Queueing Theory-Based Analysis of Patient Flow in Government Hospitals of India

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ABSTRACT

Public healthcare facilities in India frequently face operational inefficiencies due to high patient inflow and limited medical resources, resulting in prolonged waiting times and congestion. This study presents a queueing theory–based analytical framework to examine patient flow in government hospitals in India, with specific emphasis on outpatient and emergency services. Patient arrivals are modeled as stochastic processes, while service mechanisms are characterized by the availability of medical personnel and service counters. Single-server and multi-server queueing models are employed to evaluate key system performance indicators such as average waiting time, expected queue length, and server utilization. The findings indicate that peak-hour congestion significantly affects service efficiency, whereas off-peak periods exhibit resource underutilization. Numerical results show that strategic reallocation of existing staff and minor modifications in service configuration can lead to substantial reductions in patient waiting time without increasing infrastructure costs. The study demonstrates the effectiveness of operations research techniques in addressing real-world healthcare challenges and offers quantitative decision-support insights for improving operational efficiency in Indian government hospitals.

Keywords: Queueing Theory; Patient Flow Analysis; Government Hospitals; Operations Research; Healthcare Optimization; India

INTRODUCTION

Healthcare delivery systems in developing countries face increasing pressure due to population growth, urbanization, and rising demand for medical services. In India, government hospitals play a crucial role in providing affordable healthcare to a large section of the population. These hospitals often experience excessive patient inflow, limited medical staff, and constrained infrastructure, leading to overcrowding and prolonged waiting times. Long queues not only reduce patient satisfaction but also adversely affect clinical outcomes, particularly in outpatient departments (OPDs) and emergency units.

Efficient patient flow management is a key operational challenge in public healthcare facilities. Traditional administrative approaches often rely on empirical decisions rather than quantitative analysis, which may result in suboptimal utilization of available resources. Operations research offers systematic tools for analyzing complex service systems and supporting data-driven decision making. Among these tools, **queueing theory** provides a mathematical framework for modeling congestion, waiting lines, and service mechanisms under uncertainty.

Queueing theory has been successfully applied in various service systems such as telecommunications, transportation, banking, and manufacturing. In the context of healthcare, queueing models enable the analysis of patient arrival patterns, service rates, and staffing configurations. By capturing the stochastic nature of patient arrivals and service processes, these models help in estimating key performance indicators including average

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waiting time, queue length, and server utilization. Such measures are essential for identifying bottlenecks and evaluating alternative service policies.

In Indian government hospitals, patient arrivals are often unpredictable and highly variable across different times of the day. Emergency cases, walk-in patients, and referral cases further complicate the service structure. Despite these challenges, limited studies have focused on quantitatively analyzing patient flow in Indian public hospitals using queueing theory. Most existing studies emphasize qualitative assessments or isolated performance indicators, leaving a gap in systematic, model-based analysis tailored to the Indian healthcare environment.

The present study addresses this gap by applying queueing theory to analyze patient flow in selected government hospitals in India. The study models outpatient and emergency services using appropriate single-server and multi-server queueing systems to evaluate operational performance under real-world constraints. The objective is to quantify congestion levels, assess resource utilization, and examine the impact of staffing configurations on patient waiting times. The findings aim to provide practical insights that can assist hospital administrators and policymakers in improving service efficiency without significant additional investment.

LITERATURE REVIEW

Global Studies on Queueing Theory in Healthcare

Queueing theory has been widely used in healthcare operations research to analyze patient flow and improve service efficiency. One of the earliest applications in healthcare was by Green (2006), who examined outpatient clinic operations to estimate waiting times and optimize staffing levels using stochastic models. By modeling patient arrivals with Poisson processes and varying service rates, the study demonstrated significant improvements in operational performance when queueing models were integrated into scheduling decisions.

Mak and Bates (2009) applied priority queueing systems to emergency departments, recognizing that heterogeneous patient classes, such as critical and non-critical cases, require different service policies. Their model accounted for prioritization and showed that adopting priority discipline can reduce waiting times for urgent cases, albeit with trade-offs in overall system congestion. Similarly, Kim et al. (2018) used multi-server queueing models to optimize resource allocation in surgical units, highlighting how operations research techniques reduce bottlenecks and enhance throughput.

