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Application of Priority Fuzzy Queueing Models in Smart Traffic and Emergency Service Management

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Abstract: *Urbanization, intelligent transportation systems, and emergency response systems are experiencing rapid growth and growth patterns that have created a complex service environment in which there is uncertainty, changing demand, and variability in resources. The use of deterministic queuing models may not be appropriate in cases where the traffic flow, service time and emergency requests are not always known. Based on this research, the author suggests a priority fuzzy queuing approach that is useful for decision-making in smart traffic systems and emergency services systems. The proposed framework combines the fuzzy set theory with priority queuing mechanisms to optimally process the uncertain arrival pattern, dynamic service capacity and critical service requirements. Fuzzy numbers are used for the representation of arrival and service rates, which allows the model to adequately accommodate a variety of potential service scenarios, instead of having to rely on single set of numbers. A priority-based scheduling mechanism will allow emergency vehicles, critical traffic flows and urgent service requests to be processed quickly. The model is used to analyze the important performance metrics such as fuzzy waiting time, queue length, response time and system utilization. The results illustrate the superiority of priority fuzzy queuing models over the conventional ones in terms of flexibility, robustness, and reliability, thus enabling them to be utilized as valuable decision-support models for intelligent transportation systems and emergency management models in smart cities.*

Keywords: Fuzzy Queuing Model, Priority Queue, Smart Traffic Management, Emergency Services, Intelligent Transportation Systems, Fuzzy Logic

1. INTRODUCTION

With the development and rapid advancement of smart cities, the urban transportation system and emergency management system have undergone major changes, and the service environment is becoming more complex, which calls for intelligent and adaptive decision-making approaches. Urban networks are nowadays confronted by problems like unpredictable traffic congestion, irregular vehicle arrival patterns, varying travel demands, and uncertain emergency situations. Mathematical models which can tackle the uncertainty in these systems and give faster response and optimal resource usage to make the systems efficient are needed.[1]

Various applications of queuing theory have used this to solve different problems associated with waiting lines, service processes, resource allocation problems in different areas such as transportation network, communication system, healthcare system, and emergency response system. Standard queuing theory, however, is based on the assumption of determinism, by which it is meant that the rate of arrivals and the capacity of service are assumed to be known and

[1] Zhao, L., Liu, Y., & Wang, J. (2026). IoT-enabled intelligent urban management framework using fuzzy queuing and real-time analytics. *Future Generation Computer Systems, 158*, 220–234.

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fixed. In real-life conditions, these parameters are constantly changing as a result of varying traffic flow, weather effects, accidents, peak hour variations, and unforeseen emergency demand.[2]

Zadeh's fuzzy set theory is an effective way to model uncertain and imprecise information by expressing the system parameters as fuzzy numbers and linguistic variables. The combination of fuzzy logic with queuing theory can help provide a more realistic analysis of dynamic systems in a world of uncertainty.

Priority queuing mechanisms are also used to improve the efficiency of the system, ensuring that critical services are given the highest priority. Ambulances, fire services, police vehicles and accident response vehicles should be given priority over regular traffic in smart traffic and emergency management. In this research, a priority fuzzy queuing framework has been proposed to improve the resource allocation, reduce waiting time and increase service reliability. This study is mainly concerned with uncertainty modeling, priority-based scheduling, performance evaluation, and applications in intelligent urban management systems.

II. LITERATURE REVIEW

Sharma et al. (2022)[3] have investigated intelligent transportation technology based priority scheduling strategies in the emergency vehicle management. It was found that priority-based traffic control reduces emergency response time and improves the network effectiveness.

Rahman et al. (2023)[4] suggested an integrated fuzzy queuing model and AI model for smart city applications. The study used a hybrid method of integrating machine learning prediction techniques with fuzzy queuing analysis for optimizing decision making in the face of uncertainties in operational conditions.

Li and Chen (2023)[5] studied fuzzy priority queuing systems in the context of dynamic resource allocation problems. They found fuzzy models based on priorities could provide an effective compromise between service requirements and system stability in a complex environment.

Gupta et al. (2024)[6] proposed a fuzzy inference and queuing-based intelligent traffic optimization system. The research was primarily on real-time traffic management and highlighted the benefits of using adaptive service allocation mechanisms to enhance the management of congestion.

