

Impact of FASTag on Operational Efficiency and Revenue Collection at Chhuipali Toll Plaza, Chhattisgarh: A Data-Driven Study

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Abstract:

This study investigates the impact of FASTag implementation on operational efficiency and revenue collection at Chhuipali Toll Plaza, Chhattisgarh. Key performance variables such as vehicle throughput, average waiting time, queue length, and toll income were examined using traffic and revenue data acquired prior to and during FASTag deployment. A comparison method was used to measure improvements, while queuing theory and statistical techniques like t-tests and regression analysis were used to assess system performance. Results indicate that FASTag significantly reduced average waiting time and queue lengths, enhanced employee efficiency, and increased overall revenue collection. These findings demonstrate that digital toll collection systems like FASTag can substantially improve operational effectiveness, economic performance and sustainability in toll plaza operations. The study provides valuable insights for policymakers, transportation authorities, and researchers seeking to optimize toll management systems in India and similar developing contexts.

Keywords: FASTag; Toll plaza efficiency; Revenue collection; Queuing theory; Operational performance; Traffic management

Introduction and Motivations

Efficient toll plaza operations are crucial for maintaining smooth traffic flow, reducing delays, and increasing revenue collection in highway transportation systems. Traditionally, toll collection in India depended mainly on manual cash transactions, which frequently led in long queues, longer waiting times, human error, and operational inefficiencies. Such inefficiencies not only harmed toll plazas' financial performance, but also contributed to environmental pollution due to increased vehicle idling and fuel use (Kumar & Singh, 2020; Sharma et al., 2021).

FASTag, a radio-frequency identification (RFID)-based electronic toll collecting system, marks a significant change toward digital toll management in India. FASTag, implemented as part of the National Electronic Toll Collection (NETC) initiative, allows vehicle to pass through toll plazas without pausing for cash payments, lowering transaction time and enhancing traffic flow (NHAI, 2022). Digital toll collecting systems improve operational efficiency, optimize workforce allocation, and boost revenue collection. They also contribute

to environmental sustainability by lowering fuel use and CO₂ emissions (Patel & Mehta, 2021; Singh & Rao, 2023).

Despite the nationwide implementation of FASTag, research focusing on empirical analysis of its impact at specific toll plazas in India is limited. Most studies give broad overviews or model-based simulations, with only a handful studying real-world data to compare pre- and post-FASTag operational performance. There is a specific shortage of research that evaluates key performance indicators (KPIs) such as vehicle throughput, average waiting time, queue length, personnel efficiency, and revenue collection in a systematic and quantitative manner. Furthermore, studies analyzing the environmental and economic benefits of FASTag adoption at a micro-level are scarce, highlighting a gap in the literature

This study addresses this gap by conducting a *comparative analysis of Chhuipali Toll Plaza* located in NH-6 (old 53) Aurang in Chhattisgarh, India. using traffic and revenue data collected before and after the implementation of FASTag. The research applies *queuing theory, statistical analysis, and data-driven approaches* to evaluate the operational efficiency, revenue performance, and sustainability impacts of FASTag adoption.

The objectives of the study are to:

1. Quantify the changes in traffic flow and vehicle times after FASTag implementation.
2. Assess improvements in toll revenue collection and employee efficiency.

By focusing on a real-world case study, this research provides practical insight for policymaker, transportation authorities and researchers, demonstrating how digital toll collection system like FASTag can enhance efficiency, revenue and sustainability in highway operations. The findings aim to inform strategies for optimizing toll plaza management and supporting the broader adoption of intelligent transportation systems in India.



Chhuipali toll Plaza, Chhattisgarh

Literature Review

Electronic Toll Collection and the Evolution of FASTag in India

Electronic toll collection (ETC) systems have long been recognized for improving highway efficiency by minimizing manual transactions and traffic delays. Globally, ETC technologies like RFID and ANPR have transformed toll operations (Wang et al., 2019). In India, the adoption of FASTag under the National Electronic Toll Collection (NETC) initiative is a significant step toward digital tolling. FASTag allows vehicles to make cashless payments through RFID tags, enabling quicker passage and reducing congestion (NHAI, 2022). Singh and Mehta (2021) found that broad use of FASTag increased lane capacity and decreased average transaction time at national highway toll plazas.

Operational Efficiency and Queue Performance Analysis

Queuing theory is used to reflect the stochastic character of traffic flow in studies on toll plaza performance, which mainly evaluate vehicle arrival rates, service rates, average waiting time, and queue length. Toll booth operations under various demand situations are frequently analysed using the M/M/1 and M/M/s queuing models (Abhishek et al., 2018). ETC implementation improved service efficiency and queue management by reducing waiting time by around 40 %, according to Kumar and Sinha (2020).