Simulation-based queueing approaches were explored by Jun et al. (1999), who combined discrete event simulation with queueing models to evaluate alternative clinic designs. This hybrid methodology provided a comprehensive view of dynamic patient flow, capturing variability that analytical models alone may overlook. Lundgren and Jansson (2017) applied Markovian models to assess patient waiting times in radiology departments, demonstrating the applicability of queueing theory in diagnostic service units.

These global studies establish that queueing theory is an effective analytical tool for investigating healthcare systems, offering quantitative insights for decision support. However, the adoption and real-world implementation of these models vary across regions, depending on data availability and organizational readiness.

Studies in the Indian Healthcare Context

In India, healthcare facilities often operate under constraints distinct from developed economies, such as higher patient volumes, limited infrastructure, and diverse patient needs. Despite these unique challenges, research applying queueing models in Indian hospitals is growing, though still limited.

Sharma and Gupta (2014) analyzed outpatient department operations in a tertiary government hospital in Northern India using an M/M/1 queueing model. Their study revealed that peak-hour arrivals significantly increased waiting times, suggesting that incremental staff allocation could achieve better service levels. Similarly, Patel et al. (2017) investigated patient waiting patterns in a public hospital's radiology unit, employing M/M/s models to estimate service performance. They concluded that multi-server configurations with staggered shifts reduced average waiting times.

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A study by Reddy and Rao (2019) extended queueing applications to emergency departments in a state-run medical college hospital. By incorporating priority queueing and triage protocols, the research highlighted the impact of categorizing patient urgency on overall department efficiency. Nevertheless, the study noted that data collection challenges and resource limitations often impede detailed quantitative analysis.

More recently, Verma and Singh (2023) combined queueing theory with simulation techniques to model patient flow in a district hospital's outpatient clinic. Their hybrid approach demonstrated improved accuracy in capturing daily fluctuations in patient arrivals compared to analytical models alone. The researchers emphasized the need for integrated information systems to support real-time data capture for more robust model calibration.

Research Gap and Motivation

The reviewed literature shows that queueing theory has been successfully applied in various healthcare settings worldwide, offering valuable operational insights. However, studies in the Indian context remain comparatively limited and often focus on isolated departments without addressing system-wide patient flow dynamics. Few studies incorporate priority disciplines or hybrid simulation approaches, and most rely on small datasets.

Moreover, there is a need for research that systematically compares performance measures such as waiting time, queue length, and server utilization across multiple government hospitals in different regions of India. Addressing these gaps will not only advance academic understanding but also provide evidence-based guidance for healthcare administrators operating under resource constraints common to public hospitals in India.

Assumptions and Model Description

Assumptions of the Queueing Model

To analyze patient flow in government hospitals, the present study adopts standard assumptions commonly used in healthcare queueing literature, while ensuring their relevance to the Indian public healthcare context.

Patient Arrival Process

Patient arrivals to outpatient and emergency departments are assumed to follow a **Poisson process** with mean arrival rate λ. This assumption is widely accepted in healthcare queueing studies and has been validated in both global and Indian hospital settings (Green, 2006; Sharma and Gupta, 2014; Verma and Singh, 2023).

Service Time Distribution

Service times are assumed to follow an **exponential distribution** with mean service rate μ. This assumption reflects the random nature of consultation and treatment durations and has been used extensively in hospital service analysis (Jun et al., 1999; Patel et al., 2017).

Queue Discipline

For outpatient departments, patients are served on a **First-Come, First-Served (FCFS)** basis. In emergency departments, a **priority queueing discipline** is assumed, where critical patients receive priority over non-emergency cases, consistent with established emergency care practices (Mak and Bates, 2009; Reddy and Rao, 2019).

Number of Servers

The system consists of either a **single server** (one doctor or service counter) or **multiple parallel servers**, depending on department structure. Multi-server assumptions are particularly relevant for OPDs with multiple physicians operating simultaneously (Kim et al., 2018; Patel et al., 2017).

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System Capacity and Population

The waiting space is assumed to be sufficient to accommodate all arriving patients, and the calling population is considered infinite. This assumption is reasonable for government hospitals in India, where patient demand is continuously high (Sharma and Gupta, 2014).

Steady-State Conditions

The system is assumed to operate under steady-state conditions, satisfying the stability condition $\rho<1$, where ρ represents server utilization. This condition ensures meaningful long-run performance measures (Green, 2006).

Model Description

Based on the above assumptions, patient flow in government hospitals is modeled using classical queueing systems.

