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Dynamic vehicle parking pricing. A review

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Abstract

Dynamic parking pricing refers to the adjustment of the price of parking to achieve the required occupancy rates. It plays a significant role in parking management systems to minimize traffic congestion and cruising time, as well as to maximize revenue. The optimization of parking pricing and supply through a time-varying pricing strategy is a crucial issue. This paper reviews academic work on approaches to parking pricing, giving emphasis to time-varying pricing strategies. Approaches based on game theory, dynamic and stochastic control, multiobjective and multilevel programming, queuing theory, artificial intelligence, statistics, among others, are reviewed. We categorize these techniques to examine various issues of dynamic parking pricing. The main contributions and methods used are summarized. Furthermore, a brief discussion of the strengths, limitations, and possible future work is given.

Keywords: *parking pricing, dynamic pricing, parking management, optimization*

1. Introduction

Parking is a crucial part of a sustainable urban mobility plan and strategy. Due to the increasing number of vehicles and the limited amount of parking spaces, typically in urban areas, finding a vacant parking lot in central urban areas is becoming a frequent problem faced by drivers worldwide. Drivers who need parking spaces during busy hours are often forced to cruise around parking places until they get vacant parking spaces. This practice is labeled in the literature as cruising for parking [96] which is known to cost a lot of time, and gas for drivers, propagate unnecessary traffic congestion, and affect the environment due to emissions of CO_2.

Some researchers like [3, 44, 98, 99] considered parking as a public resource and examined the benefits of pricing it. In line with the general economic theory, the price of a good changes with demand when changes in supply are costly as stated in [97]. The tremendous effect of free parking in urban development has been investigated by [88]. Shoup [86] studied how factors including parking time, car

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occupancy, walking speed, and the value of saving time spent walking affect parking decisions when costs rise as drivers get closer to their destinations.

Parking pricing is one of the key elements of proposals for parking transformation and proper regulation. Dynamic parking pricing enables more economical space usage, lower searching for parking space, and upgrade gratification to the parking experience. Parking pricing is expected to reduce parking demand and dexterously allocate commuters to spaces. Parking can significantly impact the driver's behavior and thus is one of the urban problems that are top priorities for traffic management policymakers and planners. It plays an important role in the effectiveness of the parking industry and life quality for travelers and commuters. Studies indicated that a typical car trip pays a parking charge of at least $\$5$ on average and almost 70% of the direct travel cost in some major cities of USA [101]. Parking prices, availability, and accessibility are the main components of parking facilities, which substantially affect travelers' decisions when to leave, which path to choose, and where to park. All these parking components should be optimized to effectively manage the traffic and build a sustainable transportation, traffic, and parking system. Optimal parking pricing can be a flexible and desirable tool for most system planners and regulators of limited urban space for parking facilities in most mega cities. Parking is a growing problem in many large cities, especially in business centers, and both on-street parking and the limited parking supply can lead to significant travel delays [13].

Curb parking is a public resource [53]. Drivers' preference to cruise or to pay for a parking lot can be decided using the model presented in [87]. The model also forecasts the market price for curb parking and the tariff of neighboring off-street parking which are almost equal. Drivers do not explicitly determine whether to cruise or to pay, but many factors like the price of curb parking, price of off-street parking, parking duration, cruising time at the curb, fuel cost of cruising, number of commuters, and value of time spent cruising influence the decision. Based on certain studies conducted in Europe and the USA on cruising for parking spaces in large business centers, it was concluded that cars searching for free parking space contribute to over 8% of total traffic. Some studies in large city downtown areas concluded that on average 30% of vehicles in traffic congestion are cruising for a parking space [107]. In London, [60], parking searches accounted for between 30% and 40% of the travel distance for trips ending in the downtown area, whereas in Frankfurt, the percentage was predicted to be 40% when there was the most traffic [12]. Some studies showed that 60% of drivers have abandoned their search for a slot at least once and 25% of them have gotten into an argument with other drivers. This issue is also supported by the fact that the average time cars are parked at home for about 80% of the time, parked somewhere for nearly 16.5% of the time, and used for the remaining 3.5% [18].

Numerous research has been conducted on parking and related issues. Bifulco and Gennaro [11] presented many parking types, fees, and average walking times to the steady-state traffic assignment model, to analyze the effectiveness of governing parking policies in a network. DÁcierno et al. [17] discussed the optimal parking pricing for a set of fare zones to balance the modal split between private cars and transport systems. Although these static models give a basic idea of traffic congestion and network realization, they overlook the dynamic queuing of traffic flow and time-varying traffic flow. Arnott et al. [4] examined the effects of parking availability on morning scramble hour congestion and assessed the relative efficiency of road tolls and parking charges. In the absence of pricing, drivers occupy parking in order of increasing distance from the central business area. As for parking modeling in the dynamic context, they studied the dynamic user equilibrium for parking preference. Qian et al. [73] developed a method to maximize parking management advantages through optimal dynamic parking pricing. For a collection of sequential parking places, a generic parking model was offered. The outcome also demonstrated that each parking space should be charged in a way that imposes maximum occupancy. Additionally, they calculated the optimal parking rates based on average occupancy, which may serve as a guide for parking rate adjustment for traffic management.

A spatially explicit approach for setting on- and off-street parking rates that ensure a preset uniform level of occupancy over the surrounding place is the GIS-Based Nearest Pocket for Prices algorithm which has been developed in [23]. Gu et al. [25] developed a macroscopic parking dynamics model for an adjacent parking area, where the interaction between on- and off-street parking places was explicitly considered in the search for parking spaces. Results indicated that proactive pricing performs better due to its capacity for prediction helped by optimization.

Numerous models have been developed to analyze parking issues. Young et al. [114] discussed in detail parking models categorized into choice models, [2, 5, 6, 35], optimal allocation models [24, 108, 109] and interaction models [10] most of them considered walking distance, parking cost, search time, and capacity. Parking models and pricing in traffic impact studies were modified by [9] to account for factors influencing motorist behavior.

Leclercq et al. [46] studied the dynamic macroscopic simulation of on-street parking search using a tri-phased approach and investigated the relationship between the average travel distance to the park and the parking occupancy over an urban area. Dynamic macroscopic parking pricing and optimization model to maximize the parking pricing revenue and minimize the total cruising time on the network was proposed in [38]. The model also provides main recommendations for stakeholders concerning an optimal parking pricing policy contributing to financial revenues without having a serious negative effect on short-range traffic efficiency and environmental conditions.

Tilahun et al. [94] studied the cooperative multiagent system for parking availability prediction based on time-varying Markov chains with a learning parameter [93]. Qin et al. [76] investigated the impact of time-varying parking prices on parking demand and built a multi-agent-based simulation of on-street parking. The result supports the idea that demand-driven dynamic parking pricing may effectively control the distribution of parking demand. Based on a multi-agent system, Hassine et al. [30] proposed a dynamic parking charging system that aimed to maximize the demands of parking management. They showed that the multi-agent smart parking system can reduce traffic congestion and make optimal use of available parking spaces, particularly during peak hours.