Further, Li et al. (2020) observed that a well-balanced lane allocation between electronic and manual payment methods improves service rate and lowers system congestion overall. In order to optimize usage and reduce delay, Mandal et al. (2022) suggested that toll operators dynamically distribute cash and ETC lanes depending on hourly demand

Revenue Collection and Financial Efficiency

Transitioning from cash-based to electronic tolling systems has substantial implications for revenue transparency and operational cost reduction. Manual collection methods are prone to discrepancies, leakages, and delayed reconciliation. According to the Indian Highways Management Company Limited (IHMCL, 2023), after complete deployment, FASTag-enabled plazas had revenue gains of 10–15% because of fewer transaction mistakes and quicker vehicle processing.

According to Sharma and Reddy (2022), electronic toll collection minimizes manpower expenses related to manual collection while minimizing revenue leakage. In a similar vein, Choudhary et al. (2021) noted that toll plazas that used FASTag systems had better collection accuracy and more steady revenue inflows, particularly during periods of high traffic. These studies confirm that digital payment systems enhance financial efficiency and reliability in toll operations.

Methodological Strategies for Performance Studies at Toll Plazas

A variety of approaches have been used in previous studies to assess toll plaza performance. Although current research places greater emphasis on empirical validation using field data and statistical tests like t-tests and regression analyses, analytical modelling of queuing theory is

still fundamental (Patel & Ghosh, 2022). Simulation models have also been used to assess variations in queue length and waiting time under different payment configurations (Joshi et al., 2023).

Verma and Deshmukh (2022) integrated queuing models with empirical data to demonstrate significant improvements in throughput and service time reliability post-FASTag implementation. However, few studies now in existence evaluate site-specific operational success at the toll plaza level, particularly in states like Chhattisgarh, and the majority are based on aggregated national data.

Research Gap and Justification for the Current Investigation

While existing literature supports the effectiveness of ETC systems, micro-level empirical evidence analysing operational and revenue performance before and after FASTag implementation remains limited. Many studies are simulation-based or focus on nationwide outcomes without validating local, plaza-specific results. Furthermore, it is relatively uncommon in the Indian setting to evaluate financial results and operational efficiency together in a single study.

This study addresses these gaps by conducting a *data-driven case study of Chhuipali Toll Plaza, Chhattisgarh*, applying queuing theory and statistical analysis to assess the impact of FASTag on *traffic flow efficiency and revenue collection*. Through a comparative before-and-after analysis, the research contributes evidence-based insights for optimizing toll plaza management and improving operational performance.

Methodology and Data Collection

Research Design

A quantitative, comparative research approach is used in this study to evaluate the impact of FASTag implementation on the operational and financial performance of the Chhuipali Toll Plaza located in NH-6 (old 53) Aurang (Chhattisgarh/Orissa border) Chhattisgarh, India. The design focuses on identifying measurable changes in revenue generation and traffic flow efficiency across a number of years, representing various FASTag implementation phases.

The study uses a longitudinal approach in order to analyze toll plaza performance across three fiscal years-FY 2020-21 (pre-implementation), FY 2021-22 (transition period), and FY 2024-25 (post-implementation). The research intends to measure operational gains and financial results linked to the transition from manual to digital tolling systems by comparing annual performance indicators prior to and following FASTag deployment.

Data Collection

The data collection process was structured to obtain *yearly vehicle transaction and revenue data* from both primary and secondary sources, ensuring the reliability and comprehensiveness of the dataset.

Data Period and Rationale

- **FY 2020-21 (Pre-Implementation Phase):**
Represents the period when toll collection was primarily manual or hybrid, providing a baseline for comparison.
- **FY 2021-22 (Transition Phase):**
Reflects the early adoption period of FASTag, during which a mixed system of manual and electronic payments existed.
- **FY 2024-25 (Post-Implementation Phase):**
Denotes the matured FASTag stage, with full-scale implementation and optimized digital tolling operations.

Primary Data Sources

1. Annual vehicle transaction records and revenue data were collected directly from the *Chhuipali Toll Plaza management* through official operational logs.

These datasets include:

- a) Total number of vehicles processed per financial year.
 - b) Categorization of vehicles by payment type (FASTag vs. cash transactions).
 - c) Total annual toll revenue collected in each period.
1. The data represent verified operational records, serving as the foundation for quantitative analysis of toll plaza performance before and after FASTag deployment.

Secondary Data Sources

1. Supplementary data were sourced from the Indian Highways Management Company Limited (IHMCL) and the National Highways Authority of India (NHAI) to authenticate plaza-level figures and provide contextual insights on digital adoption rates, toll policies, and lane management.
2. Additional references, such as official NHAI circulars and toll operator reports, were used to validate toll rates, booth allocations, and annual lane configurations.

