Proceedings of the 3rd International Conference on Mathematical Physics and Computational Simulation
DOI: 10.54254/2753-8818/92/2025.22038

Configuration of Electric Vehicle Charging Facilities Based on Queuing Theory

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Abstract: With the ongoing energy crisis, the development and utilization of clean energy is an issue that the world is increasingly confronted with. In addition, the number of electric vehicles in both domestic and international markets have steadily increased, making efficient charging solutions essential. Queueing theory provides an effective approach to optimizing charging station locations and capacity allocation, helping to minimize wait times, improve charging pile utilization, and meet electric vehicles charging demands. Research based on queueing models suggests that strategically allocating charging piles and refining queuing mechanisms, such as reservation systems or priority scheduling, can alleviate congestion and enhance service quality. Additionally, integrating queueing theory with energy storage technology enables electric vehicles charging stations to participate in grid dispatching. Through intelligent regulation, these stations can help balance power demand during peak hours, improving grid stability and addressing further challenges related to electric vehicles infrastructure. This work highlights the importance of queueing theory in optimizing the charging stations.

Keywords: Electric vehicle, Charging facilities, Queuing theory

1. Introduction

The current global energy crisis is becoming increasingly serious, and fossil energy has become very scarce. Therefore, electric vehicles, as a kind of renewable energy source, have become an important venue for energy consumption. The development and utilization of clean energy is an issue that the world is increasingly confronted with. Over the past decade, the electric vehicle industry both at home and abroad has undergone significant changes. With the increasing number of electric vehicles in the market, various contradictions and problems of electric vehicles have emerged. Therefore, how to optimize these issues is a significant social problem at present. Meanwhile, it also implies the underlying mathematical principles and methods.

Queuing theory is a typical solution method. Queuing theory plays a significant role in multiple industries at the same time. In traffic management, based on queuing theory, the M/M/C/N model is constructed. It is concluded that the optimal occupancy rate of parking spaces within the area is related to the size of the parking spaces, demand and parking duration. The larger the size, the higher the optimal occupancy rate. The parking policy needs to be dynamically adjusted to balance the utilization efficiency and traffic congestion [1]. In the medical industry, based on queuing theory, use M/M/N combines the quality control circle analysis to explore the influencing factors of the appointment rate of medical resources, proposes a unified medical resource appointment management

DOI: 10.54254/2753-8818/92/2025.22038

system, integrates multiple channels of appointment resources, and achieves a 20% increase in the appointment rate, significantly improves the waiting time and satisfaction of patients, and optimizes the efficiency of hospital appointment services [2]. In communication networks, based on queuing theory and reinforcement learning, a joint optimization strategy for edge computing resources in vehicular networks is proposed. Through KNN task offloading and multi-objective resource allocation, the total system cost is significantly reduced. Compared with traditional methods, it saves an average of 46.3%, effectively improving the collaborative efficiency of communication and computing in high-dynamic environments [3]. In the manufacturing industry, based on queuing theory analysis of the bottleneck process in the production line, the machine combination of process 5 and 6 was optimized to (3, 3), which reduced the average waiting time by 69.54%, the number of work-in-progress by 52.62%, significantly enhancing production efficiency and achieving global optimization of resource allocation. Queuing theory is applied in many fields with the aim of optimizing resource allocation, reducing customer waiting time and enhancing overall operational efficiency.

In Section 2, the author introduced queuing theory, M/M/1, M/M/c, M/G/1 and M/M/∞. This is followed by an introduction of their applications in Section 3. Finally, the conclusion is devoted in Section 4.

2. Theory and Method

2.1. Components of a Queueing System

In this system, it has the following components [4]. The first is Customers. It means that Individuals who need to receive services, such as bank customers, hospital patients, data packets, etc. The second is Servers. This component means the resources providing services, such as cashiers, customer service staff, computer servers, etc. The third is Arrival Process. It means the pattern of describing the arrival of customers to the system is usually modeled by using the Poisson Process. The forth is Service Mechanism. This means the distribution of service time is described by common models such as exponential distribution and general distribution. The fifth component is Queue Discipline. It determines the service sequence, for example FCFS, LCFS, SJF and Priority Scheduling. FCFS (First Come, First Served) means that customers are served in the order of their arrival. LCFS (Last Come, First Served) means the most recent arrival is served first. SJF (Shortest Job First) means the customer with the shortest service time is prioritized. Priority Scheduling means Higher-priority customers are served first.

