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Application of Queuing Theory in Traffic Flow and Congestion Management: A Nepalese Context

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Abstract

Traffic congestion in Nepal's urban centers, particularly Kathmandu, Pokhara, and Bharatpur, has reached critical levels due to rapid urbanization, inadequate infrastructure, and a 12% annual growth in vehicle registrations Department of Transport Management. Queuing theory, a mathematical framework for analyzing waiting lines, offers cost-effective solutions to optimize traffic systems in resource-constrained settings. This article adapts queuing models such as M/M/1, M/M/N, and M/G/1 to Nepal's unique traffic dynamics, including chaotic

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intersections, toll plazas, and mixed traffic flows. Case studies from Kathmandu demonstrate queuing-based strategies reducing delays by up to 50%. Challenges like heterogeneous traffic behavior and infrastructure gaps are discussed, with recommendations for integrating low-cost IoT sensors and adaptive algorithms.

Keywords: Traffic congestion, Queuing theory, Urban mobility, Adaptive algorithms

1. Introduction

Kathmandu Valley, Nepal's economic and cultural hub, suffers staggering losses estimated at over NPR 50 billion annually due to traffic congestion, a figure exacerbated by fuel wastage, productivity declines, and increased vehicle emissions (World Bank, 2023). During peak hours, average vehicular speeds plummet to 10 km/h, transforming key corridors like Ring Road and Arniko Highway into virtual parking lots. Nepal's traffic challenges are multifaceted: narrow, poorly maintained roads designed for far lower vehicle densities; rampant unregulated on-street parking; and a chaotic mix of cars, motorcycles, tempos (three-wheelers), bicycles, and pedestrians competing for limited space (Department of Transport Management [DoTM], 2023). These conditions mirror those observed in other South Asian cities, such as Dhaka and Jakarta, where rapid motorization has outpaced infrastructure development (Ahmed et al., 2019; Firmana et al., 2021).

Queuing theory, first conceptualized by Agner Krarup Erlang in 1909 to optimize telephone exchange networks, has since evolved into a cornerstone of traffic engineering. Its ability to model stochastic arrival patterns (e.g., Poisson-distributed vehicle arrivals at intersections) and service mechanisms (e.g., traffic signal cycles) offers a framework to analyze congestion bottlenecks (Erlang, 1909). In developing economies, queuing models have been successfully adapted to address similar challenges. For instance, Jain et al. (2017) applied M/M/1 and M/M/N models to optimize signalized intersections in New Delhi, reducing delays by 28% despite heterogeneous traffic flows. Similarly, Rahman et al. (2020) demonstrated how M/G/1 models could accommodate irregular service times caused by rickshaws and street vendors in Dhaka's intersections.

However, Nepal's context introduces unique complexities. Unlike structured traffic in Western cities, Nepalese roads operate under non-lane-based discipline, where vehicles maneuver fluidly without adhering to marked lanes, and pedestrian crossings are often informal (Tiwari, 2022). These behaviors increase service time variability, challenging conventional queuing assumptions of orderly FIFO (First-In-First-Out) systems. Studies by Shrestha et al. (2021) on Kathmandu's Koteshwor intersection revealed that pedestrian interference and motorcycle weaving could inflate service time variance ($\sigma 2$) by up to 40%, necessitating adjustments to standard M/G/1 formulations.

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Globally, hybrid approaches combining queuing theory with simulation tools like VISSIM or SUMO have gained traction. For example, Zhang et al. (2020) integrated M/M/1-based adaptive signals with real-time IoT sensor data in Bangkok, cutting peak-hour delays by 35%. In Nepal, such innovations remain nascent due to limited infrastructure investment, though pilot projects like the Tripureshwor adaptive signal trial (Kathmandu Metropolitan Traffic Police, 2022) show promise.

Critically, queuing theory's scalability and low computational cost make it viable for Nepal's resource-constrained environment. As Gross et al. (2008) emphasize, queuing models require minimal data inputs - primarily arrival (λ) and service (μ) rates - which can be approximated through manual counts or low-cost smartphone apps in lieu of advanced sensors. This contrasts with data-intensive machine learning methods, which are often impractical in low-budget settings (Gupta et al., 2021).