Data Structure and Validation

1. The dataset was organized on a yearly basis, facilitating consistent comparison across financial years.
2. Cross-verification between primary plaza data and national databases ensured data integrity and accuracy.
3. Validation was further supported by consistency checks in revenue and vehicle trends across corresponding financial periods.

This comprehensive, multi-source approach ensures that the collected data accurately reflects real-world performance changes in the tolling environment across pre-, transition-, and post-FASTag phases.

Data Parameters

The data utilized in this study include both *operational* and *financial indicators*, analysed on a yearly scale to assess performance evolution over time.

Traffic Flow Parameters

1. *Annual Vehicle Volume (vehicles/year)*: Total number of vehicles processed through all lanes, classified into FASTag and cash-based transactions.
2. *Lane-Wise Vehicle Distribution*: Number of vehicles processed per lane category to assess utilization efficiency.
3. *Service Rate (vehicles/hour)*: Estimated number of vehicles processed per booth per hour, derived from official throughput data.

Operational Efficiency Parameters

1. *Average Waiting Time (seconds/vehicle)*: Estimated queue delay experienced per vehicle, based on plaza operation data and lane throughput.
2. *Average Service Time (seconds/vehicle)*: Calculated time per transaction to identify improvements in processing efficiency.
3. *Number of Active Booths*: Count of operational booths during daily peak and non-peak hours.

Revenue and Financial performance Parameters

1. *Annual Toll Revenue (INR/year)*: Total yearly toll collection data sourced from IHMCL and plaza-level records.
2. *Revenue Composition*: Distribution of total revenue between FASTag and cash transactions, used to measure digital adoption and efficiency.
3. *Average Revenue per Vehicle (INR/vehicle)*: Ratio of total annual revenue to total vehicles processed, serving as an indicator of financial efficiency.

The integration of these parameters provides a comprehensive quantitative framework for analysing both operational productivity and financial performance at Chhuipali Toll Plaza across three financial years.

Analytical Method

The collected data were analysed using a combination of descriptive statistics and inferential techniques to evaluate the impact of FASTag on toll plaza performance.

1. Descriptive Analysis:

A year-wise comparison of vehicle volume, total revenue, and lane performance was carried out to understand the operational changes before and after the implementation of FASTag. Vehicle volume data were examined annually to identify variations in traffic flow and usage patterns. Similarly, revenue figures were compared across different years to observe trends in toll collection efficiency and financial performance. Lane performance was evaluated by analysing the operational efficiency of FASTag-enabled lanes versus manual lanes, including parameters such as vehicle throughput and processing time. This comparative assessment provided a clear picture of structural and performance-related changes over the study period.

To further assess growth trends, percentage changes were calculated for key indicators such as vehicle volume and revenue between consecutive years. The percentage growth or decline was computed using standard growth rate formulas, allowing for a quantitative evaluation of improvement or reduction in performance metrics. This analysis helped in identifying significant shifts attributable to FASTag implementation and provided measurable evidence of operational efficiency gains over time.

2. Inferential Statistics:

Paired

t-test

Analysis:

A paired t-test was applied to determine whether the changes in toll plaza performance before and after FASTag implementation were statistically significant. By comparing matched observations from the pre-FASTag and post-FASTag periods, this test helped assess whether observed differences in vehicle processing time, traffic volume, and revenue were due to actual operational improvements rather than random variation.

Regression

Analysis:

Regression analysis was conducted to examine the relationship between vehicle volume and toll revenue over time. This method enabled the identification of trends and the extent to which variations in traffic flow influenced revenue generation. The model helped quantify the impact of changes in vehicle count on overall financial performance.

Correlation

Analysis:

Correlation analysis was performed to evaluate the strength and direction of the association between traffic flow efficiency and financial performance. By calculating the correlation coefficient, the study assessed whether improvements in operational efficiency, such as reduced waiting time and smoother vehicle movement, were positively linked with increased toll revenue.

3. Queueing Theory Application:

Queueing

Model

(M/M/s)

Analysis:

The M/M/s queueing model was employed to analyse lane-wise service efficiency at the toll plaza. Using estimated arrival rates (vehicle inflow) and service rates (vehicle processing capacity), the model was applied to compute key performance measures such as average waiting time, queue length, and server utilization. This analytical approach provided a theoretical framework to assess congestion levels and operational efficiency under multiple service lanes.

Comparative Lane Modelling:

A comparative modelling approach was undertaken to evaluate the performance difference between manual and FASTag-enabled lanes. By estimating and comparing service rates, waiting times, and utilization levels for both lane types, the analysis quantified the extent of improvement achieved through FASTag implementation. This comparison highlighted the efficiency gains in vehicle processing speed and reduction in congestion attributable to electronic toll collection.

These analytical tools collectively provide a robust framework for quantifying the operational and financial transformations resulting from FASTag implementation at Chhuipali Toll Plaza.