Guo et al. [26] proposed both a static game-theoretic model and a dynamic capacity model to handle the competition among drivers for limited available parking spaces. These are some of the research directions focused on by researchers. Interested readers can refer to [36, 59, 68, 114] and the reference for parking-related research in general. Several theoretical studies analyzed parking markets by assuming hourly uniform parking fees. On the other hand, empirical studies likely found parking fees to be concave in parking duration. Parking agents are in spatial competition with each other and with curbside parking spaces. They are mostly privately operated, while curbside parking spaces are mostly publicly operated. Guo et al. [27] developed a pricing structure to increase the total revenue of parking agents. The study provided parking lot operators with a mathematical model of a new price system and three dynamic scenarios (such as uncontrolled charging, limited charging, and smart charging). The proposed model demonstrated to the operators which charging scenario will generate the maximum revenue.

Willson and Irish [110] compared evaluation techniques for dynamic parking pricing. Sandeep et al. [81] presented a systematic literature review on various dynamic pricing techniques applied in the area of Intelligent transportation systems in smart cities. Dynamic parking pricing, congestion pricing, road pricing, and toll pricing were all included in the systemic study. Mei et al. [61] used simulation-based analysis to evaluate various parking price strategies.

Parking pricing was not explored in the existing reviewed papers to their full potential. Thus, there is a need for a comprehensive review that discusses dynamic parking pricing from various methodological perspectives. The major contributions of this paper are as follows.

- Considering the importance of dynamic parking pricing.
- Classification of Various techniques used to determine dynamic parking prices into broad categories.
- Considering the strengths and limitations of various methods used for dynamic parking pricing.

This review paper is focused on dynamic parking pricing. It is organized as follows. Besides the already provided Introduction, Section 2 describes the review method. Section 3 explains various parking pricing approaches used to review the previous research papers. Section 4 provides a discussion of strengths, shortcomings, and future research directions.

2. Review method

The review process and strategy were made based on the principles suggested by Kitchenham et al., [43, 66]. The study started with the exploration of databases, methods to determine information and evaluation. The identified studies, articles, and books were first assessed for adequate relevancy and then extracted and organized. To find information, the inclusion of a wider range of references has been extracted.

We conducted a review that employs scientific strategies. We systematically assembled and synthesized many relevant studies on dynamic vehicle parking pricing. Following that, we applied a reproducible search of previous works on the Web of Science and Scopes databases by including keywords related to dynamic vehicle parking pricing strategies listed in Figure 1. Each of the searches in the database is combined with further keywords taken from the referred papers.

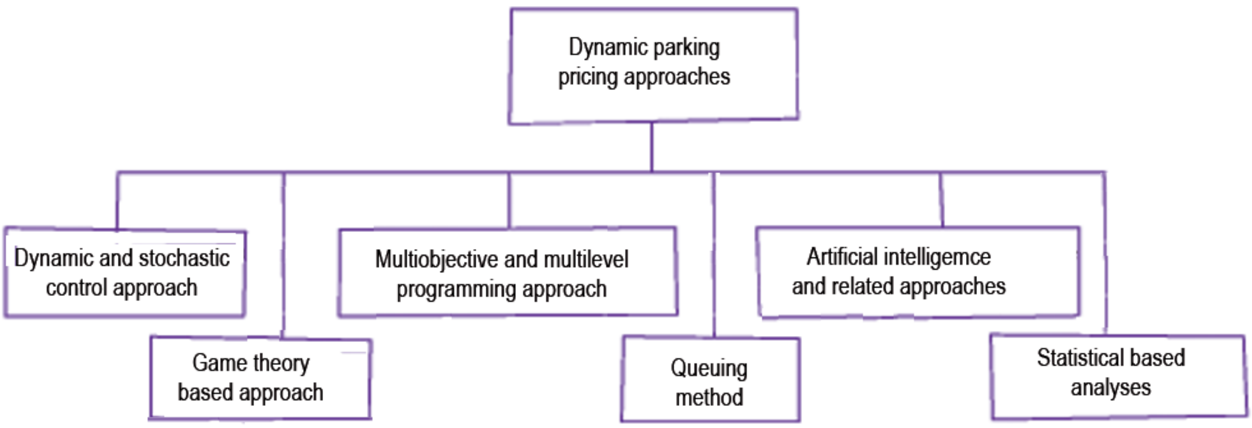

Figure 1. Dynamic parking pricing approaches

By identifying the redundant works between different searching mechanisms, we retrieved 140 unique works from which 117 were found relevant to the topic of this research. Among those, 53 prior studies are more related and divided into the following categories: 6 dynamic and stochastic control, 10 game theory, 10 multiobjective and multilevel programming, 2 queuing models, 10 Artificial Intelligence and related approaches, and 15 statistical parking pricing approaches. Figure 1 summarizes the parking pricing approach which is our focus methodologically.

3. Parking pricing approaches

The issue of parking pricing has received a lot of attention in the literature. According to [61], there are three parking pricing strategies which are: different parking lots constantly charge the same price, charge different prices, and charge different prices during peak periods concerning occupancy percentage thresholds. The first parking pricing strategy is commonly used in China.

Hassija et al. [29] analyzed the effects of dynamic parking pricing on travel demand in the change of time hourly. Based on the study, the adaptive pricing model enhances the overall revenue of the parking lot owners and users. The proposed model is deterministic, which is used to minimize the average parking cost and time. The model impacts accurate parking space allocation, minimizing cost, and parking space utilization.

Rodriguez et al. [80] developed a model with the aim of simulating dynamic pricing policies and their impact on parking demand, driving habits, and mobility. They were able to show several advantages of dynamic fares as a result, including decreased searching time, a reduction in traffic and pollution, and a new modal redistribution of parking options between off-street and on-street supply. Parking pricing policy is used to govern the parking market and reduce traffic congestion in general and parking in particular to improve the utilization of the limited parking capacity at higher demanding places. The pricing policy fulfilled its objective to increase the ease of finding a vacant parking place. Parking pricing policy and its impact attracts significant research attention. Shoup [88] developed parking guidelines that suggest that the optimal pricing results in 85% of parking occupancy.

In this section, we categorized the previous works into six mathematical and computational approaches with a common objective of parking price setting as described in Figure 1 (namely, Dynamic and stochastic control-based approaches, Game theory Technique, multiobjective and multilevel programming based approaches, Queuing model, Artificial Intelligence and related methods $\&$ statistical analysis approaches). Optimization methods play a fundamental role in the determination of dynamic parking prices. These techniques are of utmost importance to maximize or minimize one or many parameters subject to various constraints.

3.1. Dynamic and stochastic control approach

Dynamic programming can be used to develop a time-varying parking pricing framework. The relations between dynamic parking prices and provision of parking information can be represented in a general parking network as below in Figure 2 where the red nodes (O_i), blue nodes (P_i) and black nodes (D_i) represent the origins, parking lots and destinations of drivers, respectively. In the general parking network, each parking lot could be used by demands associated with multiple origins and multiple destinations. The arrows $\overrightarrow{O_iP_i}$ with indigo color and $\overrightarrow{P_iD_i}$ of green color are the searching direction for parking place and waking path to the desired place respectively.