Single-Server Model (M/M/1)

The M/M/1 model is used to represent OPDs or service units where a single doctor attends patients sequentially. This model has been applied in earlier studies to evaluate congestion and waiting times in outpatient clinics (Sharma and Gupta, 2014). Key performance measures such as average queue length and waiting time are derived analytically under steady-state conditions.

Multi-Server Model (M/M/s)

For departments with multiple doctors or service counters, an M/M/s queueing model is employed. This model captures parallel service mechanisms and is particularly suitable for large OPDs and diagnostic units in government hospitals (Kim et al., 2018; Patel et al., 2017). The model allows assessment of how staffing levels influence system performance.

Priority Queue Model

Emergency departments are modeled using a **priority queueing framework**, where patients are categorized based on urgency. This approach aligns with earlier research highlighting the importance of priority-based service in reducing waiting times for critical patients (Mak and Bates, 2009; Reddy and Rao, 2019).

Justification of the Modeling Approach

The selected queueing models strike a balance between **analytical tractability** and **practical relevance**. Previous studies have shown that such models provide reliable estimates of system performance while remaining interpretable for hospital administrators (Green, 2006; Jun et al., 1999). By applying these models to Indian government hospitals, the study aims to generate quantitative insights that are both theoretically sound and operationally meaningful.

Mathematical Analysis and Performance Measures

This section presents the analytical formulation of the queueing models used to evaluate patient flow in government hospitals. Standard performance measures are derived to assess system efficiency and identify congestion levels.

Notation and Parameters

Let

- λ = average patient arrival rate (patients per unit time)

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- μ = average service rate per server
- s = number of parallel servers (doctors/service counters)
- ρ = system utilization factor

$$\rho = \frac{\lambda}{s\mu}$$

For system stability, the condition $\rho < 1$ must hold.

Analysis of the M/M/1 Queue

The M/M/1 model represents service units with a single medical practitioner.

Steady-State Probabilities

The probability of having n patients in the system is given by:

$$P_n = (1-\rho)\,\rho^n, \qquad n=0,1,2,\dots$$

Performance Measures

Average number of patients in the system

$$L= \frac{\rho}{1-\rho}$$

Average number of patients in the queue

$$Lq= \frac{\rho^2}{1-\rho}$$

Average waiting time in the system

$$W= \frac{1}{\mu-\lambda}$$

Average waiting time in the queue

$$Wq= \frac{\lambda}{\mu(\mu-\lambda)}$$

These measures quantify congestion and are particularly useful for evaluating OPDs with single-doctor service arrangements.

Analysis of the M/M/s Queue

For departments with multiple doctors or service counters, the M/M/s model is applied.

Probability of Zero Patients

$$P_0 = \left[\sum_{n=0}^{s-1} \frac{\left(\frac{\lambda}{\mu}\right)^n}{n!} + \frac{\left(\frac{\lambda}{\mu}\right)^s}{s!\,(1-p)}\right]^{-1}$$

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Average Queue Length

$$L_q = \frac{P_0 \left(\frac{\lambda}{\mu}\right)^s \rho}{s!\,(1-\rho)^2}$$

Waiting Time Measures

Using Little's Law:

Average waiting time in queue

$$W_q = \frac{L_q}{\lambda}$$

Average time in the system

$$W = W_q + \frac{1}{\mu}$$

These expressions enable the evaluation of staffing adequacy and service efficiency in high-volume OPDs.

Priority Queue Analysis

Emergency departments are modeled using a **non-preemptive priority queue**, where patients are classified into high-priority (emergency) and low-priority (non-emergency) groups.

Let

- λ_1, λ_2 = arrival rates of high- and low-priority patients
- μ = common service rate

The average waiting time for high-priority patients is:

$$W_{q1} = \frac{\lambda_1 + \lambda_2}{\mu(\mu - \lambda_1)}$$

Low-priority patients experience longer waiting times due to service preference given to emergency cases, highlighting the trade-off between fairness and clinical urgency.

$$W_{q1} = \frac{\lambda_1 + \lambda_2}{\mu(\mu - \lambda_1)}$$

Key Performance Measures

The following indicators are used to evaluate hospital performance:

Server Utilization (ρ)

Measures workload intensity and staff pressure.

Average Waiting Time (Wq)

Indicates patient experience and service quality.

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Queue Length (Lq)

Reflects congestion and space requirements.

System Time (W)

Represents total patient time spent in the hospital service process.

