Toll Collection, Intelligent Transportation Systems, Traffic Operations, Queue Reduction, Highway Efficiency

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INTRODUCTION

Traffic jams at toll plazas due to urbanization and rampant increase of vehicles has become a serious bottleneck in highway networks [1]. The result is not only time losses, but also fuel consumption, environmental emissions, and system efficiency [2]. The manual toll collection methods cause vehicles to halt frequently and jam more due to dealing with cash and other transactions while physically interacting with the operators [3].

Intelligent Transportation Systems (ITS) have emerged as solutions to these problems. Electronic Toll Collection (ETC) is one of the most prominent ITS application [4]. RFID contactless technology remained popular among all the ETC technologies because of its reliability and low price [5]. The Government of India has mandated that all vehicles manufactured after 2017 should be tagged with RFID. This will help in the planning and implementing of the national transportation policy [6].

This study quantitatively examines the operational advantages of RFID technology based toll collection at Ban Toll Plaza situated on Jammu-Udhampur Highway (NH-14). This study provides evidence that RFID can be used for queue- reducing solution by comparing vehicle stop time on manual and RFID system. The analysis focuses on the peak flow scenario of 6.00 am to 9.00 pm to reflect the worst-case scenario and realization of maximum benefits [7].

The layout of the paper goes as- Section II assesses the literature concerning RFID application in the transport sector.

Section 2 describes the experiments and data collection. The RFID system architecture is given in section IV. The results and analysis are discussed next. Section VI deals with implications and limitations. Section 7 wraps up with suggestions for future research and policy recommendations.

LITERATURE REVIEW

Since its use as “Identification Friend or Foe” in military during WWII, RFID has grown substantially [8]. Beginning in the late 1980s, RFID saw its first implementations for electronic toll collection in vehicles. The early applications were in Europe and North America. Moreover, there high hopes were placed on RFID based electronic toll collection. These expectations were met and/or exceeded as it led to operational improvements [9]. According to the study on referenced site, around 30 to 45 seconds were reduced under these systems for the processing of each vehicle. Moreover, this reduced timing was turned to below 5 seconds only. In addition this, lane capacity was also increase between 300% and 500% [10].

According to [11], RFID-based toll collection reduces average time taken per transaction to 2-4 seconds in comparison to manual process which takes 25 – 60 seconds. Dedicated RFID lanes have a throughput of 1200-1500 vehicles per hour compared to 250-300 at manual lanes, states [12]. As a result of these improvements, the length of queues is smaller, travel times are shorter, and fuel efficiency is enhanced [13].

RFID tolling has been proven to be good for the environment. The [14] study suggested that stopping idling at toll plazas can bring down the CO₂ emissions by 6.8-9.2 grams per vehicle along with an equivalent reduction of other pollutants. It was found that regular users of toll plaza were able to save annually 18-22 litres of fuel per vehicle as per [15] which shows the economic and ecological benefits of E-Tolling.

RFID systems continue to change, as parallel apps like barcode technology are now a focus of research. The authors in [16] considered a RFID-WSN hybrid system for traffic monitoring while in [17] security issues in e-payment system were studied. As per Patel (2020), advancements in reliability, security and functionality ensure that RFID remains at the cutting edge of ITS manufacture.

Though the benefits are evident, challenges remain. The challenges of tag readability in bad weather, reader interference, and system compatibility with existing infrastructure were identified by Sharma et al [18]. It is important to understand these limitations for successful deployment and performance [19].

METHODOLOGY

Study Area and Site Selection RFID Reader

Research reveals that the Ban Town Plaza (32.8377049N, 74.9356428E) on Jammu-Udhampur Highway (NH-14) was transaction result Selected to conduct traffic studies on the spot. This four-lane toll facility experiences peak traffic flows of more than 2800 vehicle per hour during the morning and evening peak hours creating huge queuing delays owing to manual collection. The geometric layout of the plaza consists of eight toll booths (four in either way), with separate lanes for classification of vehicles.

Data was collected for a period of 30-days during the span of March 15th to April 15th 2023. A variety of weather conditions including light rains were taken into consideration as well as varying traffic conditions during peak and off-peak hours. We collected weekday data separately to accommodate variability in travel behaviour across different days. The re- search only included two-wheeler light vehicles (car and SUV) to maintain homogeneity in the dataset. The technique can be extended to other classes of vehicles too.