Qian et al. [74] investigated the interaction of dynamic parking prices with the provision of parking information in a general parking network shown in figure 2. They proved that any optimal flow pattern can be achieved by lot-based parking pricing schemes depending on occupancy. Drivers make parking choices to minimize their generalized travel costs using the accessed parking information. The main components of the generalized travel cost are dynamic parking prices and cruising time.

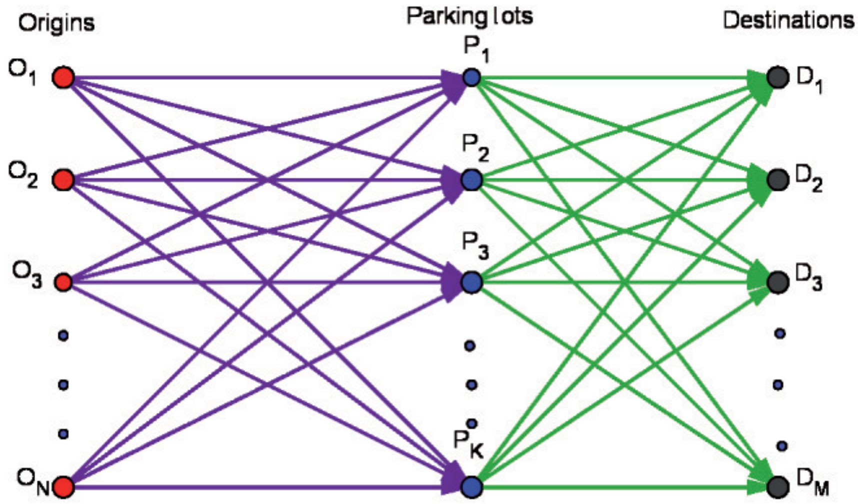

Figure 2. General Parking Network based on [74]

To increase the expected profit for the parking manager, Tian et al. [92] presented a dynamic pricing approach for parking reservations. The stochastic dynamic programming approach has been used to formulate the dynamic pricing problem, where the optimal price maximizes the manager's expected income. The result showed that the dynamic pricing plan may significantly increase income and fully utilize parking resources during peak hours. Wang et al. [105] developed a continuous time stochastic dynamic model for the optimal parking management of vehicles using multiple parking. Bolza optimal control problem is formulated aiming at preserving the available parking space at a desired level, resulting in significantly reduced traffic congestion and fuel consumption. They also developed an algorithm to solve a nonlinear optimization problem and prove its convergence. Optimal parking price has been proposed in [75] as a stochastic control issue to control parking demand. The cost of parking and the availability of information are discovered to be dynamically stabilized controllers for the traffic demand. Researchers used a stochastic control strategy to simulate the ideal parking fee in the desired (better) parking cluster. Demand uncertainties and user heterogeneity in the value of time were considered. Additionally, it is discovered that stochastic control models are promising methodologies.

Lei et al. [47] studied a demand-driven parking pricing and reservation problem provided that the agency is interested in achieving its objectives by having a spatial and temporal distribution of parking prices. Drivers compete for limited parking spaces through online reservations with different origins and destinations. The dynamic Stackelberg leader-follower game is formulated as a multiperiod non-cooperative equilibrium bilevel model. The agency makes pricing decisions in the upper level and the drivers make parking location decisions in the lower level. The multiperiod model is solved using a non-myopic approximate dynamic programming(ADP) method.

Magsino et al. [57] assessed the socially optimal range and economic effects of temporal and spatiotemporal-based dynamic parking pricing methods on users and parking management authorities. The evaluation of various pricing strategies shows the effect of the parking charge rate on the income generation of business owners as well as the impact on the daily parking expenses of frequent parkers. Table 1 summarizes the solution approach and the corresponding Results found of dynamic and stochastic control methods discussed above.

Table 1. Summary of dynamic and stochastic control methods

Solution approach	Factors considered	Main result	Ref.
ADP algorithm	parking demand and supply	demonstrates consistency in managing with the temporal and spatial changes in parking demand	[47]
Stochastic control and Poisson process	parking reservation	reduce cruising time and maximize the expected revenue	[92]
Variational inequality	general parking network	derived the system optimal prices	[74]
Pontryagin's minimum principle	interactions between the parking agents and maintaining demand	determines the optimal pricing policy for each parking lot	[105]
Dynamic programming	demand and travelers' parking choice	proved that stochastic pricing strategies perform better than deterministic pricing methods	[72]
Dynamic programming	various demand levels (high, low, or unstable)	demonstrated that based on demand and traveler heterogeneity, parking fees are altered in real-time	[75]
Temporal and spatial-temporal based dynamic pricing	land value, entry time, demand value and unique services	proposed adaptive pricing methods enabling online reservations and valet services	[57]

3.2. Game theory approach

Game theory is the study of mathematical models of strategic interactions among different agents. Recently, parking has been the main focus of dynamic pricing research. Game theory can be used to determine parking pricing. Different interactions, such as those between parking agents, between parking agents and drivers, and among drivers, affect how much parking charges. Various interactions like between parking agents, parking agents, and drivers and among drivers in determinations of parking pricing. Parking agents set prices with the aim of maximizing their profit whereas drivers aspire to access parking lots with minimum cost and another criterion. Mathematical models are used to establish dynamic pricing based on various game theories applied in various situations. Wang et al. [104] proposed a pricing model that applies the principal-agent theory to the parking pricing problem. The parking pricing game consists of the government, drivers, and parking firms as players.

The interaction between these players on parking pricing has been summarized as shown in Figure 3. It is assumed that everyone participating in the parking pricing game is unbiased and seeking to optimize their interests. The relationship between players must be stated in game theory. To determine how players are connected, game theory is applied. Finally, each player develops their dominant strategy. If there is a Nash equilibrium for the entire game system, it is produced by a combination of their dominating tactics. Game theory can be applied in the determination of parking pricing. Private parking garages and public ones may compete on and cooperate in open markets. Sometimes there is competition among drivers for a limited parking space.

Game theory matches with situations involving cooperation and competition among rational decision-makers. Due to the adaptability to pricing problems, game-theoretic methods, especially the Stackelberg model [51], Bertrand model [85], and Cournot model [100] have been extensively used. Even though game theory has historically been used to solve a variety of issues, few studies particularly analyzed the pricing behavior of parking spaces. The only difference between the Stackelberg and Cournot leadership models is how players are prioritized. The parking agent who adjusts the price is considered as leader and the one deciding later after observing the leader's strategy acts as folls.