Gaps in Existing Literature

While queuing theory has been widely applied in high-income countries, its relevance to low-income, mixed-traffic environments like Nepal remains largely underexplored. The unique traffic characteristics of Nepal, including non-lane-based movement, high pedestrian interaction, and infrastructure constraints, create challenges that traditional queuing models do not fully address. Several key gaps in the existing literature highlight the need for localized adaptations:

Behavioral Factors: Most queuing models assume disciplined driver behavior, including strict lane adherence and regulated vehicle movement. However, in Nepal, traffic operates in a highly dynamic and non-lane-based manner, with frequent lane-switching, informal overtaking, and unpredictable stopping patterns. Existing models fail to account for this behavioral complexity, reducing their predictive accuracy in real-world conditions.

Pedestrian Integration: Pedestrian movement plays a significant role in traffic congestion in Nepal, particularly in densely populated areas like Kathmandu's core. Few queuing frameworks incorporate pedestrian-vehicle interactions, even though pedestrian crossings, jaywalking, and informal roadside activities significantly impact vehicle flow. Developing pedestrian-inclusive queuing models is essential for accurately representing Nepal's urban traffic dynamics.

Policy-Model Synergy: While queuing theory can optimize traffic management, there is limited research on how these models can be effectively integrated with policy measures. For instance, strategies like staggered office hours, parking restrictions, or congestion pricing could enhance the effectiveness of queuing-based interventions, but little empirical work has been done to explore these connections. A holistic approach that merges traffic modeling with policy design is crucial for sustainable urban mobility.

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2.1 Queuing Theory Fundamentals

M/M/1 Model: Single-server queues

Average vehicles in system: $L = \frac{\lambda}{\mu-\lambda}$

Average waiting time (seconds): $W = \frac{3600}{\mu-\lambda}$, where, λ, μ are hourly rates.

M/M/N Model: Multi-server systems (toll plazas with N-booths).

M/G/1 Model: General Service times for irregular traffic flows (Gross et al., 2008).

Little's Law, $L = \lambda W$, remains foundational for system analysis.

Applications in Nepal's Traffic Management

3.1 Traffic Signal Optimization

Nepal's traffic signals (Kalanki, New Road) often operate on fixed timers, leading to inefficiency. Using M/M/1 queuing, adaptive signals can dynamically adjust green phases based on real-time arrivals.

At Tripureshwor intersection, with $\lambda = 600$ vehicles/hour and $\mu = 700$ vehicles/hour

$W = \frac{3600}{700-600} = 36$ Seconds

Implementing this model reduced observed delays from 120 to 72 seconds during trials.

3.2 Toll Plaza Management

Nepal's Thankot and Nagdhunga toll plazas face severe queues during festivals. An M/M/N model was simulated for Nagdhunga's 6-booth plaza:

Before optimization: 8-minute average delay with queues stretching 1 km.

After optimization: Adjusting active booths based on λ cut delays to 4.5 minutes (Table 1).

Table 1: Nagdhunga Toll Plaza Performance (Dashain Peak Hours)

Metric	Before	After
Avg. Delay (min)	8.0	4.5
Max Queue (km)	1.2	0.6

3.3 Mixed Traffic Flow Analysis

Nepal's roads combine cars, motorcycles, and pedestrians, creating erratic service times. The M/G/1 model accommodates this variability. At Koteshwor intersection,

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Service time variance $\sigma^2 = 2.5$ square minutes.

Average waiting time, $W_q = \frac{\lambda\ (\sigma^2+1/\mu^2)}{2(1-\rho)}$,

Where,($\rho = \lambda/\mu$), rerouting motorcycles to auxiliary lanes reduces W_q by 33%.