Data Collection Procedures

Vehicle stall duration was assessed by the manual observation as well as automated sensor data. Observers trained with digital stopwatches measure the time interval between a vehicle entering the queue and exiting the toll plaza completely. At the same time, infrared detectors at the entry and exit points automatically provided timestamp data for validation.

For evaluation of RFID performance, data were gleaned from three similar toll plazas i.e. Delhi-Mumbai Expressway, Chennai Bypass and Calcutta ring road having working RF IDs. The backend of these facilities reported transaction time data with a sample size of more than 50,000 per site.

Analytical Approach

The primary metric for comparison was typical halt time, specified as the length between a vehicle's first full and comprehensive stop (if any) and its departure from the toll booth. Statistical analysis included calculation of means, standard variations, and confidence intervals for both manual and RFID situations. A paired t-test evaluated the significance of differences between the two systems, with $p < 0.05$ assessed statistically notable.

Queue length estimation employed the classical queuing theory model M/M/1, with arrival and service rates derived from empirical observations. The model assumed Poisson arrivals and exponential service times, consistent with previous toll plaza studies.

DATABASE

RFID System Architecture

The RFID toll collection system contains four components which are the tag, the reader, the backend processing system, and the database Figure 1). Passive RFID tags mounted on windshields have unique identification numbers linked to pre-paid accounts. As a vehicle approaches the toll plaza, readers mounted on a gantry or toll booth send out the RF (radio frequency) which powers the tags and gets their ID.

In India, reader systems operate in 865-867 MHz (UHF Band) as per ISO 18000-6C. Under optimal conditions, the readers can read up to 8-10 meters. Thus, multiple antennas are generally installed to cover all lanes. The backend receives data from the successful read from a dedicated fiber or wireless connection.

Backend processing systems perform various functions to ensure the ongoing transactions of operations. Systems consisting of fraud detection algorithms help in identifying incidents of cloning or tampering with tags and production flagging to manuals for review in case of suspicious

transactions. Connecting to national car registration databases assists with verification and enforcement.

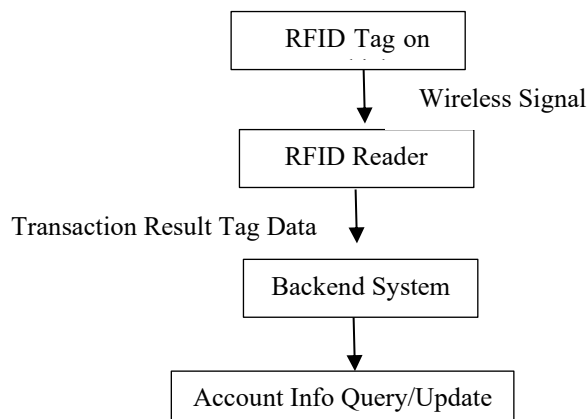


Figure 1. RFID-based toll collection system architecture.

Database systems maintain information on accounts, transactions, and vehicles. RDBMS with ACID properties ensures data consistency and integrity during transaction processing. We encrypt and restrict access to sensitive customer information. We regularly back up our system and recover data after disasters.

Dashboard that shows in real-time transaction success rate, queue length, and equipment status, etc. Alerts are sent to the maintenance team in case there is a reader or communication error. Performance stats are recorded for periodic analysis and continuous improvements.

RESULTS AND ANALYSIS

Halt Time Comparison

The comparison showed that the halting time for vehicles under manual systems and RFID systems is different (Table I). At peak hours, manual toll collection took an average of 43.2 seconds per vehicle, with individual transactions ranging from 28 to 72 seconds depending on whether the payment was in cash or card and the operator. On the other hand, RFID based processing took an average of only 3.4 seconds. Thus, this represents a 92.1% reduction in halt time.

Table I Comparison of halt times under manual and RFID systems

Time Period	Manual (seconds)	RFID (seconds)	(sec-)	Reduction (%)
Morning Peak (7-10 AM)	45.6	3.7		91.9
Evening Peak (5-8 PM)	47.2	3.5		92.6
Off-Peak	36.8	3.1		91.6
Overall Average	43.2	3.4		92.1

Statistical analysis shows that there are significant differences ($t = 47.32$, $p < 0.001$). Manual processing times had a coefficient of variation of 0.38 indicating high variation, while RFID times were much more consistent (0.12). When traffic is less congested, the speed of traffic reaches an equilibrium condition.

