

INTEGRATED MODELS AND METHODS FOR DYNAMIC PRICING AND QUEUE MANAGEMENT IN AMUSEMENT PARKS

SLOBODYANUK V, KHOSHABA O (pzmag2022@gmail.com)

Vinnitsia National Technical University (Ukraine)

Abstract. This work develops and evaluates an integrated framework for dynamic pricing and queue management in amusement parks. We model time-varying arrivals, heterogeneous visitor segments, and attraction service processes using stochastic queueing models coupled with demand functions linking price, quoted waiting time, and perceived utility. Control is formulated as a finite-horizon optimisation that selects time-of-day prices and queue policies (including virtual queues and slot-based admissions) to maximise a multi-objective criterion balancing revenue, average waiting time, and service-level constraints. Parameter estimation combines historical ticketing and entry-gate data with attraction-level telemetry. Simulation studies calibrated on realistic park scales indicate that coordinated pricing and queue control can reduce mean waiting times by 30–40% while increasing revenue by 10–20% relative to flat pricing with FIFO, subject to fairness caps and satisfaction constraints. The approach uses well-established results from revenue management and queueing theory, making it suitable for deployment as a digital twin for operational decision support.

Keywords: dynamic pricing; queueing; revenue management; virtual queueing; demand elasticity; stochastic optimisation; amusement parks; digital twin.

Amusement parks face persistent peak-time congestion, volatile demand and heightened expectations of transparency and equity in service delivery. We address these challenges with an integrated framework that couples a time-varying queueing network with cross-price and cross-delay elasticities, enabling joint control of dynamic prices, virtual queues and capacity quotas under explicit fairness constraints. The approach draws on revenue-management fundamentals to shape willingness to pay and arrival timing [1], [2], classical and modern queueing theory to map operational states to delays and throughputs [3]–[6], and Markov decision processes for sequential control under uncertainty [7]. Uniquely, we make quoted waiting time (QWT) a first-class, customer-visible signal that co-drives demand alongside price, while guaranteeing fairness and accessibility via enforceable constraints.

Arrivals are modelled as piecewise-stationary Poisson processes with distinct weekday and holiday profiles; service times are log-normal fits per ride category (thrill, family, kids). Demand sensitivities include own- and cross-elasticities to (i) posted price and (ii) the QWT forecast published to guests at booking or entry. Control actions—price levels, virtual-queue admissions and per-ride capacity quotas—are computed through a rolling-horizon optimisation with 15-minute receding windows. Elasticity parameters are updated online using a Bayesian scheme every hour based on a seven-day sliding window of operational traces; priors are truncated to maintain stability under sparse data. To ensure operational realism, each attraction is limited to at most one price change per 30 minutes. Fairness is enforced via three hard caps: intra-day price dispersion between equivalent customer groups $\leq 15\%$; P90 waiting time for non-priority guests ≤ 35 minutes; and an accessibility quota reserving $\geq 5\%$ of capacity. These constraints institutionalise transparency and equity without removing managerial degrees of freedom [1], [2].

We instantiate the framework as a digital-twin testbed comprising 14 rides (5 thrill, 6 family, 3 kids), operating 10:00–20:00. Calibrated peak arrival rates at the three flagship rides are 220–260 guests/hour, while across the park per-ride arrivals range from 40 to 260 guests/hour depending on time-of-day and scenario. Median service times span 2.8–4.1 minutes (IQR 1.1–1.6) across categories. Scenarios cover weekday, holiday and light-rain conditions (the latter reducing arrivals by $\sim 12\%$) with bimodal peaks around 12:00–14:00 and 16:00–18:00. The queueing backbone

follows standard results linking arrival and service characteristics to sojourn times and throughput [3]–[6]; we invoke Little’s law qualitatively to interpret load–delay trade-offs without recourse to explicit formulae [5]. The controller is solved as a finite-horizon decision problem in the spirit of MDPs, with approximate dynamic programming elements used to warm-start the rolling optimisations [7].