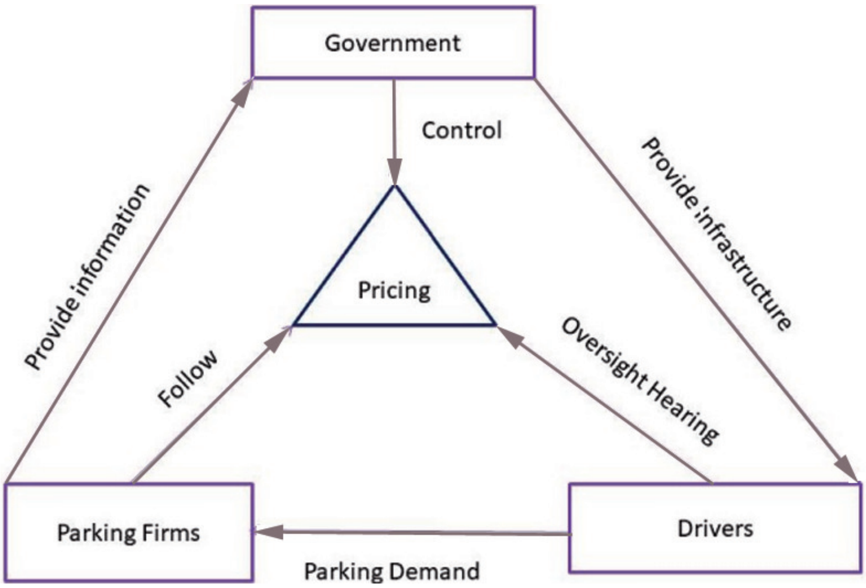

Figure 3. Players Relationship [104]

Tsai et al. [95] constructed a three-stage Stackelberg game model considering the government, drivers, and the parking firm as stakeholders to analyze the interaction between them. The government releases more parking spaces to private parking firms to maximize welfare. Hollander et al. [33] formulated a non-cooperative Stackelberg game and used a logit model to obtain the choice distribution of all drivers. They also introduced a preference coefficient for each combination of destination and transportation mode of drivers. Following this, [118] presented an extended three-stage Stackelberg model with user equilibrium.

Xiao et al. [111] studied a parking pricing problem of a game between public and private parking infrastructures. For the parking pricing problem, they created a two-player Nash game model in which the government, which manages the public parking infrastructure, seeks to maximize social welfare (also known as minimizing the total social cost), and the private operators who manage the private parking infrastructure seek to maximize their profit. They discovered the ideal parking charge levels for two players at the Nash game equilibrium. The sensitivity analysis is used to determine how changes in the number of public parking lots, their capacity, and overall demand affect parking rates. For capturing the competition among drivers for a finite number of attractive parking spaces, Guo et al. [26] presented two different types of parking choice models, a static game-theoretic model and a dynamic model. The static model was designed to capture the rational aspect of parking choice behavior without considering the characteristics of each driver. However, the dynamic model takes into account the driver's behavioral characteristics, which reflects the effects of both the rational and irrational sides of parking behavior. The results of [26] showed that the outcome of the prediction of the dynamic model is more precise than the static game theoretic model.

Mackowski et al. [56] presented the Stackelberg leader-follower game to adjust parking prices in real time to utilize parking access and space. An integrated parking pricing and management system is fitted in the model where parking reservations and transactions are facilitated to ensure the availability of convenient spaces at equilibrium market prices. For efficient parking access and space usage, the Stackelberg leader-follower game has been devised to establish parking charges in real time. The suggested dynamic parking price model is demonstrated with numerical results to have the capacity to almost eliminate cars searching for parking, which leads to a substantial reduction of detrimental socioeconomic effects like traffic congestion and emissions.

Zheng et al. [116] proposed an aggregated and dynamic modeling of multimodal traffic systems to design dynamic parking pricing strategies. The proposed approach captures the congestion dynamics at the network level for single-mode and bi-modal systems based on the macroscopic fundamental diagram (MFD. Pricing strategies were developed to reduce traffic congestion and minimize the total travel cost of all users. Additionally, the Stackelberg equilibrium was examined about the rivalry between parking agents. There is capacity control and pricing for on-street parking. Zong et al. [119] described an optimal structure of parking rates in terms of parking places and time duration. A bi-level parking model based on game theory is established. The Nash equilibrium and Stackelberg game were used to estimate the model. The parking system was used to explore both the interactions between drivers and the government as well as among drivers. Ayala et al. [7] presented a game-theoretic framework to analyze parking situations provided that Vehicular parking can be viewed as vehicles (players) competing for parking slots. The authors also examined games for assigning parking spaces in situations with full and incomplete knowledge. They described the Nash equilibrium for the game and demonstrated that it applied to all cases of pure strategies with complete information.

Mamandi et al. [58] developed parking selection methods including those based on game theory and priority heuristics. In the game theory paradigm, drivers are viewed as rational agents that want to maximize their payoffs. On the other hand, the priority heuristic model considers driving attributes while selecting a parking space. Based on the total number of drivers, the available on-street parking spaces, the cost distinction between private and on-street parking, and the influence of each factor on the effectiveness of the parking guidance system, they compared their model to similar existing models and found it to be more effective.

Using a game theory-based evaluation of the neighbors' strategies, Li et al. [49] investigated a parking lot discovery method to identify the best and most accessible parking lot. As drivers cruise around the parking area, the competing parking agents' costs are continuously evaluated in a cooperative approach, which helps to raise the parking efficiency of the system. The parking lot discovery problem is also formulated as an instance of a resource selection game. Each driver's choice over the competing parking lot reflects the extra cost of an opponent's loss. Based on this principle, the total efficiency of all competitors is derived as Nash equilibrium, and the simulations of the algorithms give information for parking lot management that aims to raise the efficiency of the parking area.

Aghajani et al. [1] proposed a cooperative game model to determine price adaptively. The profit maximization of utilities and cost minimization of parking lots are computed. The numerical results prove that higher deviation over the spot market price leads to both higher mean and deviation over profit considering the effect of price's uncertainty.

Priya et al. [71] focused on the optimization of parking spaces and obtained optimal results for different scenarios. The nested logit model is used to give segregation between the public transit systems, which might be more beneficial for the government. The Stackelberg game model is applied to represent the interaction between the public authority and the travelers. The solution provided in this study can be collaborated with existing smart parking systems for optimal results.

He et al. [31] considered a finite number of drivers with various origins competing for the same number of parking spaces found at different sites in the central business area to minimize their parking costs. Equilibrium assignments are described as a system of nonlinear equations and discussed through optimal pricing schemes that steer the parking competition to the system's optimum parking spaces. A valid price vector was introduced taking the non-unique equilibrium state of parking competition into account and ensuring that the parking competition outcome becomes the system optimum. Table 2 summarizes game theory-based parking pricing approaches mentioned in subsection 3.2.