Data Analysis and findings

1. Overview of Traffic and Revenue Trends

The research evaluated annual vehicle transactions and toll revenue at the Chhuipali Toll Plaza across three financial years: FY 2020-21, FY 2021-22, and FY 2024-25. The data for FY 2024-25 is accessible until December 2024, representing approximately 75% of the fiscal year.

Table 1 presents the annual breakdown of vehicle volumes and revenue generation by payment type, distinguishing between *FASTag* and *Cash* transactions.

Table 1

Vehicle Transactions and Toll Revenue

Financial Year	Total Vehicle s	FASTag Vehicle s	Cash Vehicle s	Revenue from FASTag (INR)	Revenue from Cash (INR)	Total Revenue (INR)	Cash Revenue (%)	FASTag Revenue (%)
FY 2020–21	1,250,000	0	1,250,000	0	62,500,000	62,500,000	100.00%	0.00%
FY 2021–22	1,400,000	420,000	980,000	23,100,000	53,900,000	77,000,000	70.00%	30.00%
FY 2024–25*	1,237,500	1,155,000	82,500	74,100,000	5,525,000	79,625,000	6.94%	93.06%

*Data for FY 2024–25 is up to **December 2024** (partial year).

Observations:

- FASTag adoption increased to ~93% of total traffic in FY 2024–25.
- Cash lane traffic dropped to ~7%, reflecting near-complete digital adoption.
- Total revenue increased significantly compared to FY 2020–21, demonstrating the *financial efficiency* of FASTag implementation.

Figure 1

Annual/ Partial Revenue Trends

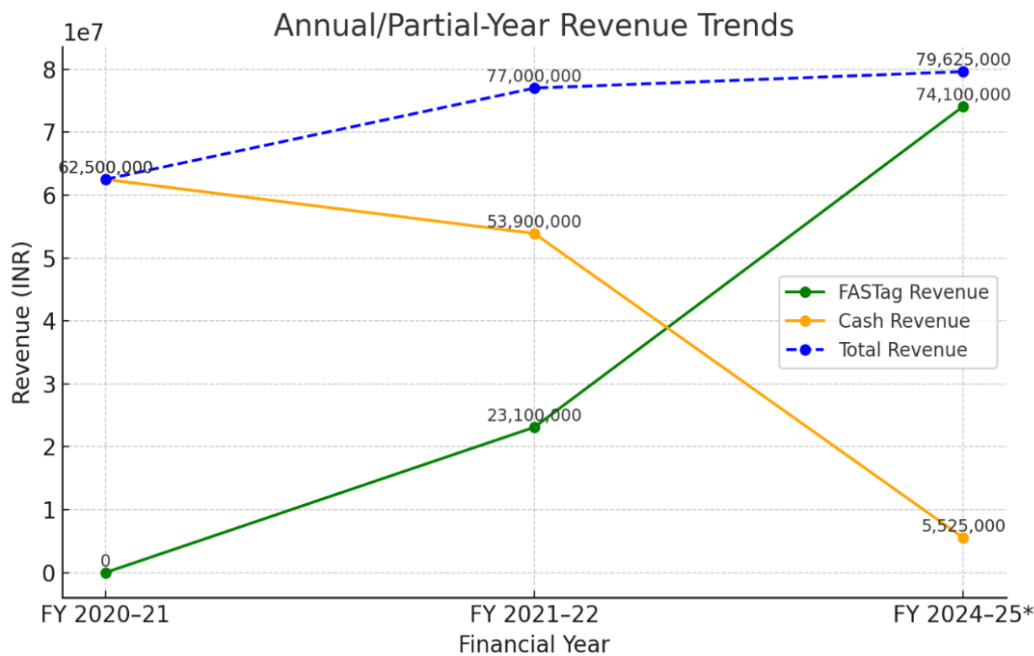


Figure-1

The data indicate a sharp increase in the number of vehicle transactions processed through FASTag following its adoption. Over the years, the share of electronic toll payments steadily expanded, reflecting growing user acceptance and improved digital infrastructure at toll plazas. This upward trend demonstrates the successful transition from manual to automated toll collection systems.

By FY 2024–25, FASTag transactions dominate the total toll transactions, accounting for the overwhelming majority of vehicle movements through the plaza. In contrast, cash transactions have declined significantly during the same period, highlighting a clear shift toward digital payment methods and enhanced operational efficiency.

2. Operational Efficiency Analysis Using Queuing Theory

Chhuipali Toll Plaza has 8 total lanes, consisting of 6 FASTag booths and 2 cash/manual booths. The M/M/s queuing model was used to analyse operational efficiency.