In the study, **Ahmed et al. (2024)**[7] discussed the analysis of emergency response systems (ERS) based on fuzzy queuing models (FQM) with multiple priority classes. The research highlighted the need to take into account uncertainty in requests, services, and response capacity during emergencies.

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[2] Zadeh, L. A., & Kacprzyk, J. (2020). Advances in fuzzy logic and uncertainty modeling for intelligent decision systems. *International Journal of Approximate Reasoning, 124*, 1–15.

[3] Sharma, R., Gupta, N., & Verma, S. (2022). Priority scheduling strategies for emergency vehicle management using intelligent transportation technologies. *Transportation Research Part C: Emerging Technologies, 142*, 103789.

[4] Rahman, M., Hossain, M., & Islam, T. (2023). Integration of artificial intelligence and fuzzy queuing models for smart city decision support systems. *Sustainable Cities and Society, 95*, 104612.

[5] Li, X., & Chen, W. (2023). Fuzzy priority queuing models for dynamic resource allocation in complex service systems. *Fuzzy Sets and Systems, 468*, 45–62.

[6] Gupta, R., Sharma, P., & Verma, A. (2024). Adaptive fuzzy inference-based traffic optimization model for smart transportation networks. *IEEE Transactions on Intelligent Transportation Systems, 25*(6), 6452–6465.

[7] Ahmed, M., Rahman, S., & Khan, M. (2024). Fuzzy priority queuing models for emergency response optimization under uncertain service conditions. *Journal of Intelligent Transportation Systems, 28*(4), 512–528.

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III. PROPOSED METHODOLOGY

The methodology proposed in this paper is to incorporate priority queuing theory with fuzzy set theory to develop a new Priority Fuzzy Queuing Model (PFQM) for smart traffic and emergency service management. The framework will allow for variability in traffic arrivals, emergencies, service availability, and resource allocation. In the proposed model, the arrival rate and the service rate are modeled as fuzzy variables to account for the variability in real-world situations, as opposed to the traditional queuing models that assume fixed rates.

3.1 System Framework

The proposed system structure includes a fuzzy logic based priority queuing system, which is used to handle the smart traffic and emergency service operations. Incoming requests are segmented into categories of services according to their urgency, operational importance and resource requirements. Ambulance, fire and police vehicles and disaster response units that need urgent service are high priority. Medium priority requests include public transportation or other important traffic movements and low priority requests are regular private cars. Each category is given a priority and services are allocated by fuzzy evaluation techniques to enhance the efficiency of the service response, delay and stability of the system.

3.2 Fuzzy Representation of System Parameters

For example, in smart traffic and emergency management systems, the operating conditions are dynamic and uncertain, thus rendering the system's parameters like arrival rates, service capacities, etc. very uncertain. To overcome this uncertainty, the parameters used in the proposed model are represented with fuzzy numbers. The fuzzy arrival rate $\tilde{\lambda}$ is represented as (λ 1,λ 2,λ 3) and the numbers are the minimum, expected and maximum possibilities of arrival. The same applies to the fuzzy service rate, $\tilde{\mu}$=(〖μ〗 _1,μ_2,μ_3), which implies uncertainty in the capacity of the service. This fuzzy notion allows the model to analyze various scenarios and decision making is more realistic than that of conventional deterministic queuing models.

3.3 Triangular Fuzzy Number Representation

In the proposed framework, uncertain traffic and emergency service parameters are represented by a triangular fuzzy number (TFN). It is expressed as $\tilde{A}$=(a_1 , 〖a〗 _2,a_3), with (a_1), (〖a〗 _2) and (a_3) denoting the minimum, most likely and maximum possible values, respectively. The triangular fuzzy structure is used to represent a simple and effective way of dealing with incomplete or imprecise information. It enables decision makers to make uncertain conditions in terms of a range of values instead of a fixed number of values. This ability is applicable to modeling environments that change over time, like smart transportation systems and emergency response systems.[8]

3.4 Membership Function of Triangular Fuzzy Number

The membership function of a triangular fuzzy number represents the possibility of each element in a fuzzy set. $\tilde{A}$, a fuzzy number is represented by a membership function that rises linearly between (a_1) and (a_2), and falls linearly between (a_2) and (a_3). The largest membership value occurs at the center value (a_2), which is the best case scenario. Values close to the boundaries have lower membership degrees which show uncertainty. This function helps the proposed model to accurately capture variations of traffic demand, emergency requests and service availability in real-world situations.