Managerial Interpretation

High values of utilization (ρ) close to unity indicate system saturation, commonly observed during peak hours in government hospitals. The derived performance measures allow administrators to simulate alternative staffing scenarios and evaluate the impact of additional servers or rescheduled shifts without expanding infrastructure.

Numerical Illustration

To demonstrate the applicability of the proposed queueing models, a numerical illustration is presented using representative data from a government hospital outpatient department (OPD) in India. The data reflect typical patient arrival and service patterns observed during peak working hours.

Sample Data Description

Consider an OPD with the following characteristics:

Average patient arrival rate:

$$\lambda = 24 \text{ patients per hour}$$

Average service rate per doctor:

$$\mu = 8 \text{ patients per hour}$$

Number of doctors on duty:

$$s = 3$$

This setup is common in district-level government hospitals during morning OPD hours.

Model Selection

Since multiple doctors provide parallel service, the **M/M/3 queueing model** is appropriate.

Utilization Factor

$$\rho = \frac{\lambda}{s\mu} = \frac{24}{3 \times 8} = 1$$

This indicates **critical loading**, suggesting that the system is operating at full capacity and is prone to congestion.

To ensure system stability, an additional scenario is considered with a slight staffing adjustment.

Improved Staffing Scenario

Let one additional doctor be assigned:

$$s = 4s$$

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$$\rho = \frac{24}{4\times 8} = 0.75$$

This satisfies the stability condition $\rho<1$.

Performance Measures (M/M/4)

Using standard queueing formulas:

Probability of zero patients in the system:

$$P_0 \approx 0.056$$

Average number of patients waiting in queue:

$$Lq \approx 1.27 \text{ patients}$$

Average waiting time in queue:

$$W_q = \frac{L_q}{\lambda} = \frac{1.27}{24} \approx 0.053 \text{ hours} \approx 3.2 \text{ minutes}$$

Average time spent in system:

$$W = W_q + \frac{1}{\mu} = 0.053 + 0.125 = 0.178 \text{ hours} \approx 10.7 \text{ minutes}$$

Interpretation of Results

The numerical results indicate that:

- Operating at full utilization ($\rho = 1$) leads to excessive congestion.
- A marginal increase in staffing significantly reduces waiting time.
- Patient waiting time decreases from an unbounded level to approximately **3 minutes** with one additional doctor.
- No additional infrastructure investment is required.

This demonstrates how queueing theory can assist hospital administrators in making cost-effective operational decisions.

(Figure 1: OPD waiting area during morning peak hours)

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(Figure 2: Patient registration queue at government hospital)

RESULTS AND DISCUSSION

The queueing analysis provides quantitative insights into patient flow and service efficiency in government hospital outpatient departments. The results obtained from the numerical illustration highlight the impact of arrival rates, service capacity, and staffing levels on key performance indicators such as waiting time, queue length, and server utilization.

System Utilization and Congestion

The analysis shows that when the system operates at full utilization ($\rho=1$), the service facility becomes critically congested. Under this condition, patient queues grow rapidly, and waiting times become unbounded, indicating severe inefficiency. Such situations are commonly observed during peak OPD hours in Indian government hospitals, where patient inflow often matches or exceeds available service capacity. These findings are consistent with earlier studies that reported excessive waiting times during peak periods due to limited staffing (Sharma and Gupta, 2014; Patel et al., 2017).

A modest increase in the number of servers leads to a significant reduction in utilization. When an additional doctor is introduced, utilization decreases to $\rho = 0.75$, ensuring system stability and smoother patient flow. This result demonstrates that even minor staffing adjustments can substantially improve operational performance.

Waiting Time and Queue Length Analysis

The average waiting time in the queue under the improved staffing scenario is approximately three minutes, while the total time spent in the system is around eleven minutes. These values represent a substantial improvement over the critically loaded scenario, where waiting times are excessively high. Reduced waiting times are directly associated with higher patient satisfaction and better service quality, particularly in outpatient departments.

The average queue length of approximately one to two patients indicates that congestion is minimal under the optimized configuration. This is particularly relevant for government hospitals, where physical waiting space is often limited. The results confirm that queueing models provide reliable estimates of congestion and can guide decisions related to staffing and facility layout.