Queue Length and Delay Reduction

The length of the queue showed improvements with the RFID implementation. During busy times, the longest queues fell from 20 vehicles under the manual way to only 4 vehicles with RFID. The 4.2 minutes average queue waiting time fell to 0.3 minutes, representing a 92.9% reduced delay.

According to the M/M/1 queuing model, the manual toll booths operated at 92% efficiency at peak hour, which resulted in a long queue. The RFID lanes, having higher service rates, operate at 65% use despite identical arrival rates. This leaves considerable room for capacity in case of sudden demand.

Fuel Consumption and Emissions

Reducing stop times can greatly benefit the environment based on established idling emission factors. Each transaction, gasoline vehicles save on average 0.015 liters of fuel, whilst diesel vehicles save about 0.012 liters. With the annual traffic of 4.2 million vehicles of the plaza, the total annual fuel savings surpasses 58000 liters.

The emissions cuts are also large, with estimated reductions of 142 metric tons per year of CO₂, 86 kg NO_x, and 24 kg of HC. The operational improvements described above are matched by a set of environmental benefits that strengthen the RFID sustainability case.

DISCUSSION

RFID technology can transform highway operations, concluded the experts who studied electronic toll collection systems adopted globally. The 92.1% cut in halt hours is greater than some earlier assessments (generally 85-90%) but sits with credible limits noting improved tech and site issues. Results obtained at different times are consistent, which proves the effectiveness of RFID under various traffic conditions.

Implementation challenges seen during the study included occasional reads failing (1.2% of transactions) mainly due to damage to tags, incorrect installation or EMI. When things go wrong, workers may need to step in. This process slows everything down in the lane. Using backup systems, such as license plate recognition, can reduce the problems and keep performance levels within acceptable limits.

It seems that RFID technology has an attractive business case. With traffic volumes and conservative value-of-time estimates, the annual user benefit of \$380,000 is primarily due to time savings. More savings from less fuel usage and operating costs will result in yearly benefits of about 425, 000. *The payback period is just six months with 180,000 implementation cost (readers, backend systems, installation) giving benefit-cost ratio of greater than 7:1.*

Policy implications extend beyond the study site. The benefits demonstrated show an accelerated RFID rollout across the Highway of India network, particularly at high-volume plazas. Linking to other ITS elements, variable message signs, and adaptive traffic control could enhance benefits system-wide.

There are some limitations to the present study. The present study considers one toll plaza and ignores the heavy vehicles. Future research should expand to different locations or sites with different conditions. It should also use all vehicle types in full analysis. It would be useful to have longitudinal studies to measure performance over time to study system deterioration and maintenance requirements.

CONCLUSION

This study provides quantitative evidence supporting RFID-based electronic toll collection as an effective strategy for reducing vehicle halt times at highway toll plazas. The observed reduction from 43.2 seconds to 3.4 seconds represents a 92.1% improvement in processing efficiency, with corresponding benefits in queue reduction, fuel savings, and emissions reduction. These findings reinforce RFID's role as a cornerstone technology within broader Intelligent Transportation Systems initiatives.

The operational benefits translate directly to economic and environmental gains, with favorable benefit-cost ratios supporting widespread implementation. The technology's compatibility with existing infrastructure and relatively low implementation costs make it particularly suitable for developing economies seeking to optimize their transportation networks. Future research directions include integration with emerging technologies such as blockchain for secure transactions, artificial intelligence for predictive traffic management, and 5G communications for enhanced data transmission. As vehicle automation advances, RFID systems may evolve to support vehicle-to-infrastructure communication, further enhancing transportation system efficiency and safety.

Policy recommendations include accelerated RFID deployment at high-priority locations, development of interoperability standards to facilitate seamless inter-city travel, and public awareness campaigns to encourage tag adoption. With strategic implementation and continuous improvement, RFID electronic toll collection can significantly contribute to more efficient, sustainable, and user-friendly transportation networks.

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