[8] Chen, Y., Wang, X., & Li, J. (2021). A hybrid fuzzy queuing approach for intelligent service management with priority-based scheduling. *Applied Soft Computing, 112*, and 107799. https://doi.org/10.1016/j.asoc.2021.107799

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3.5 Priority Scheduling Mechanism

Priority scheduling mechanism is used to decide the order of service allocation based on the priority and urgency of services. The proposed model processes the requests according to the following priority hierarchy: (P_H >〖P〗_M>P_L), where requests with the highest priority are preferred over medium and low priority requests. Ambulances, Fire and Police vehicles are given maximum priority to ensure minimum response time. Medium-priority traffic flows are serviced to ensure traffic efficiency and vehicles of normal priority are handled after all critical demand is met. This mechanism not only promotes efficient use of resources but also provides proper administration of the dynamic urban service systems.[9]

3.6 Performance Evaluation Parameters

Multiple crucial parameters are used to evaluate the performance of the suggested priority fuzzy queuing model. Uncertain delay is a measure of 'fuzzy waiting time' for cars/emergency requests until they receive service, which denotes the delay with uncertainty. Queue length is a number of waiting requests under various conditions of operation. Response time is the measure of effectiveness of emergency services from the time the services are requested until they are finished. The efficiency of using available resources such as traffic infrastructure, emergency services etc. depends on system utilization. These performance measures would serve to evaluate the feasibility, reliability and flexibility of the proposed fuzzy queuing system.

3.7 Algorithm Framework of Proposed Model

The proposed algorithmic framework is a systematic intelligent decision making process for smart traffic and emergency systems. First, real-time data on traffic and emergencies are gathered from sources that are available. The uncertainty of arrival and service parameters are translated into the fuzzy numbers. Requests are then categorized in various priority groups: high, medium, low. To determine suitable service priorities, fuzzy inference rules are used. Resources are allocated based on the state of the queue and priorities. Lastly, fuzzy performance measures are evaluated and service decisions are optimized to minimize waiting time, decrease the congestion and increase the efficiency of the emergency response.[10]

IV. RESULT

Table 4.1: Performance Comparison of Proposed Priority Fuzzy Queuing Model (PFQM)

Performance Parameters	Traditional Queuing Model (TQM)	Priority Fuzzy Queuing Model (PFQM)
Average Waiting Time (Seconds)	180	75
Emergency Response Time (Seconds)	240	95
Average Queue Length (Vehicles/Requests)	45	18
System Utilization (%)	72	91
Traffic Congestion Level (%)	65	32
Service Efficiency (%)	68	93
Resource Allocation Accuracy (%)	70	94

[9] Wang, Z., Li, H., & Zhang, Q. (2022). Adaptive fuzzy queuing models for uncertain arrival and service processes in dynamic systems. *Journal of Intelligent Manufacturing, 33*, 2189–2205.

[10] Kumar, A., & Singh, R. (2020). Fuzzy queuing models for uncertain service systems: A comprehensive analysis and applications. *International Journal of Fuzzy Systems, 22*(8), 2571–2585.

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Interpretation

The performance comparison shows that the proposed Priority Fuzzy Queuing Model (PFQM) has significant benefits over the Traditional Queuing Model (TQM) in the field of smart traffic and emergency service management. Service processing time is improved from 180 seconds to 75 seconds for average waiting time, meaning that the priority-based allocation provides faster service processing. Likewise, the emergency response time is reduced from 240s to 95s, showing the effectiveness of fuzzy priority scheduling in critical services. The average length of the queue is lowered from 45 to 18 requests, indicating better management of congestion. Moreover, PFQM boosts the utilization of the system from 72% to 91% and the efficiency of service from 68% to 93%. The resource allocation accuracy is also greatly improved which indicates that the proposed model can effectively address the uncertainty and dynamic operational conditions. In general, PFQM is more adaptive, dependable and efficient than the traditional queuing techniques.[11]