Furthermore, the queuing system also involves two key parameters. The first is System Capacity. It means the maximum queue length, which can be finite (e.g., limited parking spaces) or infinite (e.g., internet traffic). The other is Customer Behavior which means Customers may leave if the wait is too long (balking) or switch between queues (jockeying). Queuing systems are usually described using Kendall notation A/B/C/K/N/D. Table 1 shows the Kendall's Notation.

Table 1: Kendall notation for Queuing systems

Notation	Expression	Notation	Expression
A	Arrival process (M for Poisson arrivals, G for general distributions).	B	Service time distribution (M for exponential, G for general distributions).
C	Number of servers.	K	System capacity (omitted if infinite).
N	Total population size (omitted if infinite).	D	Service discipline (e.g., FCFS).

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2.2. Mathematical Models of Queueing Theory

In this subsection, the author will introduce four selected models.

The first is M/M/1 Model. The Assumptions of this model are following. Poisson Arrival Process means Customers arrive randomly at a rate of λ(average arrival rate per unit time). Exponential Service Time means the service rate per server follows an exponential distribution with an average rate μ. Single Server ($c = 1$) means There is only one service provider. First Come, First Served (FCFS) mean Customers are served in order of arrival. Infinite Queue Capacity and Population mean No limit on the number of waiting customers.

There are several formulas. The formula for System Utilization (ρ) is $\rho = \lambda/\mu$ $(\rho < 1)$. In this formula system utilization (ρ) represents the degree of busyness of the service desk, which represents the ratio of arrival rate to service rate. When $\rho < 1$, the system is in a stable state; if $\rho \geq 1$, the queue will grow indefinitely. The equation for the Average Number of Customers in the Queue ($\boldsymbol{L_q}$) can be expressed as $\lambda^2/\mu(\mu - \lambda)$. This equation is used to calculate the average number of customers waiting in the queue, not including those currently being assisted. Its applicable conditions are: A single service counter (such as the M/M/1 model). Customer arrivals follow a Poisson distribution, and service times follow an exponential distribution. The queue capacity is unlimited and the system is stable ($\rho < 1$). The formula for Average Number of Customers in the System (L) is $L = \lambda/(\mu - \lambda)$. This equation represents the average total number of customers in the system, including both those being served and those waiting in line. Its relationship with L_q is $L = L_q + \rho$. The applicable conditions are the same as those for L_q, and it is necessary to satisfy ρ. The formula for Average Waiting Time in Queue (W_q) is $W_q = \lambda/[\mu(\mu - \lambda)]$. λ is customer arrival rate and μ is service journey of a single service desk. This formula represents the average time that customers have to wait for service in the queue. The formula for calculating the average system occupancy time (W) is $W = 1/(\mu - \lambda)$. This formula represents the total average time (waiting time + service time) of customers in the system. It must satisfy $\rho = \lambda/\mu < 1$.

The second is M/M/c Model (Multiple Servers). The assumptions of this formula are: similar to M/M/1 but with c parallel servers and suitable for service environments with multiple operators, such as hospital reception desks or bank tellers.

There are two key formulas. First is for System Utilization. It is p = $\frac{\lambda}{c\mu}$. This formula is used to calculate the overall utilization rate of a multi-service counter queuing system (such as the M/M/c model), which is the total busy level of all service counters. The system utilization rate p is the ratio of the arrival rate λ to the total service capacity of all service counters cμ. In order to ensure the stability of the system, it will be necessary to conform to ρ<1, i.e. The total capacity of the service exceeds the number of people that can be accommodated. The second is for Average Number of Customers in Queue (Lq) (using Erlang-C formula). It is $Lq = \frac{(c\rho)^c}{c!(1-\rho)} \times \frac{P_0}{(1-\rho)}$ where $\boldsymbol{P_0}$ is the probability that no customers are in the system, computed through a more complex equation.

The third is M/G/1 Model (General Service Time Distribution). There are some assumptions: Poisson arrival process and the service time follows a general distribution G, instead of an exponential one. The Pollaczek-Khinchin Formula is for Average Waiting Time in Queue (Wq): $W_q = \frac{\lambda E[S^2]}{2(1-\rho)}$ where $\boldsymbol{E[S^2]}$ is the second moment of service time, and $\rho = \lambda/\mu$.

The fourth is M/M/∞ Model. It Assumes that the service resources are unlimited, such as the server resource allocation in cloud computing. Since there is no need to queue, the waiting time of this model is always zero.

