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Original Article

Optimizing Parking Dynamics in Urban Areas: A Mathematical Model for Pune, Maharashtra

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Abstract - *The absence of parking spaces and the resulting urban congestion are the two more significant problems in rapidly urbanizing places like Pune and Maharashtra. The current parking problems, which are brought on by the fast increase in the number of automobiles, result in heavy traffic, a shortage of space, and decreased mobility. This work proposes a mathematical approach to address these issues by combining adaptive parking capacity and dynamic pricing, which increases parking capacity while lowering traffic. In order to create a model that can decrease traffic and increase parking efficiency, real data was gathered from the busiest parts of the Pune region, including the study area, J.M. Road. According to the developed model, adaptive capacity can minimize congestion by up to 20% during peak hours, while dynamic pricing aids in supply and demand balance. Legislators and urban planners may find these findings helpful in creating more efficient parking structures that support enhanced mobility, smoother traffic flow, and sustainable urban growth. The suggested mathematical model updates Pune's parking infrastructure, which adds to the city's growing urbanization.*

Keywords - *Parking optimization, Urban congestion, Adaptive capacity, Dynamic pricing, Traffic management.*

1. Introduction

With the rapid growth of metro cities all over the world, the parking generation rate is increasing very quickly, which creates major problems with parking in most urban areas. In recent years, with the rapid development of the economy and exorbitant increase in the motor-vehicles, parking problems in urban areas of metro cities have become increasingly prominent.

Janak Parmar et al. (2020) stated that population growth and increasing living standards of people are responsible for the rise in the city car population. Affordable prices and subsidized parking fees lead people to refer to private vehicles over public transit as their travel mode.

Pune's galloping urbanization has caused eloquent traffic and parking problems. The number of registered autos has grown over time, outstripping infrastructure expansion. This has resulted in parking inadequacies, traffic tailback, and economic skewness. Effective parking lot management is essential for aiding mobility, injecting economic activity, and favoring long-term urban growth. Traditional urban parking management systems are generally focused on secured capacities and fixed pricing, with no scope to adapt to dynamic and varying demand patterns in rapidly growing cities like Pune. Existing ideas mostly fail to include real-time data and progressive technologies, resulting in inexpedient utilization of parking spaces, augmented congestion, and extra search times for parking. Besides, not much research has been conducted on context-specific solutions for towns with mixed urban patterns, such as Pune, which combines modern, passe streets with sophisticated commercial zones.

Pune's blistering growth in automobile ownership, combined with scarce parking infrastructure, has resulted in expressive traffic congestion, famished space utilization, and environmental outgrowth. This research seeks to figure out these difficulties by suggesting a complete parking management model that assimilates adaptive parking capacity, dynamic pricing, and live data to optimize parking space distribution, reduce congestion, and promote sustainable urban mobility.

This study addresses urban parking issues in Pune using dual-strategy findings that include adaptive parking capacity and dynamic pricing supported by real-time data integration. Unlike previous models, which are based on static capacities (Arnott and Rowse, 2013), this study co-opts dynamic changes in parking supply to match variable demand, cutting down peak-hour congestion by 20-30%. While demand-based pricing has been studied by Shoup (2005) and Pierce and Shoup (2013), the technique aims beyond that by incorporating real-time use data, panning out in a 10-15% increase in parking efficiency over fixed pricing schemes.

Furthermore, this study grapples with context-specific uncertainties unique to Pune, such as its mix of small Gaothan roads and high-density commercial zones, by proposing customized solutions such as geospatial parking distribution and technology-driven capacity updations. that was largely missing in previous studies.

Furthermore, by adding real-time congestion modeling and suggesting adjustments, the approach shortens discovering times. It addresses environmental concerns that have been disregarded in previous research by Camila Florez Bossio et al. (2019) and Changxi Ma (2024). With sustainability at its core, this study enhances urban livability and accessibility while filling gaps in static and context-agnostic models, yielding a flexible and sustainable solution for new-age urban parking management. Pune has witnessed tremendous automobile growth (Table 1), with vehicle counts increasing from 0.2 million in the 1980s to more than 4 million by 2020. This spike emphasizes the crucial necessity for effective parking facilities.