Table 2. Summary of game theory based parking pricing approaches

Solution approach	Factors considered	Main result	Ref.
Lagrangian function	parking agents and parking fees	developed pricing model that applies the principal-agent theory to regulate dynamic traffic demand	[104]
Stackelberg game	parking fee and the searching time cost	maximizing welfare making a profit for the firm	[95]
Stackelberg game	transportation mode, choice distribution and Logit model	maximization of utility	[33]
Stackelberg models	parking space allocation and route choice	maximize profit of the parking agents and minimize the total social cost	[118]
Nash game model	parking pricing and transportation network	maximize social welfare and profit of parking owners	[111]
Stackelberg game	vehicle circling for parking and dynamic pricing	eliminate vehicle circling for parking which reduces emissions and traffic congestion	[56]
Stackelberg equilibrium	total travel cost and traffic congestion	suggested pricing strategies maintained system performance under capacity reduction	[116]
Stackelberg and Nash equilibrium	temporal and spatial distribution of parking demand	optimize parking price to balance the temporal and spatial distribution of the parking demand	[119]
Dynamic game	the parking competition among finite number of drivers	proposed a robust pricing strategy to improve the worst-case performance	[31]
Evolutionary game	trip mode choice behavior and total social cost	minimizing the total social cost	[54]

3.3. Multiobjective and multilevel programming approach

In this section, we present various previous works related to parking pricing treated by using multiobjective and multilevel programming approaches. Multiobjective programming is a mathematical optimization problem involving more than one conflicting objective function to be optimized at the same time. Multi-objective programming has been applied to many fields of science, engineering, economics, logistics, transportation, etc., where optimal decisions need to be taken in the presence of trade-offs between two or more objectives that may be in conflict. Whereas a multilevel programming problem partitions the control of the decision variables among various decision makers, each acting sequentially or simultaneously to optimize their objective function. Some parking-related studies are using a multiobjective and multilevel optimization approach.

To deal with parking space fairly, Rehena et al. [79] suggested a multiple criteria-based parking space reservation algorithm. The simulation outcomes demonstrate that the algorithm fairly met the users' requests for all preferences. Mondal et al. [64] extended the multiple criteria-based parking space reservation algorithm which enables commuters to access and reserve the required parking lot. To increase revenue, the system also takes into account the idea of a dynamic pricing strategy when determining parking fees.

Ratli [77] studied the application of multiobjective programming to parking management systems in a dynamic environment. The consequences of the lack of parking slots along with the inadequate management of these facilities are tremendous. A robust powerful algorithm is created to boost parking managers' income and help drivers save time and money. The problem was formulated as a multiobjective assignment problem in static and dynamic environments. The approximation of the set of efficient solutions for a bi-objective problem is computed using a bi-phase heuristic algorithm with the static environment as the first phase. In the second phase, the meta-heuristics technique is used to generate and approximate the non-supported efficient solutions. Huang et al. [50] examined the competitive equilibrium between road pricing and parking charges. A multiobjective bilevel programming approach with an equity constraint was developed to optimize the time differential road tolls and parking fees throughout the day. The problem was solved using a penalty function approach combined with a simulated annealing technique. A bi-objective facility location problem with many servers, price regulations, and immobile servers was formulated by [28]. A multiobjective vibration damping optimization has been created to solve the model. Wang et al. [106] explored the influence of the number of facilities on the optimization objectives and applied the multiobjective optimization model of car occupant transfer facilities.

With demand forecasting as the basic data and on the premise of ensuring occupancy, their model takes the maximization of intercepted vehicle mileage and the maximization of transfer utility as goals to establish the collaborative layout decision model. The model can give a reasonable scheme as a reference for improving the operational efficiency of multimodal transportation networks and meanwhile provides theoretical support for improving the effectiveness of urban transportation planning. Moradijoz et al. [65] investigated the optimal size of parking lots and total benefit using multiobjective programming. In some of the previous studies like [14] parking pricing is determined to the public and used by authorities as a tool to manage transport demand. Parking pricing was discussed, including dual pricing, the private environment, and multicriteria decision-making. Goal programming (GP) is the main technique used to model the issue. A dynamic parking price maintains a balance between the parking demand and fixed parking supply.

Li et al. [52] developed a bilevel model in which the upper level seeks to maximize the net benefit to the network in response to parking fees and parking supply; as a result, the lower level is a time-dependent network equilibrium issue with elastic demand. To solve the model, a descent-gradient-based solution algorithm is used. To manage demand in the central business district and determine the lower bound for dynamic parking fees, Eftekhari et al. [20] devised a bilevel optimization model. The stochastic user equilibrium model converges to the predicted flow system optimum model based on the indicated prices. Sub-section 3.3 is summarized in Table 3.

Table 3. Summary of multiobjective and multilevel programming methods

Solution approach	Factors considered	Main result	Ref.
Multiple criteria based parking space reservation algorithm	smart parking and parking reservations	the algorithm enables to balance parking save time, reduce traffic and pollution	[79]
Multiple criteria based parking space reservation algorithm	dynamic pricing strategy and revenue of government agencies	reduces the average extra driving and reduce traffic congestion	[64]
Bi-objective problem	static and dynamic environment	developed effective algorithms that assist drivers save time and money and help parking management generate more revenue	[77]
Bi-objective optimization and genetic algorithm	investment cost, optimal site and size of parking lots	maximized the overall profit and determined the parking lot's size and optimal capacity	[65]
Multiobjective bilevel programming	elastic demand, departure time, route and parking location	examined the equilibrium problem of road pricing and parking charging	[50]
Multi-objective evolutionary algorithm	traffic congestion and pricing policy	maximized total profit and simultaneously minimized the sum of waiting time in queues	[28]
Multi-objective optimization	imbalance between supply and demand	the model ensured the occupancy rate of parking spots and enhanced the overall service level of vehicle occupant transfer facilities	[106]
Goal programming	parking fee and the customer's threshold	the finding addressed the part that parking charges play a significant role in parking policy	[14]
Bilevel model	descent-gradient-based solution algorithm	demonstrate the value of implementing time-varying parking fees and parking availability	[52]
Bilevel programming	dynamic parking prices and stochastic user equilibrium model	determined capacity for public transportation and examine different public transportation cost function	[20]

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3.4. Queuing theory approach

The queuing model is used to analyze the relationships between parking pricing, current parking demand, and parking time as explained by some researchers. Parking dynamics queuing models and model-based prediction methods are used to give real-time probabilistic estimates of future parking occupancy. Parking prices are an effective tool for managing parking demand because they motivate clients to shift their parking needs from peak to off-peak hours, increase vehicle turnover at particular times or in specific locations, and balance parking demand across various lots. Larson et al. [45] developed a model that depicts patrolling drivers seeking on-street metered or free parking. Driving around the streets was expected of drivers looking for parking spots to find the first vacant spot. Modeling the overall process of parked cars relocating from parking places was done using the Poisson process. Based on their findings, parking pricing can control local and time-varying traffic congestion using the price differentials between on-street parking and off-street parking. It is also indicated that the queuing delay and reneging rate are inversely proportional. When on-street parking spaces are all taken, patrolling drivers are assigned using a Poisson distribution, and the marginal delay cost imposed by an extra road user becomes constant as a result of reneging. Parking pricing can be modeled as a queuing model to minimize cruising time and traffic jams. In the model, drivers who were searching for on-street parking have been considered. Here, parking pricing can be seen as an alternative to road pricing. Given that the arrival rate and the length of stay depend on the parking price, Keren and Hadad [42] employed queuing models $M/G/N/N$ to establish the appropriate parking pricing. The model proved useful in scenarios when the objective function was to maintain a specific park occupancy rate. The findings indicated that parking price is a crucial instrument for a car park's process management and benchmarking (Table 4).