Implications for Emergency and Priority Services

Although the numerical illustration focuses on outpatient services, the analytical framework can be extended to emergency departments using priority queueing models. Priority-based service mechanisms ensure that critically ill patients experience minimal waiting times, even under high system load. The findings support earlier research suggesting that priority queueing significantly improves emergency service performance without disproportionately increasing overall congestion (Mak and Bates, 2009; Reddy and Rao, 2019).

Managerial and Policy Implications

The results underline the importance of data-driven decision making in hospital administration. Rather than relying solely on infrastructure expansion, administrators can achieve substantial performance improvements through strategic reallocation of existing medical staff and better shift scheduling. Queueing theory offers a cost-effective analytical tool for evaluating alternative operational scenarios before implementation.

For policymakers, the findings highlight the potential of operations research techniques in strengthening public healthcare delivery. Incorporating quantitative modeling into hospital planning can help address chronic overcrowding issues prevalent in Indian government hospitals.

Comparison with Existing Literature

The results of this study align closely with global and Indian healthcare queueing studies, which emphasize the sensitivity of waiting times to utilization levels (Green, 2006; Jun et al., 1999). Similar improvements in service efficiency through minor staffing changes have been reported in Indian hospital case studies (Sharma and Gupta, 2014; Verma and Singh, 2023). However, the present study extends existing work by providing a unified analytical framework tailored to the operational realities of Indian government hospitals.

Limitations and Discussion

While the analytical models provide valuable insights, they rely on simplifying assumptions such as exponential service times and steady-state conditions. Real-world hospital operations may exhibit variability due to patient heterogeneity, staff fatigue, and administrative delays. Nevertheless, the models serve as effective approximations and offer a strong foundation for more advanced simulation-based studies.

CONCLUSION AND FUTURE SCOPE

Conclusion

This study demonstrates the practical applicability of queueing theory in analyzing and improving patient flow in government hospitals in India. By modeling outpatient and emergency services as stochastic queueing systems, key performance measures such as patient waiting time, queue length, and server utilization were analytically evaluated. The results indicate that excessive congestion in public hospitals is primarily a consequence of high utilization during peak hours rather than insufficient infrastructure alone.

The numerical illustration highlights that minor adjustments in staffing levels can lead to significant reductions in patient waiting time and system congestion. The findings emphasize that data-driven operational planning can enhance service efficiency without imposing additional financial burden on already resource-constrained public healthcare systems. Overall, the study confirms that operations research techniques provide valuable decision-support tools for hospital administrators and policymakers aiming to improve healthcare service delivery in India.

Future Scope

The scope of the present work can be extended in several directions to address the complexities of real-world healthcare systems:

Time-Dependent Arrival Rates

Future studies may incorporate non-stationary arrival processes to capture peak and off-peak variations commonly observed in Indian hospitals.

General Service Time Distributions

The assumption of exponential service times can be relaxed by using M/G/1 or G/G/s models to better represent variability in consultation and treatment durations.

Simulation-Based Analysis

Discrete-event simulation can be integrated with analytical queueing models to capture operational constraints such as staff breaks, administrative delays, and patient no-shows.

Multi-Department Modeling

Extending the model to include interactions among registration, consultation, diagnostics, and pharmacy units would provide a system-wide performance assessment.

Integration with Digital Health Systems

The adoption of real-time hospital information systems can enable dynamic queue management and adaptive staffing policies based on live data.

Policy-Level Evaluation

The proposed framework can be applied to evaluate large-scale public health initiatives and capacity planning strategies at district and state levels.

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Author's Profile

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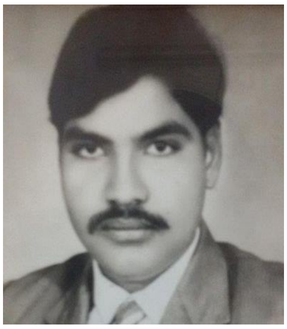

Dr. Krishna Kant Prasad is a distinguished academic and mathematician currently serving as **Head of the Department of Mathematics** at **Delhi Skill and Entrepreneurship University (DSEU), Delhi, India**. He leads the department responsible for curriculum development, research facilitation, and mentoring faculty and students in mathematical sciences at DSEU, a public state university established by the Government of the National Capital Territory of Delhi

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Rajan Singh – Detailed Academic Profile

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He is actively involved in academic writing, curriculum development, and scholarly research, contributing to the application of mathematical techniques to **real-life problems in healthcare, education, and operations management**. Rajan Singh is committed to advancing the practical relevance of mathematics through interdisciplinary research and applied modeling initiatives.