Dynamic Pricing for Urban Parking Lots: A Capstone Project Report

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📌 Project Overview

Urban areas worldwide face increasing demand for parking, leading to inefficiencies when static pricing models are used. This project addresses this challenge by developing a **real-time, dynamic pricing engine** for urban parking lots. The solution is built using fundamental Python libraries (NumPy, Pandas) and the real-time data streaming capabilities of Pathway, simulating realistic operational conditions. The core aim is to optimize parking lot utilization and improve urban mobility.

🎯 Objective

The central objective is to create **intelligent models that can adjust parking prices in real-time**. This dynamic adjustment is driven by a comprehensive set of real-world factors:

- **Occupancy rate:** Current utilization of parking spaces.
- **Queue length:** Number of vehicles waiting to park.
- **Traffic level:** Real-time congestion in the vicinity.
- **Vehicle type:** Differentiating pricing based on vehicle size or impact (e.g., cars, bikes, trucks).
- **Special events:** Adapting to increased demand during holidays or local events.
- **Proximity to competing lots:** Considering the pricing of nearby alternative parking.

A crucial design principle is to ensure that all pricing changes are **smooth, explainable, and conducive to business operations**. Additionally, the system provides **optional rerouting suggestions** to drivers when a particular lot reaches full capacity, aiding in congestion control.

📊 Data Description

The project leverages a rich dataset that comprehensively captures parking lot conditions. It includes data for **14 urban parking lots** over a period of **73 days**, with observations recorded every **30 minutes** (18 time slots per day). Each data record contains vital information:

- **Capacity:** Maximum number of vehicles the lot can hold.
- **Occupancy:** Current number of parked vehicles.
- **Queue length:** Number of vehicles waiting to enter.
- **Traffic congestion level:** Categorized as low, medium, or high.
- **Vehicle type:** Classification of vehicles (car, bike, truck).
- **Special day indicator:** Flags for holidays or significant events.
- **Geolocation:** Latitude and longitude coordinates for each lot, enabling spatial analysis.

🧠 Models Implemented

Three distinct pricing models have been developed, each building upon the previous one to incorporate more sophisticated demand and competitive factors:

✅ Model 1: Baseline Linear Model

This foundational model provides a simple, direct relationship between price and occupancy, serving as a benchmark for pricing sensitivity.

- **Logic:** Price adjusts linearly based on the proportion of occupied spaces to total capacity.
- **Formula:** $Price(t+1) = Price(t) + \alpha \times (Occupancy / Capacity)$

✅ Model 2: Demand-Based Pricing

This model expands on the baseline by integrating multiple factors that influence demand, creating a more nuanced pricing strategy.

- **Inputs:** Occupancy rate, queue length, traffic level, special day flag, and a vehicle weight factor.
- **Demand Formula:** $Demand = \alpha \cdot (Occ/Cap) + \beta \cdot QueueLength - \gamma \cdot Traffic + \delta \cdot SpecialDay + \epsilon \cdot VehicleTypeWeight$ *Where $\alpha, \beta, \gamma, \delta, \epsilon$ are coefficients determining the influence of each factor.*
- **Price Calculation:** Prices are scaled and normalized to stay within a predefined range (0.5x to 2x the base price). $Price = BasePrice \times (1 + \lambda \times NormalizedDemand)$

✅ Model 3: Competitive Pricing Model

The most advanced model, it introduces an external factor: the pricing strategies of nearby competing parking lots.

- **Inputs:** Geographic distance between lots (derived from latitude-longitude data) and average competitor prices.
- **Logic:**
  - If the current lot is full and nearby lots are cheaper, the system may suggest reducing price or rerouting.
  - If nearby lots are more expensive, the system may recommend increasing the current lot's price.
- **Goal:** Enhance market efficiency and prevent significant price discrepancies between adjacent lots.

🔁 Real-Time Streaming (Pathway)

A critical component of this project is the real-time simulation capability provided by **Pathway**.

- **Mechanism:** Pathway simulates a data stream from the historical dataset, ensuring that data records are processed in chronological order.
- **Operation:** The dynamic pricing logic for each model runs at every "time tick" of the simulated stream, generating a suggested price for the current moment.
- **Benefit:** This approach accurately mimics near real-time operational behavior using native Python, allowing for robust testing and validation of the dynamic pricing engine.

📈 Visualization (Bokeh)

To effectively analyze and present the behavior of the dynamic pricing models, **Bokeh** is used for interactive visualizations.

- **Display:** Line plots visually compare the price trends generated by the Baseline, Demand-Based, and Competitive models over time.
- **Analysis:** The plots highlight the smoothness of temporal trends for each model, demonstrating their responsiveness and stability.
- **Interactivity:** A hover tool allows users to precisely view the time and exact price for any point on the graphs, facilitating detailed analysis and understanding of the pricing logic.

✅ Key Outcomes

This project successfully demonstrates a robust and intelligent solution for urban parking lot management, leading to several key outcomes:

- **Real-time Responsiveness:** The developed pricing models effectively respond to dynamic demand signals, enabling agile price adjustments.
- **Improved Market Efficiency:** The inclusion of competitive awareness fosters a more efficient and balanced parking market.
- **Enhanced Urban Mobility:** The system supports smart rerouting and congestion control, contributing to smoother urban traffic flow.
- **Clear and Explainable Logic:** The visualizations provide transparent insights into how the pricing logic operates, making it understandable for stakeholders.