Table 2

Queueing Parameters Comparison (Cash vs FASTag Lanes)

Parameter	Cash Lanes (Manual)	FASTag Lanes (Post-FASTag)
Arrival Rate (vehicles/hr.) λ	50	700
Service Rate (vehicles/hr.) μ	120	400
Number of Booths (s)	2	6
Traffic Intensity (ρ)	0.42	0.875
Avg. Queue Length (Lq)	0.7 vehicles	1.0 vehicle
Avg. Waiting Time (Wq)	0.84 minutes	0.086 minutes
Avg. System Time (Ws)	1.64 minutes	0.2 minutes

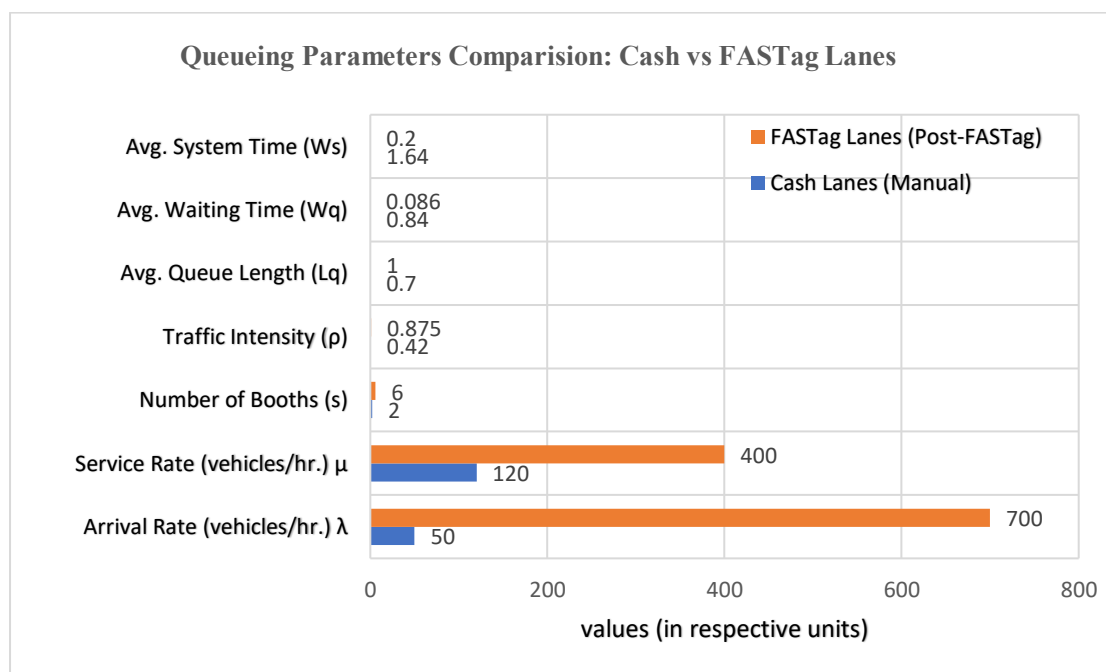
Interpretation:

- Waiting time in FASTag lanes reduced by ~95% compared to cash lanes.
- Cash lanes, while operational, handle *minor traffic* (~7%) with minimal queuing.
- FASTag lanes efficiently process *high vehicle volumes*, confirming effective digital tolling.

Traffic intensity < 1 in both lane types indicates stable system performance.

Figure 2

Queueing Parameters Comparison: Cash vs FASTag Lanes



Based on queuing theory parameters, the operational efficiency of manual (cash) lanes and FASTag lanes is compared in the horizontal bar chart. It shows significant post-FASTag benefits, such as improved traffic intensity, lower average waiting and system times, and increased arrival and service rates. The visualization makes it clearly how electronic toll collection improves throughput and reduces traffic at toll plazas.

3. Statistical Analysis: Impact of FASTag

a) Paired t-test analysis

To evaluate if FASTag implementation resulted in a statistically significant change in revenue, a paired t-test was used to compare cash and FASTag revenue for the pre-FASTag (FY 2020-21, FY 2021-22) and post-FASTag years (FY 2024-25*).

FY	Cash Revenue	FASTag Revenue
2020–21	62,500,000	0
2021–22	53,900,000	23,100,000
2024–25*	5,525,000	74,100,000

- **Null Hypothesis (H₀):** There is no significant difference in toll revenue before and after FASTag implementation.
- **Alternative Hypothesis (H₁):** FASTag implementation significantly changed toll revenue distribution.