Table 4. Summary of queuing model approach

Solution approach	Factors considered	Main result	Ref.
Queuing model	congestion pricing	found that using the price differences between on-street and off-street parking, parking pricing can reduce time-varying traffic congestion	[45]
Queuing model M/G/N/N	arrival rate, staying time and parking price	parking pricing is one of the most crucial tools for process management and benchmarking of a parking lot	[42]

3.5. Artificial intelligence and related approach

Artificial intelligence has become an essential part of our daily lives. This section provides specific instances of how artificial intelligence and related topics are being used in parking pricing strategies. Machine learning techniques optimize parameters through its iterative learning capabilities. Saharan et al. [82] proposed an occupancy-driven machine learning based on on-street parking pricing. A machine learning-based approach is used to predict the occupancy of parking lots and reduce occupancy-driven prices for arriving vehicles. The results obtained using the method on-street parking pricing scheme demonstrated its effectiveness over other existing schemes. For dynamic pricing and allocation of parking spaces in on-street parking scenarios, Saharan et al. [83] proposed machine learning and game theory. The Stackelberg game is used to model the dynamic pricing and allocation problem, and Nash equilibrium is used to solve it.

To enhance the driving experience in congested regions, provide current parking costs, and offer reservation as well as guidance services, Jioudi et al. [39] developed a smart parking system based on multiagent characteristics. The system assigns optimal parking for a driver based on proximity to the destination, parking cost, and dwell time, allowing users to share public space fairly and enhance traffic conditions. In light of the findings, pricing regulations are an effective management tool for reducing cruising for parking spaces as well as managing parking occupancy and stay duration.

Simhon et al. [89] proposed a demand-based parking pricing used to reduce the amount of cruising for parking. The occupancy rate of a parking area is predicted by employing a machine-learning approach based on the past occupancy rates and prices of the entire neighborhood. An optimization problem is formulated for the prices in each parking area that minimizes the root mean squared error between the predicted occupancy rates of all areas in the neighborhood and the target occupancy rates. Luque-Cerpa et al. [55] presented dynamic prices in regulated parking services. Low-quality episodes are predicted and diverse deep-learning strategies are evaluated to discourage motor vehicle parking using dynamic pricing in the parking service.

Table 5. Summary of Artificial Intelligence and Related Methods

Solution approach	Factors considered	Main result	Ref.
Learning model	occupancy rates and prices of the entire parking lots	using nearby block prices considerably increases the machine learning model's accuracy in forecasting occupancy	[89]
Learning model	curbing congestion, cruising time and smart city environment	predicted occupancy of parking lots which is used to deduce occupancy driven prices for arriving	[82]
Machine learning and Stackelberg game	paid parking users and restricted parking users	minimization of parking prices, maximization of revenue and balancing the congestion at parking lots	[83]
Multi-agent smart parking	smart parking and multi-agent features	introduced the e-parking system, which includes reservation and assistance services as well as real-time parking prices	[39]
Deep learning	economic parameters and prediction of the alert level of pollution	proposed dynamic prices to regulate parking services	[55]
Cloud computing	multiple sensors and appropriate communication network	maximize parking space availability for drivers and revenue for the parking authority	[84]
Artificial intelligence	parking management and pricing	using intelligent algorithms, prices are forecast based on distance, time, services offered, and vehicle type	[78]
Reinforcement learning dynamic pricing	time series based prediction model	maximize parking resource utilization and parking revenue for parking management	[19]
Deep learning	black box and white box search methods	provide a proactive, prediction-driven optimization approach for adjusting parking prices	[34]
Deep reinforcement learning	parking occupancy data	investigated a dynamic pricing system based on parking revenue and vehicle arrival rate for the parking industry	[70]

Sarker et al. [84] proposed a dynamic pricing algorithm to yield the maximum possible revenue for the parking authority and optimum parking slot availability for the drivers. Reebadiya et al. [78] developed a dynamic parking pricing scheme based on an integrated vehicle. The finding reflected that static parking pricing leads to traffic congestion, air pollution, and illegal parking around parking areas as a driver always chooses the nearest parking space. The result also shows that the system allows users to interact with parking service providers. Considering vehicle type, they predicted prices and provided fair price distribution services to minimize congestion and maximize revenue. As indicated in the study, prices are changed based on demand and availability.

Deng et al. [19] offered a system that makes use of public resources that are already accessible while maximizing revenue with predetermined constraints in the area of parking management. A dynamic pricing model based on reinforcement learning has been utilized to add price restrictions and prediction models using data-driven time series. To dynamically change parking prices, Hong et al. [34] introduced a proactive prediction-driven optimization methodology. Future parking occupancy and price data have been designed using neural ordinary differential equations of the deep neural network.

More recently, Poh et al. [70] developed a dynamic pricing model based on deep reinforcement learning to control parking prices depending on traffic volume and parking occupancy rate. The model forecasts vehicle volume and traffic congestion while distributing vehicle flows. Table 5 summarizes Section 3.5.

3.6. Statistical-based analysis

This section presents statistical methods based parking pricing previous works of which most of them uses empirical data and analysis. In many studies of parking policy, the role of parking pricing has been considered. Parking charges can directly contribute to decreased greenhouse gas emissions and air pollution. As shown in Table 6, statistical techniques were applied to examine parking pricing-related works in various studies. Simi ćević et al. [90] developed a meth for parking price determination, which will balance parking supply and demand. Simićević et al. [91] extended the model to predict the effects of changing parking prices and time limitations using logistic regression based on stated preference data. It is shown that parking pricing can affect car usage and time limitations to determine on-street or off-street parking. Van et al. [97] studied the consequences of non-optimal pricing of parking by estimating the employees' demand for parking and analyzed the effects of price on parking demand. The loss produced by free parking for workers is about 10% of the organization's parking costs.

Wan et al. [102] investigated several variables that affect the curb parking price and the time-varying curb parking price regulations using the time series technique and regression analysis method. The suggested approach has several flaws, but this curb parking price forecast can aid in the development of improved parking plans, the balancing of parking supply and demand, and the resolution of the urban parking issue.

A dynamic macroscopic parking pricing model was the subject of Jacob et al. [37] study. Recent research has highlighted the need for demand-responsive pricing. Parking pricing was extended from a previous dynamic macroscopic urban traffic and parking study. The demand-responsive pricing scheme and cruising for parking space was considered in the study. It appears that parking rates fluctuate depending on demand. The model also examined how parking pricing affected drivers' decisions on whether to pay the required parking fee or keep looking for a lower one.