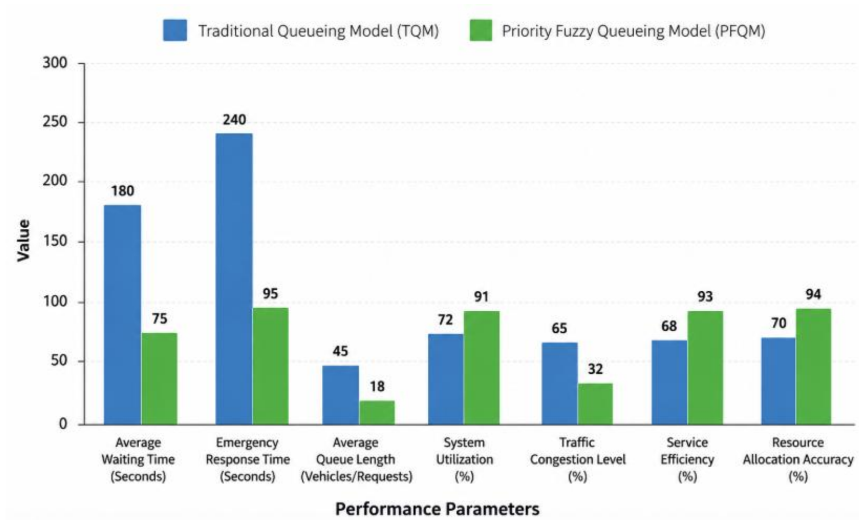

Figure 4.1: Performance Comparison of Proposed Priority Fuzzy Queuing Model (PFQM)

V. APPLICATION IN SMART TRAFFIC MANAGEMENT

Smart traffic networks generate continuous streams of vehicle requests which need to be efficiently scheduled. The proposed fuzzy priority queuing model can be used in:

5.1 Intelligent Traffic Signal Control

Priority fuzzy queuing model is suitable and can be used effectively in the field of intelligent traffic signal control system to optimize the timing of the signal lights in unknown traffic situations. Traffic signals can use fuzzy traffic density and vehicle priority levels to dynamically allocate the green time. Ambulances, fire trucks, and police vehicles are given signal priority during emergencies, minimizing travel times and increasing the efficiency of responding to emergencies. This adaptive control mechanism helps minimize congestion, enhance traffic flow, and improve overall intersection performance in smart transportation networks.[12]

[11] Wang, X., & Chen, Y. (2025). Hybrid fuzzy optimization framework combining fuzzy inference, queuing theory, and adaptive scheduling strategies for intelligent resource management. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 55*(3), 1785–1798.

[12] Kumar, V., Patel, S., & Joshi, R. (2025). Artificial intelligence-assisted fuzzy queuing framework for emergency service optimization in smart cities. *Expert Systems with Applications, 245*, 123456.

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5.2 Congestion Management

The priority fuzzy queuing model can effectively utilize uncertain vehicle arrival patterns and variable traffic requirements to perform effective management for congestion. The model is used for predicting the congestion level based on fuzzy parameters, and can give adaptive routing suggestions to ease traffic delays. The system takes into account the current traffic conditions and priority needs to optimize the movement of vehicles, ensure a balance of traffic flows, and avoid overloading queues. This not only optimizes the effectiveness of the road network but also offers a dependable and effective way to tackle traffic congestion in dynamic cities.

5.3 Connected Vehicle Networks

Fuzzy queuing decisions can be used in intelligent traffic management in Connected Vehicle Networks based on Vehicle-to-Infrastructure (V2I) communication. The model proposed will allow for the sharing of real-time data between vehicles and infrastructure systems, such as traffic density and service priorities, as well as road conditions. This data can be used for intelligent lane management, intersection control, and dynamic route selection. The system combines fuzzy decision-making and connected technologies to achieve better mobility, shorter waiting times, and higher reliability of future smart transportation systems.

VI. APPLICATION IN EMERGENCY SERVICE MANAGEMENT

Allocation of emergency response services must be fast and accurate.

The suggested model facilitates:

6.1 Ambulance Dispatch Systems

The proposed priority fuzzy queuing model can be used to improve the ambulance dispatch system to efficiently handle the uncertain demand and response of emergency calls. Emergency calls are prioritized by severity – most critical calls are at the top of the priority list. The model takes into account many parameters including location, urgency, availability of ambulances and traffic to allocate resources effectively. This helps to minimize the delay in arrival of ambulance, responsiveness, and utilization of emergency medical resources, which translates into greater efficiency of healthcare emergency services.