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3. Application

3.1. Planning of Urban Electric Vehicle Charging Facilities

Ye et al. conducted a study on the design of electric vehicle (EV) stations using queueing theory [5]. As electric vehicles become more crucial for achieving green and low-carbon development due to rapid economic growth and environmental concerns, the research addresses key issues such as site selection, capacity determination for charging stations, and the battery distribution and scheduling problems for battery swapping stations.

The study examines urban EV charging infrastructure, exploring theories and factors that influence the site selection and capacity of charging stations. It also discusses the vehicle routing problem for battery distribution in swapping stations. A hybrid algorithm combining Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) is proposed to optimize the location and service range of charging stations, using traffic flow data from road network nodes and Voronoi diagrams for prediction. This aims to minimize customer wait times and reduce shipping costs. The algorithm, which seeks to minimize overall social costs, is implemented through the PSO-GA hybrid method.

For the battery distribution problem, the paper presents a serialization technique using a B-cell evolutionary algorithm. To meet time window constraints and minimize vehicle route distances, the bee reproduction and evolution mechanism is incorporated into an improved genetic algorithm. MATLAB was used to compute optimal distribution routes, resulting in 9 optimal charging stations and three efficient vehicle dispatching routes for battery distribution.

3.2. Optimal Configuration of Electric Vehicle Charging Facilities

Li and Su examined the optimal configuration of EV charging facilities using queuing theory [6]. They first analyzed the randomness and flexibility of EV charging behavior, where the arrival rate of vehicles followed a Poisson distribution, and the service time followed a negative exponential distribution. A queuing model was developed for the charging facilities service system to analyze its probabilistic characteristics. The model calculated key performance metrics, such as the average number of EVs in the system, average waiting time, and the probability of an EV having to wait for service. The goal was to minimize the total infrastructure service cost, including expenses related to the average number of EVs in the system.

The study also explored how different configurations of charging facilities impact the power grid's load rate. It recommended guiding users to charge during off-peak hours, with a network model designed to reduce peak load gaps and increase overall load speed. Example scenarios confirmed the model's effectiveness, showing that the proper configuration of charging facilities could significantly improve the power grid's load rate.

3.3. Battery Energy Storage Assisting Rapid Charging Stations

The Ref. [7] presents an optimal decision-making model for battery energy storage (BES)-assisted electric vehicle fast charging stations participating in emergency demand response (EDR). The model incorporates costs associated with BES, electric vehicle charging times, and ADR response times, aiming to improve the economic efficiency and flexibility of charging stations.

The study addresses the challenges electric vehicle integration poses to the power grid and examines how demand response (DR) projects can alleviate these issues [8]. The focus is on the flexibility of EDR and the attractive incentives driving consumer participation. The paper outlines the typical structure of BES-assisted charging stations in EDR and develops a load model for EV charging stations using queuing theory. The vehicle arrival rate follows a Poisson process, while

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service times are based on battery charging behaviors derived from the National Household Transportation Survey (NHTS).

The optimization problem seeks to maximize the charging station's operating profit, considering revenue from EV charging, EDR participation, and electricity purchasing costs. Constraints include load reduction requirements, BES operational limits, and battery state-of-charge restrictions [9]. Case studies confirmed the model's validity, showing that deploying BES significantly boosts the economic benefits of fast charging stations participating in EDR, providing an optimal operational strategy for the stations.

4. Conclusion

The current queuing models mostly adopt the form of M/M/c, assuming that the arrival rate and service rate follow Poisson distribution and exponential distribution respectively. This assumption may not accurately reflect the actual charging demands and behaviors in reality. For instance, different types of charging stations (fast charging stations, slow charging stations) may have different service time distributions. Therefore, future research can consider adopting M/G/c or GI/G/c models to describe the complex charging behaviors more precisely. In the fields of emergency demand response and battery energy storage management, current research still mainly relies on static queuing models. In reality, the demand for charging is greatly influenced by factors such as weather and traffic flow. In the future, by integrating artificial intelligence and real-time data analysis, one can develop dynamic optimization algorithms to enable charging stations to intelligently respond to changes in grid demands and user behaviors. Furthermore, most of the current research focuses on optimizing the number and distribution of charging piles, while paying less attention to user behaviors (such as charging preferences and price sensitivity). Future research can integrate game theory, behavioral economics and pricing strategies to optimize the operation of charging stations and enhance resource utilization. Future research can integrate queuing theory, artificial intelligence, big data analysis and economic theory to construct a more precise and efficient optimization system for electric vehicle charging infrastructure. This will enhance user experience and promote the coordinated development of the power grid and charging facilities.

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