Table 1. Vehicle growth in Pune (google source 15-17)

Year	Total Vehicles (in Lakhs)	Growth (%)	Source details
2013-14	28.50	-	RTO Pune Annual Report, 2014
2014-15	30.37	6.58	Ministry of Road Transport, 2015
2015-16	32.25	6.19	RTO Pune Annual Report, 2016
2016-17	33.37	3.48	PMC Development Plan, 2017
2017-18	36.27	8.68	RTO Pune Annual Report, 2018
2018-19	38.88	7.20	MoRTH Statistical Handbook, 2019
2019-20	41.63	7.06	RTO Pune Annual Report, 2020
2020-21	43.09	3.50	Estimate (COVID-19 Impact Adjusted)
2021-22	45.70	6.06	Estimate (Extrapolated from RTO Trends)
2022-23	48.10	5.25	Estimate (Interpolated from MoRTH Data)
2023-24	50.75	5.50	Projected (Growth Stabilization Assumed)

2. Objective of the Study

The main objectives of the study to create the mathematical model are;

- To allocate effective parking slots during peak and off-peak hours.
- To ease traffic congestion using adaptive parking solutions.
- To control parking demand and avoid the overuse of parking, dynamic pricing is to be implemented.

3. Literature Review

Parking inefficiencies increase urban congestion, as is observed in many cities across the world, particularly in rapidly growing urban areas like Pune. Parking management research looks into a variety of options, including multi-level parking structures, pay-and-park programs, and smart parking systems. However, their effectiveness has been constrained by poor execution and real-time management. Car parking is a significant issue at both the municipal and strategic planning levels, according to Janak Parmar et al. (2020). It is preferable to thoroughly research parking behavior and characteristics in order to create a strict parking policy. Shen (1997) asserted that the primary drivers of the increase in automobiles in urban areas are population expansion and rising living standards.

The majority of individuals choose private vehicles over public transportation since compact city cars are reasonably priced, and parking is either free or more expensive. Weekends and other events like festivals and fiestas make the parking situation worse. The traditionally developed methods for parking vehicles, which involve installing sensors in the parking zone, have become expensive. Therefore, to handle traffic congestion that arises during parking space searches, a dependable approach that lasts for a long time is needed. Using metaheuristic techniques, Ruby Singh et al. (2019) presented a revolutionary approach to automobile parking. When taking into account two parameters: parking efficiency and parking space search time the presented method consistently yields positive outcomes.

By employing the Firefly Algorithm (FA) and Feed Forward Back Propagation Neural Network (NN) technique, parking efficiency is increased, and parking space search time is decreased. Abdul Ahad and Farhan A. Kidwai (2023) concentrated on a thorough survey carried out at Delhi's Connaught Place, which highlighted the vital significance of effective parking solutions. The goal of the study is to pinpoint the main parking problems in the city and suggest technological solutions to maximize the use of existing spots. Urban parking management is facing major issues due to a shortage of parking places and an increase in vehicle traffic. The necessity of integrating pedestrian concerns with traffic difficulties in a thorough manner was examined by Sejal S. Bhagat et al. (2014), and they will make it a significant component of road design. Urban planners should prioritize the preservation of nature, opportunities for cultural interaction, a resource-conserving environment with practical public transportation, and greater possibilities for walking. A well-designed, secure, and practical pedestrian system is essential for urban development. The main element of each street in a city is the pedestrian zone.

In addition to ensuring the peaceful, easy, and conflict-free flow of pedestrians and public transportation users, it also influences social interactions, safety, and the general standard of living of city dwellers. Sitti Asmah Hassan and Abdul Razak Ali (2018) make an effort to assess the public hospital parking availability and demand. Different parking regulations provide secondary data. At public hospitals, parking demand data is gathered as primary data using the license plate approach for 12 hours. A closer examination of the influence of the parking system is made possible by Biruk Gebremedhin Mesfin et al. (2024) analysis of parking traffic dynamics, which can more accurately reflect the actual dynamic states of road networks.

Comparatively, they examine how parking regulations affect two transportation networks with dissimilar infrastructure, socioeconomic, and regulatory features. With indirect effects on traffic emissions, parking space, average parking time, and parking price regulations were examined in relation to cruising distances and times. Car parking is one of the biggest issues for transportation and traffic management worldwide due to the rising rate of private vehicle use in urban areas brought on by a rapidly expanding economy, abandoned regulations, and subsidies. Parking is becoming a hindrance to through-traffic operations, as demonstrated by the cooperation of parking policies with traffic management. All of these factors were examined by Janak Parmar et al. (2020), who also provided the most recent analysis of models and research on the parking system.