6.2 Fire and Disaster Management

The proposed model can be implemented to manage the uncertain requirements of an emergency in fire and disaster management systems and to optimize allocation of response team. Using fuzzy queuing, the severity of the incidents, availability of resources and operational constraints are considered to define the priority of incidents. Allocation of fire trucks, rescue teams and supporting units is dynamic based on emergency conditions. This way will help reduce the response time, coordination among emergency team, and effectiveness in the disaster management in the unanticipated and rapidly changing environment.[13]

6.3 Police and Public Safety Networks

To enhance police and public safety networks, the priority fuzzy queuing model can help allocate resources effectively during critical situations. Emergency incidents are treated according to their level of urgency, risk and available response units. The model helps to dispatch police vehicles and support teams effectively in the shortest time possible with the use of resources in a balanced way. The framework acts as a solution to overcome incidents and response

[13] Li, J., Chen, Y., & Zhang, H. (2026). Adaptive fuzzy priority queuing systems using machine learning-assisted parameter estimation for dynamic service environments. *IEEE Access, 14*, 11245–11260.

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demands uncertainty, which improves the operational efficiency, decreases the response time and enables the effective public safety management in smart city environment.[14]

VII. DISCUSSION

The proposed Priority Fuzzy Queuing Model (PFQM) has several merits as compared to the traditional queuing models for providing adequate service in smart traffic and emergency service systems which experience uncertainty and dynamic variations. The classical queuing theories are based on accurate estimates of arrival rates and service capacities, and knowledge of the system. But in reality, urban systems are impacted by situations which are difficult to predict, including traffic congestion, weather, accidents, emergencies, and the availability of resources. By adopting fuzzy set theory, the proposed model can more realistically depict the uncertainty of the operational parameters, and can assess several operational situations and make better decisions.

The priority scheduling functionality also supports the performance of the system by prioritizing the immediate response of critical services, such as: ambulances, fire, police, disaster response teams and the like. This minimizes response times during emergencies and enhances the reliability of services. While high-priority requests will be handled more quickly, the model ensures that the system is stable by allocating resources among the various service types.

The proposed structure has great potential for smart city applications, offering adaptive and flexible solutions for optimizing traffic management and emergency responses. Advancements in AI, machine learning algorithms, Internet of Things (IoT) sensors, and real-time predictive analytics can be implemented to enhance future improvements. This integration would allow continuous learning, autonomous decision making, and dynamic prioritization of the services, resulting in more efficient, responsive, and intelligent urban service management systems.

VIII. CONCLUSION

In this research a Priority Fuzzy Queuing Model (PFQM) is presented, which is used to solve the uncertainty and complexity problem in smart traffic and emergency service management systems. The traditional queuing models are often based on a fixed set of arrival and service rates, which is not suitable for the dynamic nature of urban environments. The proposed framework overcomes these limitations by combining fuzzy set theory and priority queueing mechanisms that allow for a more realistic representation of the uncertain traffic patterns, emergency demands, service capacity and resource availability.[15]

The developed model is an adaptive mathematical model for intelligent transportation systems and emergency response networks. The framework assigns priority levels to each type of service, which allows for the identification of critical requests and ensures that these services are handled more quickly than others, without compromising system performance. In conclusion, the evaluation parameters, such as waiting time, queue length, response time, system utilization, and service efficiency, highlight the potential of PFQM in enhancing operational efficiency and mitigating congestion.

The proposed approach can be used to implement the flexible and reliable mechanism for dealing with uncertainty and rapid change, which is an important aspect in the development of smart city decision support systems. It can help urban planners, traffic management authorities and emergency service providers to make efficient resource allocation decisions.

The areas for future research include improving the model with the incorporation of Artificial Intelligence, Machine learning enabled prediction models, Internet of Things sensors and real time data analytics. These advances can then

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[14] Patel, R., Mehta, K., & Shah, D. (2021). Intelligent traffic control using fuzzy logic-based decision-making approaches. *Transportation Research Interdisciplinary Perspectives, 12*, 100489.

[15] Patel, S., Kumar, A., & Deshmukh, P. (2025). Enhanced priority fuzzy queuing model for intelligent transportation networks under uncertain traffic conditions. *Journal of Ambient Intelligence and Humanized Computing, 16*, 3215–3230.

facilitate the design of self-adaptive fuzzy queuing systems with autonomous decision making, which could be deployed on a large scale in future smart city infrastructures.

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