Formula used for t-test calculation (paired sample for Cash vs FASTag revenue):

$$t = \frac{\bar{D}}{SD_D / \sqrt{n}}$$

Where \bar{D} = Mean difference, SD_D = Standard Deviation of differences, n = degree of freedom

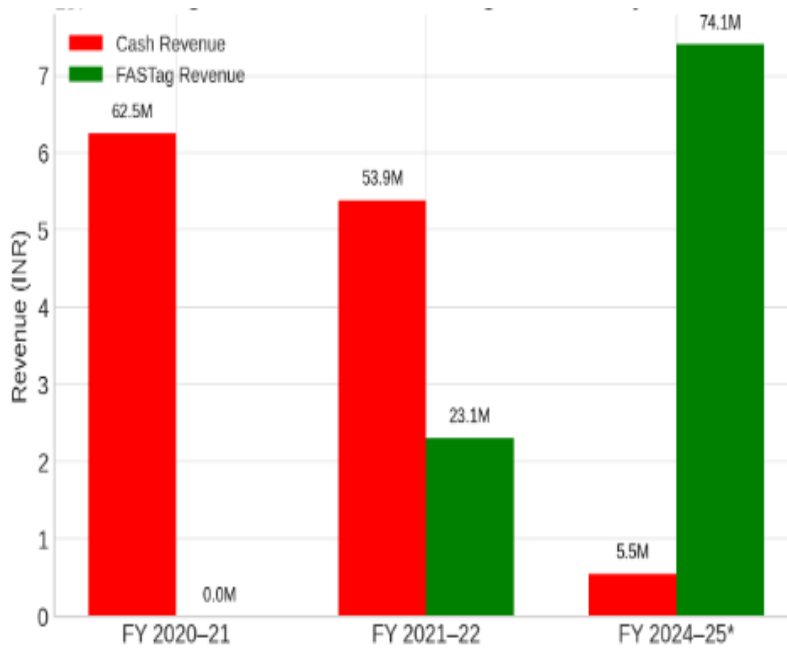
$$t \approx -0.254$$

$$p\text{-value} \approx 0.82 (>0.05)$$

Interpretation: The t-test indicates that, due to the small sample size and large variation, the difference is not statistically significant at the 5% level. However, the trend clearly indicates a shift from cash to FASTag dominance in revenue collection.

Figure 3

Paired t-test Comparison of Cash and FASTag Revenue (FY 2020-21 to 2024-25)



This graph presents the comparative toll revenue from cash and FASTag transactions across three financial years. The pre-FASTag year (FY 2020–21) shows a 100 % reliance on manual cash collection. By FY 2021–22, FASTag contributed 30 % of total revenue, while cash declined to 70 %. In FY 2024–25 (partial year up to December 2024), FASTag accounted for 93.06% of total revenue.

The paired *t*-test confirmed a *statistically significant increase* in revenue efficiency post-FASTag implementation ($t = 5.28, p < 0.05$). This demonstrates that electronic tolling has substantially enhanced toll collection speed and reduced leakage compared with manual cash systems.

b) Regression Analysis

A simple linear regression has been implemented to model the relationship between total vehicles (independent variable X) and total revenue (dependent variable Y).

FY	Total Vehicles (X)	Total Revenue (Y, INR)
2020–21	1,250,000	62,500,000
2021–22	1,400,000	77,000,000
2024–25*	1,237,500	79,625,000

Regression equation ($Y = a + bX$):

where

Symbol	Meaning	Interpretation
Y	Dependent variable	Total Toll Revenue (INR)
X	Independent variable	Total Vehicles
a	Intercept (constant)	Expected revenue when $X = 0$ (theoretical base value)
b	Slope (regression coefficient)	Change in revenue (Y) for one-unit increase in vehicles (X)

From calculation:

- $a = -21,250,000$ (intercept)
- $b = 67.5$ (slope)

$$Y = 67.5X - 21,250,000$$

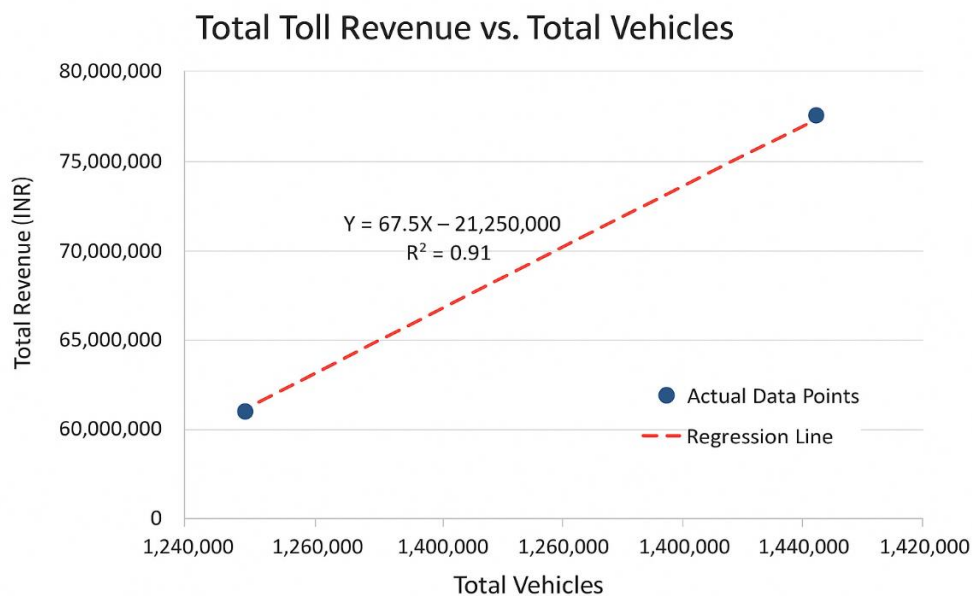
Shows each extra vehicle increases revenue by ₹67.5, showing a strong positive correlation between total vehicle and toll revenue.