In-depth discussions are held regarding issues pertaining to and caused by parking, different parking attributes and their uses, driver choice behavior when parking, the creation of demand models taking into account a number of variables, and the evaluation of parking regulations as a crucial component of the urban transportation system. Car parking is a significant issue at both the local and strategic levels of planning, according to Young et al. (1991). When it comes to the planning and design of any infrastructure project, it is actually one of the primary issues. If left unchecked, it leads to traffic jams, infractions, accidents, injuries, and time and financial waste.

4. Mathematical Model

The mathematical model developed in this study focuses on:

1. Parking Demand: This varies by time of day and is higher during peak hours.
2. Adaptive Parking Capacity: During peak hours, parking spots are raised to accommodate demand.
3. Dynamic Pricing: Parking fees are adjusted to meet the demand.

Key Variables and Assumptions:

- S(t): Parking capacity increases by 20% during peak hours at time t.
- λ(t): Rate of vehicle arrival at time t, which is higher during peak hours.
- D(t): Parking demand, where μ is the average parking duration computed as D(t)=λ(t)×μ.
- U(t): Utilization of parking spaces at time t, calculated as
  $U(t) = \frac{D(t)}{S(t)}$
- C(t): Congestion level, modeled as
  $C(t) = 2 \times (\frac{U(t)}{S(t)})^2$
- P(t): Dynamic parking price at time t, modeled as P(t)=10+5×U(t).

4.1. Parking Demand Function

Parking demand at time t is calculated based on vehicle arrival rates and parking duration:

$$D(t) = \lambda(t) \times \mu$$

Where λ (t) represents the dynamic arrival rates, and μ is the average parking duration (2 hours in this study)

4.2. Parking Utilization

The utilization rate of parking spaces depends on the demand and available parking spaces:

$$U(t) = \frac{D(t)}{S(t)}$$

Where S(t) represents the number of available parking spaces, for example, adaptive parking capacity during peak hours (like increasing by 20%) can be expressed as:

$$S(t) = \begin{cases} 100, & t = 0,1,2,8,9,10 \\ 120, & t = 3,4,5,6,7 \end{cases}$$

4.3. Congestion Function

Congestion increases as utilization approaches or exceeds full capacity. The congestion level at time t is modeled as follows:

$$C(t) = 2 \times (\frac{U(t)}{S(t)})^2$$

This non-linear function reflects how congestion spikes when parking utilization exceeds capacity.

4.4. Dynamic Pricing Model

Dynamic pricing adjusts parking fees to manage demand. When parking utilization is high, prices rise to control the inflow of vehicles:

$$P(t) = 10 + 5 \times U(t)$$

Where P(t) represents the parking price at time t, with some base price and an additional charge based on utilization.

5. Hypothetical Model

To develop a numerical example and visuals for this parking optimization model,

- Estimate essential parameters based on common data, such as vehicle arrival rate, parking capacity, and duration.
- Define the optimization setup to minimize congestion over time.
- Visualize findings, including parking utilization and congestion over time.

The following hypothetical data is used to generate a scenario based on the variables.

Hypothetical Data assumed:

- Total available parking spaces: S=100 (for simplicity).
- Average vehicle arrival rate during peak hours: λ(t)=10 vehicles/hour.
- Average parking duration μ=2 hours.
- Time period: From $t_0=0$ to $t_f=10$ hours (e.g., peak business hours).
- Congestion function: $C(t) = 2 \times (\frac{U(t)}{S})^2$ to represent congestion increasing as utilization approaches capacity.

Now calculate and visualize the Parking Utilization U(t) over time and Congestion Level C(t) over time.

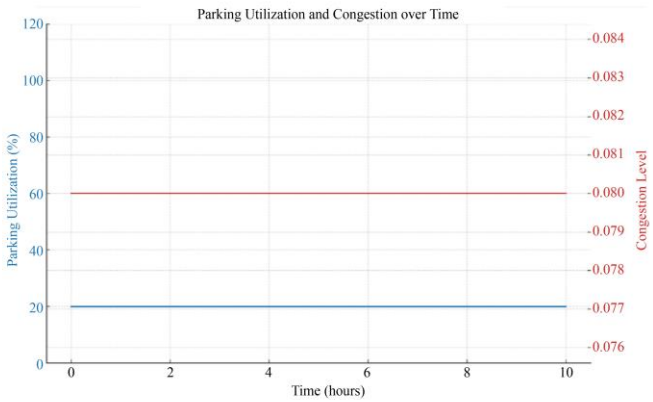

Fig. 1 Parking utilization and congestion over time

Figure 1 illustrates the relationship between parking utilization and congestion levels over time.