Primary outcomes are P50/P90 sojourn time (minutes), on-time service probability (target $\geq 95\%$), throughput (guests/hour) and revenue; we additionally track QWT error, defined as $|\text{quoted} - \text{realised}|$. All metrics are reported as medians with interquartile ranges over $K = 64$ stochastic replications per scenario, using a fixed seed set to ensure reproducibility. Baselines include (i) static pricing with FIFO queues, and (ii) time-of-day pricing without virtual queues. Ablations remove cross-elasticities or fairness constraints to isolate their marginal contributions. This stacked evaluation design adheres to best practice in operations research, separating demand-shaping, queue-structuring and ethical-governance effects [1]–[3], [6].

Across all weekday and holiday scenarios, the integrated controller reduces P90 sojourn time by 32–38% (median 35%) and increases revenue by 11–19% (median 14%) relative to static pricing, while raising throughput by 6–9%. These gains arise from two mechanisms: prices and QWTs cooperatively re-time arrivals away from peaks, and virtual queues reduce wasted physical waiting without degrading service discipline. Crucially, fairness caps are not merely feasible but active in congested periods, bounding dispersion and protecting non-priority guests. Customer-visible QWTs remain within ± 3 minutes of realised medians, reinforcing trust and mitigating perceived queue unfairness. Against the time-of-day-only baseline, additional benefits stem from cross-elasticity awareness: coordinating prices at substitutable rides prevents counterproductive load shifting and avoids local optima that inflate park-wide P90. Ablations confirm both cross-elasticities and fairness constraints are material—removing either erodes revenue–delay trade-offs and, in the latter case, increases tail waits for non-priority guests.

Robustness analyses indicate graceful degradation under model error and shocks. With $\pm 20\%$ mis-specification of elasticities and an unannounced 25% demand spike at 16:00, revenue and P90 improvements deteriorate by ≤ 4 percentage points, while fairness constraints remain satisfied. The rolling-horizon cadence is a key design knob. A 15-minute re-optimisation schedule with conservative elasticity priors offers the best balance of stability and responsiveness. Switching to a five-minute cadence yields negligible incremental benefit but higher operational complexity due to more frequent candidate changes. From a managerial standpoint, we recommend configuring the controller to prioritise adherence to fairness caps during 12:00–14:00 and 16:00–18:00 peaks, and to prefer small, predictable price movements that align with guests’ reference prices [1], [2]. The capacity-quota lever is particularly effective in protecting accessibility slots with minimal throughput loss when applied pre-peak rather than reactively.

The study contributes a practical synthesis of revenue management, queueing models and sequential decision-making tailored to the realities of themed attractions. Methodologically, it demonstrates that posting credible QWTs as a demand signal is as powerful as classical pricing in shaping flows, provided those QWTs are tightly coupled to the underlying queueing dynamics [3], [6]. Empirically, we show that a fairness-aware controller can deliver double-digit revenue gains while cutting tail delays by roughly a third, without eroding perceived equity—an outcome often presumed to be a zero-sum trade-off. Limitations include reduced headroom under extreme spikiness (e.g., concert-adjacent events) or under legally mandated price caps below elasticity thresholds. In such regimes, the gains diminish, and fairness constraints bind earlier. Future work will extend the digital twin to heterogeneous risk preferences and group arrivals. It will explore staff-scheduling co-optimisation to tighten the link between planned capacity and realised service times.

In summary, the proposed framework formalises a transparent and equitable way to blend dynamic pricing with virtual queue management in amusement parks. By anchoring control on realistic demand and service models, exposing QWTs as a meaningful promise to guests, and hard-coding fairness protections, operators can achieve robust improvements in both economic and

experiential outcomes. Our results are consistent with established theories of demand and congestion while advancing their joint application in a complex, high-variability service system [4]–[7].

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