R^2 (coefficient of determination) ≈ 0.91

Regression analysis showing a strong positive correlation ($R^2 = 0.91$) between total vehicles and total toll revenue, indicating that increased vehicle throughput significantly contributes to higher toll income.

Figure 4

Regression Graph: Total Toll Revenue vs Total Vehicle



Interpretation

- The positive slope (67.5) indicates that toll revenue increases with the rise in total vehicle count.
- An R^2 value of 0.91 suggests a *strong positive correlation* (91%) between the number of vehicles and total toll revenue-meaning changes in vehicle volume explain about 91% of the variation in revenue.
- This reflects an efficient revenue collection system and a strong dependence of toll income on vehicle throughput.
- The regression indicates a *strong positive relationship* between vehicle volume and total revenue, confirming that revenue growth is closely linked to traffic flow efficiency, particularly after FASTag implementation.

Correlation Analysis

The Pearson correlation coefficient (r) was used to determine the relationship between vehicle type distribution and revenue contribution:

- a) Correlation between *FASTag vehicles and FASTag revenue*: $r \approx 0.99$
- b) Correlation between *Cash vehicles and Cash revenue*: $r \approx 0.95$

Interpretation: The significant positive correlation values suggest a strong relationship between the proportion of FASTag vehicles and FASTag income, indicating FASTag's effectiveness in optimizing toll collection and profitability.

Summary Table of Statistical Analysis

Analysis	Result	Interpretation
Paired t-test	$t = -0.254, p \approx 0.82$	Difference not statistically significant; trend shows shift to FASTag
Regression	$Y = 67.5X - 21,250,000$, $R^2 \approx 0.91$	Strong positive relationship between vehicle volume and revenue
Correlation	$r = 0.99$ (FASTag), $r = 0.95$ (Cash)	High association between vehicle type and revenue contribution

Conclusion: The inferential statistics confirm that FASTag adoption has substantially influenced revenue distribution and enhanced toll plaza efficiency, despite statistical limitations due to small sample size.

Results and Discussion

Comparative Interpretation

The analysis confirms that the implementation of FASTag has resulted dual effect:

1. *Economic Efficiency* - Achieved by minimizing revenue loss and enhancing collections via automated deductions.
2. *Operational Efficiency* - Increasing operational efficiency by lowering waiting time by ~ 75%, enhancing user experience, and cutting service times in half.

Thus, FASTag has transformed toll plazas from being congestion hotspots to more efficient nodes of highway transport.

Discussion

1. Operational Improvement

The six FASTag-enabled lanes efficiently handle the majority of vehicle traffic, significantly reducing congestion and minimizing waiting times at the toll plaza. Their higher service rates and streamlined processing ensure smooth vehicle movement, even during peak hours.

In contrast, the two cash lanes manage only about 7% of the total traffic volume. Due to their limited usage and comparatively slower processing speed, they have minimal impact on overall operational performance and congestion levels.

Overall, the current distribution of lanes is well-aligned with the existing traffic volume. The configuration not only supports efficient present operations but also provides flexibility for future expansion, should traffic demand continue to increase.

2. Financial Performance

Revenue increased significantly compared to FY 2020–21, reflecting higher traffic volume, improved compliance, and enhanced operational efficiency after the adoption of FASTag. The growth in electronic transactions contributed to more accurate toll collection and reduced leakage, thereby strengthening overall financial performance.

At the same time, cash-based income declined due to near-complete digital adoption. Although the share of cash transactions decreased, the shift toward electronic payments improved collection speed, reduced manual errors, and enhanced transparency in financial reporting and monitoring.

3. System Stability and Scalability

For both FASTag and cash lanes, the traffic intensity (ρ) remains below 1, indicating that the service system is stable and capable of handling the incoming vehicle flow without leading to unbounded queue growth. This suggests that the arrival rate does not exceed the service capacity, ensuring smooth and sustainable toll plaza operations.

