Urban Lot Optimization using Pathway and Bokeh Report

Summary

This report outlines the development of a real-time dynamic pricing system for 14 urban parking lots, created for the Summer Analytics 2025 Capstone at IIT Guwahati. The project aims to improve parking efficiency by adjusting prices based on occupancy, queue length, traffic, vehicle type, and special events.

Using a 73-day time-series dataset, three pricing models were implemented:

- A **linear model** based on occupancy rate,
- A **demand-based model** using weighted inputs,
- A **competitive rerouting model** based on lot proximity.

Python was used for data processing, **Pathway** for real-time simulation, and **Bokeh** for interactive dashboards.

Key findings include:

- The demand-based model outperformed others in balancing usage and pricing fairness.
- Competitive rerouting reduced congestion in high-demand areas by ~12%.
- Real-time updates every 30 minutes enabled timely pricing decisions.
- The system is scalable and suitable for smart city deployment.
- Visualization helped identify price surges, underutilized lots, and rerouting opportunities.
- The approach promotes sustainability by encouraging even space usage and reducing unnecessary driving.
- The models can be integrated with sensors, mobile apps, and IoT platforms for live deployment.
- This framework supports smarter, data-driven urban mobility systems of the future.

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1 Introduction

Urban parking management faces growing challenges due to increasing vehicle density, limited space, and inefficient static pricing policies. This project proposes a dynamic pricing solution for 14 city parking lots using real-time data analysis and predictive modelling. The solution is aimed at optimizing lot usage, minimizing congestion, and improving the user experience through adaptive price adjustments.

This report examines how dynamic pricing, supported by real-time data, can balance supply and demand in urban parking systems. It explores three pricing strategies: baseline linear pricing, demand-driven pricing, and competitive rerouting based on spatial data.

This project was developed as part of the Summer Analytics 2025 Capstone at IIT Guwahati and leverages Python, Pathway, and Bokeh to create a robust real-time pricing engine.

1.1 Methodology

A time-series dataset covering 73 days of operational data across 14 parking lots was used. Each record included:

- Date and time
- Parking lot ID and geolocation (latitude, longitude)
- Capacity and current occupancy
- Queue length and traffic conditions
- Special day indicators (e.g., holiday, weekend, event)
- Vehicle type (car, bike, truck)

The methodology followed these steps:

1. **Data Preprocessing**: Handling missing values, encoding categorical features, and calculating derived metrics such as occupancy rate.
2. **Feature Engineering**: Generating composite scores (e.g., demand index) using weighted inputs.
3. **Modelling**: Implementing three strategies—baseline linear pricing, demand-based pricing, and competitive rerouting.
4. **Simulation**: Using Pathway to simulate real-time data flow at 30-minute intervals.
5. **Visualization**: Creating interactive plots and dashboards in Bokeh to analyse model outcomes.

1.2 Scope of the Report

This report focuses on analysing and comparing the effectiveness of three distinct pricing models under simulated real-time conditions:

- Linear pricing based solely on occupancy
- Demand-based pricing with multiple weighted inputs
- Competitive rerouting using geolocation of lots

While the findings are based on synthetic or anonymized data, the models are designed to be extensible to live smart-city environments.

2. Findings

2.1 Occupancy-Based Linear Pricing

A simple model that increases the price as a function of occupancy:

$$Price[t+1] = Price[t] + \alpha \times (Occupancy / Capacity)$$

Findings indicate this model adjusts pricing steadily but lacks responsiveness to other important variables like queue length or traffic.

2.2 Demand-Based Dynamic Pricing

This model uses a composite demand function:

$$Demand = \alpha 1 * (Occupancy\ Rate) + \alpha 2 * Queue\ Length - \alpha 3 * Traffic + \alpha 4 * Special\ Day + \alpha 5 * VehicleTypeWeight$$

$$Price = Base\ Price \times (1 + \lambda \times Normalized\ Demand)$$

It provides smoother, more nuanced price updates and responds well to changes in traffic conditions and vehicle type. This model performed best in balancing lot usage and preventing underutilization.

2.3 Competitive Rerouting Strategy

For lots nearing full capacity:

- Nearby lots were identified using lat-long distances.
- If nearby lots were underused, prices were decreased to encourage rerouting.
- Lot distribution improved, and congestion dropped by ~12% in simulations.

This model is especially effective when combined with mobile applications or signage that informs users about real-time prices in adjacent lots.

3. Conclusion

Dynamic pricing offers a powerful tool for optimizing urban parking systems. Through this project, we demonstrate that simple models like linear pricing can offer a basic level of adaptability, but more advanced strategies—such as demand-based pricing—can significantly improve responsiveness and fairness.

The inclusion of competitive rerouting further enhances system efficiency by diverting drivers to nearby underutilized lots, helping to reduce congestion in high-demand areas.

With real-time simulation using Pathway, and intuitive dashboards via Bokeh, this project showcases a scalable and effective approach to managing parking in smart cities. The models developed here can serve as a foundation for future real-world deployment, integrating with sensors, mobile apps, and city-wide transport systems to promote sustainable urban mobility.

Looking ahead, incorporating user feedback and predictive analytics can make the system even more adaptive. Integration with navigation tools can guide users to optimal lots in real time. Further expansion to 24/7 monitoring would allow for better off-peak pricing control. Overall, this project lays the groundwork for intelligent, equitable, and data-driven urban parking management.

4. Recommendation

- **Enhance input features**: Incorporate weather conditions, real-time event feeds, and user preferences.

- **Model refinement**: Use machine learning to fine-tune pricing weights based on historical effectiveness.

- **Mobile integration**: Integrate with navigation apps to show users cheaper, nearby alternatives.

- **Real-world deployment**: Collaborate with local authorities to run live trials in urban areas.

- **User feedback loop**: Incorporate sentiment/feedback from drivers to improve pricing fairness and experience.

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