Wang et al. [103] studied the effects of street parking pricing policies on parking characteristics. It is indicated that parking pricing is an instrument for improving parking management and relieving traffic congestion in urban areas. The result also elaborated that the parking duration decreases as its price increases. Kolmogorov–Smirnov (K-S) tests showed that on-street parking characteristics differ fundamentally before and after the implementation of a new parking pricing structure. Strategies that can improve parking services were also investigated based on the empirical data.

Three frequently employed parking regulations in European cities were examined in recent studies like [62], notably daily tickets only, daily tickets with time limits, and pricing only. In regulating the length of parking stays, findings have shown that time restrictions are more successful than pricing-only measures. Recently, researchers have given more attention to the study of the impacts of parking pricing on modal transport demand management systems. Even though the effect of a transport demand management pricing measure is estimated, the potentially varying impacts of pricing measures are often overlooked in the policy process. Policymakers considered a progressive increase of tariffs and variance of price impacts for various trip purposes. Kelly et al. [40] showed a progressively widening gap in the price sensitivity of particular market subsets which can lead to the development of a pricing policy. The methodology presented by Kelly et al. [41] can be used to produce useful data for analysis in contemporary on-street parking systems. By presenting the results of the on-street parking market's price elasticity of demand, the paper also aims to contribute to the literature on parking.

Some researchers such Ayala et al. [8] used price elasticity theory to examine people's parking and travel preferences which discovered that people are more inclined to transfer parking places than they are to alter modes of transportation. Pricing elasticity is an indicator to reflect the sensitivity of the traveler's parking demand change as a response to the pricing change. To improve user experience and accomplish the objectives of on-street parking, Li et al. [48] devised a way to optimize the price mechanics of on-street parking. It was suggested to replicate parking decision behaviors between on-street and off-street parking by using the binary logit style choice model. The value of price elasticity of predicted perceived parking cost was recommended to meet the objectives of price discrimination with a clear focus on user perceptions of parking fees. Generally, the findings imply that by discouraging users from vying for scarce on-street spaces, an optimal on-street parking price profile can assist in realizing significant time savings.

Zhou [117] presented the correlation between parking pricing and searching for parking spaces in a steady state using a theoretical economic model. Drivers are assumed to decide on the parking place based on the expected cost with the option of cruising for a vacant space or proceeding to off-street parking. It is stated that cruising generates more cost for an increasing number of drivers whose choice is on-street parking. Additionally, the increment of on-street parking fees to an optimal level reduces the number of searchers and discourages individuals from illegal parking.

Pierce et al. [69] argued that cities can more effectively manage their parking assets to maximize public benefits by setting occupancy rather than revenue targets. They supported their argument with evidence from the most promising practical example of off-street parking public management, which decreased parking prices and increased garage occupancy while maintaining revenue for the city. Statistical methods,and solution approaches with respective results found are presented in Table 6.

Table 6. Summary of statistical based analysis

Solution approach	Factors considered	Main result	Ref.
Price elasticity of demand	parking demand and predicted regular number of parking spaces	explored the potential for parking pricing to control demand	[90]
Descriptive statistics	welfare-maximising principles	evaluated the effect of the price of employee parking on demand	[97]
Time series regression analysis	curb parking price	solved the traffic problem caused by the imbalance between parking supply and demand	[102]
Probability function	maximize the revenue maximization and minimization of total cruising time	provided a preliminary idea for city councils regarding an optimal parking pricing policy	[37]
Kolmogorov–Smirnov tests	on-street parking and empirical data	demonstrated that parking duration gets shorter as the price goes up	[103]
Logistic regression model	parking policy and stated preference data	illustrated that parking prices affect car usage and time limitations determine the type of parking used	[91]
Statistical analysis	different parking policies (pricing only, pricing and time restrictions and daily tickets only)	results show that time limitations are more effective than pricing only strategies in reducing the length of parking stays	[62]
Statistical analysis	dynamic pricing and parking occupancy	the result highlights the impact of price sensitivity in developing parking policy	[40]
Statistical analysis	revealed-preference parking trend data	evaluated individual estimations for specific periods and the overall price elasticity of demand level	[41]
Simulation based analysis	parking availability and total driving distance	implementing a price strategy ensures that each car pays a cost equivalent to its equilibrium cost	[8]
Simulation based analysis	both on- and off-street parking	reduced parking congestion and improved the overall system performance using real-time parking pricing strategies	[25]
Descriptive statistics	price elasticity of on-street parking demand	determined the optimal parking rate to achieve a desired level of parking occupancy	[67]
Linear regression model	parking fee, cruising time and walking time	reduce the occupancy rates of curbside parking	[115]
State preference experiment	supply pricing scenarios on CBD parking share	supply price scenarios simulated using a nested logit model and parking choices	[32]
Economic model	parking pricing and cruising for parking in a steady state	increase the cost of on-street parking to deter people from parking their automobiles in road	[117]
Statistical method	maximization of public benefits and off-street parking public management	decreased the average driver cost while maintaining steady revenue	[69]

3.7. Practical implementations

Based on demand, parking agents can improve the parking experience for their clients by using dynamic pricing. The parking operational process can be made better and revenue can be improved with the implementation of a dynamic pricing approach. Usually, the aim of parking agents, drivers, and authorities are profit maximization, minimum price with total travel cost, and reduction of traffic congestion with minimum air pollution respectively.

The first version of the PARKSIM model was created in 1986 [112]. It has been used to simulate a parking search within a parking lot [113]. Demand-responsive parking pricing initiatives have been launched in San Francisco (SFpark), and Los Angeles (ExpressPark), which offer performance pricing for on-street parking and SeaPark in Seattle. In July 2014, the city of Madrid introduced a dynamic pricing (DP) system in which the cost of parking is determined by the kind of vehicle and the level of demand [22].

Drivers can conduct real-time online parking requests and reservations. Numerous smartphone parking apps, like SpotHero, ParkWhiz, ParkMe, and Parking Panda, have emerged, enabling drivers to check the availability of parking spaces and make reservations before their trip [15]. Parking agents may anticipate demand by utilizing smart technologies. They are also able to determine reasonable parking charges. When there is a lot of demand, they will be able to boost the cost of parking spaces. By doing this, parking lot owners and operators can increase profits and reduce possible losses during times of low demand and vacant spaces.

Furthermore, by using an effective dynamic pricing approach, parking operators may manage parking effectively. Instead of using static pricing, it is achievable by making pricing pertinent to the present supply and demand. Therefore, dynamic parking pricing allows for elastic demand and optimizes the use of parking resources.

4. Discussion

One of important factors in determining dynamic parking rates is occupancy. Drivers must obtain current occupancy and cost information to make the best choice of parking spaces. The dynamic programming method is used to solve the stochastic control formulation. The ultimate optimal parking policy ensures that a crucial occupancy occurs for each period. When the current occupancy is higher than the essential occupancy, the closer lot's parking rate should go into effect. Using dynamic parking price control mode to modify the driver's choice of trip mode, the overall social cost can be reduced.