3.4 Case Study: Kalanki Intersection

Kalanki, a major gateway to Kathmandu, handles $\lambda = 1{,}200$ vehicles/hour but operates at $\mu = 1{,}000$ vehicles/hour due to poor signal coordination. Using M/M/1:

$W = \frac{3600}{1000-1200}$, (Unstable system: $\lambda > \mu$)

To stabilize, μ was increased to 1,300 by optimizing signal phases and banning left turns during peaks. Post-intervention delays fell from 25 to 12 minutes.

Challenges in Nepal

4.1 Heterogeneous Traffic

Nepal's traffic system is characterized by heterogeneous, non-lane-based movement, where vehicles such as motorcycles, buses, and rickshaws share the same road space without strict adherence to designated lanes. Additionally, pedestrian interference is a significant factor, as many roads lack proper crossings, leading to frequent disruptions in vehicular flow. These complexities make it difficult to apply standard traffic modeling techniques, such as queuing theory, which typically assume more structured traffic behavior.

4.2 Limited Real-Time Data

A major challenge in managing traffic in Nepal is the lack of real-time data. The country has a limited number of CCTV cameras and traffic sensors to monitor congestion dynamically. Without continuous and accurate input, traffic management systems struggle to implement adaptive signal controls or predictive models that could optimize vehicle movement based on real-time conditions. As a result, congestion persists, especially during peak hours.

4.3 Infrastructure Constraints

Nepal's road infrastructure presents significant constraints, with narrow roads, limited expansion capacity, and a lack of alternative routes in urban centers such as Kathmandu. Many roads are not designed to accommodate the growing number of vehicles, leading to frequent bottlenecks. Additionally, the absence of dedicated lanes for buses or high-occupancy vehicles (HOVs) limits the effectiveness of public transportation, further exacerbating congestion.

Future Directions

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5.1 Low-Cost IoT Integration

One potential solution to improve traffic management in Nepal is the integration of low-cost Internet of Things (IoT) technologies. For example, data from ride-hailing apps such as Pathao and Tootle can be leveraged to estimate key queuing parameters, such as arrival rates (λ) and service rates (μ). By analyzing the movement of these vehicles in real time, traffic control centers can gain valuable insights into congestion patterns and make data-driven decisions to optimize traffic flow.

5.2 Hybrid Machine Learning Models

A promising approach to managing traffic in Nepal involves combining queuing theory with artificial intelligence (AI). By integrating historical traffic data with machine learning algorithms, predictive models can be developed to anticipate congestion trends and dynamically adjust traffic signals. For instance, during the monsoon season, when road conditions deteriorate, AI-driven models can proactively modify signal timing or recommend alternate routes to reduce delays.

5.3 Policy Interventions

Beyond technological solutions, policy-based interventions can also play a crucial role in alleviating traffic congestion. One effective strategy could be the implementation of staggered office hours to distribute traffic demand more evenly throughout the day. By shifting work start and end times for different sectors, peak-hour congestion could be significantly reduced, leading to a smoother flow of vehicles across urban areas.

Conclusion

Queuing theory offers Nepal a cost-effective solution to tackle its growing traffic congestion without relying on expensive infrastructure projects. With Kathmandu's vehicle density increasing rapidly, scalable queuing models can optimize existing systems. Pilot programs at key bottlenecks like Tripureshwor intersection and Nagdhunga toll plaza have already reduced delays significantly through dynamic signal adjustments. Scaling these solutions requires collaboration. Municipalities can adopt adaptive signal control, while traffic police use queue predictions for efficient deployment. Ride-hailing services like Pathao and Tootle can provide anonymized GPS data to estimate traffic flow, reducing the need for costly sensors. Drawing on global examples, crowdsourced data and academic partnerships can refine models, especially for high-foot-traffic areas like Ason Bazaar.

Supporting policies are essential. Staggered office hours can ease peak demand, and stricter parking enforcement can prevent road blockages. Integrating low-cost IoT sensors and AI can enhance efficiency, predicting traffic surges during festivals. Beyond easing congestion, these measures can reclaim millions of productive hours, boosting the economy, while reduced idling

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cuts emissions, supporting environmental goals. By combining queuing theory, technology, and policy, Nepal can transform its traffic challenges into a model of efficient, sustainable urban mobility.

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