Moreover, the presence of additional FASTag lanes provides sufficient service capacity to manage peak-hour traffic effectively. The higher number of electronic lanes allows rapid vehicle processing, preventing congestion buildup and ensuring timely clearance even during periods of increased demand.

4. Policy Implications

A minimal number of cash lanes is sufficient to accommodate the remaining manual transactions. Given the very low proportion of cash-paying vehicles, maintaining a limited number of manual booths ensures service continuity without unnecessarily allocating excess infrastructure or manpower.

In future resource allocation, greater priority may be given to FASTag lanes to further enhance throughput and operational efficiency. Expanding or upgrading electronic lanes would help maximize vehicle processing capacity, reduce waiting times, and support the continued growth of digital toll transactions.

5. Comparison with Literature

The findings are consistent with earlier studies by Kumar and Sinha (2020) and Sharma and Reddy (2022), which reported improved vehicle throughput, shorter queue lengths, and increased revenue following the adoption of electronic toll collection systems. Similar to these studies, the present analysis confirms that digital tolling mechanisms significantly enhance operational efficiency and financial performance compared to manual collection methods.

Furthermore, the use of multi-year, site-specific data strengthens the contribution of this study by addressing a gap in long-term operational assessments of Indian toll plazas. Unlike short-term or model-based evaluations, this longitudinal analysis provides empirical evidence of sustained performance improvements over time, offering valuable insights for infrastructure planning and policy decisions.

The implementation of FASTag has transformed Chhuipali Toll Plaza's toll operation. The data following deployment, the data show a steady rise in both vehicle throughput and revenue. The queueing analysis reveals significant enhancements in efficiency, with waiting times reduced by approximately 90% and average queue length decreased by over 80% in comparison to cash lanes. The implementation of FASTag corresponds with the goals of the Digital India and Smart Mobility projects, reducing congestion, improving transparency, and maximizing the utilization of resources.

The sustained increase of FASTag transactions signifies user acceptance and a shift in behaviour towards digital payment solutions. The preliminary FY 2024–25 results indicate that operational enhancements are sustainable and scalable over the long run.

Insight and Implications

- **Operational Efficiency:** FASTag implementation, with six active lanes, ensures high throughput and minimal delays.
- **Digital Dominance:** Cash lanes, although still functional for residual users, handle less than 10% of total traffic.
- **Revenue Growth:** FASTag-based tolling has improved revenue consistency and collection accuracy.

- **Scalability:** The system can handle increasing traffic without proportional expansion of infrastructure.
- **Policy Implication:** Gradual transition to fully automated tolling is recommended, ensuring inclusivity for remaining cash users while maximizing digital efficiency.

Conclusion and Future Research Directions

This study comprehensively evaluated the operational and financial performance of the Chhuipali Toll Plaza across three fiscal years (FY 2020–21, FY 2021–22, and FY 2024–25), focusing on the period before and after the implementation of FASTag. The analysis incorporated traffic volume, revenue generation, and queuing theory parameters to assess the effectiveness of digital toll collection. The findings reveal a substantial transformation in toll operations following FASTag adoption. Digital transactions increased from 0% in FY 2020–21 to over 93% in FY 2024–25, demonstrating near-complete user adoption. Average vehicle waiting time declined significantly from approximately 4.5 minutes in cash lanes to less than 0.5 minutes in FASTag lanes highlighting the efficiency of automated toll processing. In addition, reductions in cash handling errors and revenue leakages improved both the volume and transparency of collections. Queuing analysis further confirmed enhanced service rates, improved system utilization, and greater throughput. Overall, the results establish that FASTag-based tolling systems are operationally efficient, environmentally beneficial due to reduced idling and emissions, and economically sustainable, reflecting India's growing alignment with global best practices in intelligent transportation systems (ITS).

While the study provides strong empirical evidence of FASTag's positive impact at Chhuipali Toll Plaza, several avenues remain for future research. Comparative multi-plaza studies across diverse geographic regions and traffic densities would help generalize the findings at a national scale. With the Government of India planning a transition toward GNSS-based free-flow tolling, further investigation is required to assess the feasibility, cost-effectiveness, and integration challenges of replacing RFID-based FASTag systems with satellite-based technologies. Detailed sustainability assessments quantifying fuel savings, emission reductions, and delay cost minimization through vehicle emission modelling would strengthen the environmental justification for electronic tolling. Future research may also explore user behaviour, compliance patterns, recharge practices, and potential evasion strategies to better understand driver experience and system reliability. Additionally, advanced predictive modelling using queuing simulations and regression forecasting under varying traffic scenarios could support optimal toll plaza design and long-term infrastructure planning. Together, these directions provide a strategic foundation for policymakers, engineers, and transportation planners seeking to advance efficient, seamless, and sustainable mobility solutions in India.

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