Multiobjective programming is also used to model objective functions consisting of the balance between the satisfaction of drivers and the interest of parking agents. The need for the nearest parking lot and parking fee can also be formulated as a bi-objective optimization problem.

Queuing theory is also presented to model the arrival of a vehicle at a parking lot. If vehicle owners want to be part of the determination of parking pricing, then game theory can be useful. Optimization techniques are used to optimize various parameters and solve problems of uneven occupancy at different parking lots. Apart from all such dynamic pricing techniques, the acceptability of dynamic parking fares among people should be evaluated directly or indirectly. If a variety of parking lots exists, then a machine learning-based model can be a better option to determine dynamic parking prices. The machine learning approach is also applicable in predicting the occupancy rates for a set of parking areas, in a neighborhood and obtaining parking prices. These prices are the solution to an optimization problem, which aims to achieve occupancy rates close to a certain target level in each parking area.

Various open challenges and future research directions in the field of dynamic parking pricing have been discussed in the following sub-section. Dynamic parking pricing approaches have some shortcomings of increasing parking prices for drivers, missing evaluation of real-time data, and performance, lack of negotiation between drivers who are looking for parking places and parking providers. The dependency of price on parking duration and other parameters are missing like the user's value of time and dynamic change in parking price.

This paper reviews different parking pricing approaches as an integral component of urban parking management systems. The study creates model groupings based on approaches and methodologies for solving problems. Some of the previous studies like [16, 38, 63, 67] were conducted by collecting primary data on specific study areas. Others like [82] and [8] used various simulation techniques and analysis. There are also some works like [21] which have been addressed using statistical methods. Hence, it is challenging to undertake a comparison study of each methodological approach mentioned in this work due to the quantity and type of data collected, parameters taken into account, solution methods used, and several other factors. The factors considered in each method and corresponding contributions can be summarized in Table 7.

Table 7. Summary of methods, factors considered, and main contributions

Approach	Factors considered	Main contribution
Dynamic and stochastic control	parking occupancy and parking fee	reduce traffic congestion and improve parking revenue
Game theory	rational players, parking price, demand and supply	profit maximization
MOP and MLP	travel distance, parking cost, air pollution, cruising time	reserve and Obtain a suitable parking space
Queuing model	arrival rate and entrance fee	specify the preferred level of park occupancy.
AI and related	smart parking systems, parking cost, and dwell time	used to predict the occupancy of parking lots and optimise parking utilization
Statistical	empirical data	used to improve parking pricing policy based on updated data and analysis

4.1. Strength and limitations

4.1.1. Strength

As the inadequacy of parking space is becoming a series issue in many large cities, the problem attracts researchers' attention. Dynamic parking pricing is by far the most promising solution to use available spaces efficiently. Adopting an occupancy-driven parking policy is significantly more efficient than using deterministic pricing schemes. Most of the stochastic control techniques listed in Table 1 are preferable to increasing occupancy, decreasing total travel time, and used to generate revenue.

The interaction between parking agents, governments, commuters, and other stakeholders can be modeled in a multilevel programming approach using game theory. The aim of maximizing social benefits can also be achieved under the consideration of incentive compatibility and participation constraints.

Hence, the pricing strategy can regulate drivers' demand for parking, thus minimizing traffic congestion and parking space shortage. Applying the Stackelberg game and Nash equilibrium methods contributes to reducing cruising time, carbon emissions, and air pollution.

In general, the dynamic parking price-based regulatory framework has been discussed in different technical approaches that influence the organized parking management system. This study helps suggest different optimal parking pricing strategies to be used in rapidly growing urban areas that face parking problems.

4.1.2. Limitations

Some dynamic parking pricing approaches have some shortcomings of increasing parking prices for drivers, missing evaluation on real-time data performance, and lack of negotiation between drivers who are looking for a parking place and parking agents. Variations of price with the change of time, user's value of time, and change in parking price with occupancy were not considered in the previous studies.

Several of the discussed approaches have the following limitations:

- Disregarding competition among parking agencies.
- Disregarding such parameters as distance from destination, sound pollution due to cruising, parking space accessibility, etc.
- Parking fees limited to on-street or off-street parkings only; reservation fees, acceptance of reservations, and other issues not considered at the time.
- Disregarding the influence of parking information and trip purposes on parking choice.
- Lack of frequent price adjustment of a floating charge.
- Assuming the increase of parking fees concerning occupancy and time and disregarding constant travel time.
- Lack of a fully satisfactory description of the capability of parking model, parking choice, and parking search capabilities.
- Disregarding some social events, the effect of neighborhood parking lots, drivers' behavior in choice-making, and environmental situations.

4.2. Conclusions

Given the active nature of the field and the increasing number of vehicles with the increasing global population, the study of transportation in general and parking pricing-related issues, in particular, will play a vital role in the development of modern cities. Below are some of the possible topics or issues for future research in the context of our discussion:

- Performance-based analysis and robustness of dynamic parking pricing.
- Joint optimization of road pricing and parking pricing with a dynamic situation.
- Fuzzy approach of parking choice behavior of drivers under the consideration of demand and dynamic prices.
- Stochastic optimal control-based parking pricing model deals with random demand levels and system performance, which is expected to be explored more.

- Analyze situations in parking pricing problems based on rational game models, consideration of commuter behavior and benefits, demand and supply-based pricing game with various parking lot standards and early booking for reservation.
- In most of the previous studies, more attention was given to the deterministic approach, whereas in reality uncertainty widely exists in demand and user behavior. Hence, the interaction between parking agencies and drivers can be explored under uncertain circumstances, which is an interesting topic for future research.
- Stakeholders in the parking management system may have their conflicting objectives while seeking to achieve their goals.
- Drivers may consider the nearest parking place(minimum distance) and parking cost(minimum fee).
- Parking agents may adjust the price as per demand and supply, whereas the parking management authorities give more emphasis on the minimization of cruising time to regulate the traffic system, maximize social benefit, and related issues to time-varying step parking prices shall also be explored further.
- Bridging the gap between the proposed methods and the planning and operational implementation needs further study.

5. Summary

This paper presents a comprehensive literature review of the numerous dynamic parking pricing approaches in different urban areas. From various published works we infer that parking agents can utilize a dynamic pricing technique to maximize their revenue and make optimal use of the capacity of their parking lots. Instead of paying a random static price, drivers can benefit from dynamic parking rates by paying vehicular parking fees based on the real value of the parking lots. It has also numerous environmental advantages, including fewer traffic jams as well as more drivers choosing alternatives at peak hours.

With a detailed discussion of previous works, dynamic parking pricing approaches were categorized into six approaches: dynamic and stochastic control, game theory, multiobjective and multilevel programming, queuing theory, artificial intelligence and related ones, statistical, and other. A summarized discussion is presented after the detailed discussion of these methods with corresponding contributions. The general benefits and drawbacks of various techniques are outlined along with potential future works.

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