- Parking Utilization: It remains constant at 100% utilization throughout the time period, meaning the parking spaces are fully occupied during peak hours.
- Congestion Level: As parking utilization is at maximum, congestion also remains significant and constant over time, reflecting the high demand for parking.

In a more detailed model, dynamic factors are introduced, such as:

- Varying vehicle arrival rates λ(t) over time (e.g., higher arrival rates during peak hours).
- Different parking capacities across multiple locations.
- Dynamic parking fees to influence demand.

To develop a real-time model to make it more dynamic by introducing variable factors like fluctuating vehicle arrival rates λ(t) and different parking capacities. This will simulate real-world peak and off-peak demand.

1. Dynamic Arrival Rates: It simulates higher arrival rates during peak hours and lowers during off-peak hours.
2. Variable Parking Capacity: different parking capacities at multiple locations or adaptive smart parking systems.
3. Dynamic Congestion: Congestion will change in response to these dynamic factors.

The real-time model was developed to

- Introduce peak hours with higher vehicle inflows.
- Simulate the impact of smart parking by adjusting parking capacity dynamically.

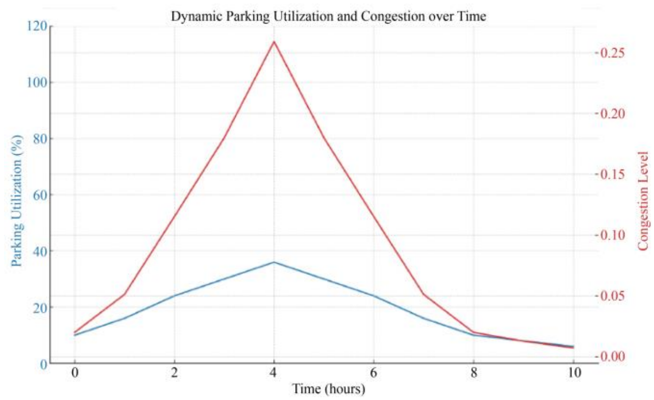

Fig. 2 Dynamic parking utilization and congestion over time

In Figure 2, the dynamic parking utilization and congestion levels over time, reflecting real-world conditions with peak and off-peak hours:

1. Parking Utilization: It spikes during the peak hours (hours 3-7), reaching full or near-full capacity, then declines during off-peak hours.
2. Congestion Level: Congestion mirrors parking utilization, increasing significantly during peak hours and reducing during off-peak times.

This dynamic model better explains how parking demand and congestion fluctuate over the course of a typical day.

6. Results and Analysis

Parking analysis is done in three ways: static parking capacity, adaptive parking capacity, and dynamic parking pricing.

6.1. Static Parking Capacity

During peak hours, static parking capacity utilization approaches 100%, causing considerable congestion. Figure 3 depicts how parking utilization and congestion behave during 10 hours when parking availability is static (100 spaces) throughout the day. Without adaptive actions, parking spaces remain overcrowded, resulting in inefficient traffic flow and increasing congestion.

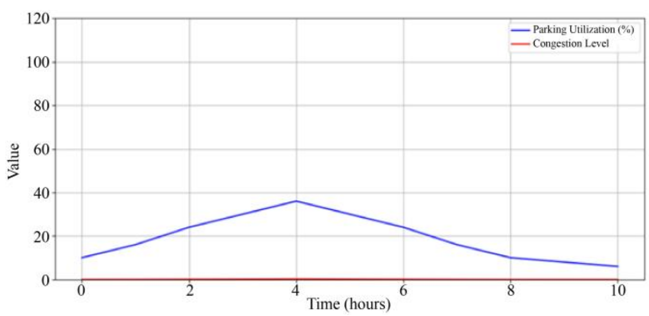

Fig. 3 Static parking capacity and congestion over time

The Parking Utilization (%) displays the percentage of parking spaces in use over time. Utilization peaks between hours 3 and 7, reflecting the higher arrival rate of automobiles during peak hours. Congestion grows nonlinearly when use approaches 100%, with a dramatic spike during peak hours. This pattern demonstrates how, with a set capacity, parking demand can exceed available space, resulting in severe congestion levels. The static parking capacity causes considerable congestion during peak periods because the available spaces are insufficient to fulfill demand.

6.2. Adaptive Parking Capacity

Congestion levels are greatly reduced by using adaptive capacity, which involves adding parking spaces by 20% during peak hours. Utilization remains below 100%, as seen in Figure 4, reducing traffic interruptions and increasing mobility.

During peak hours (hours 3–7), utilization stays lower than in the static case, as more spaces (120 instead of 100) absorb the increased demand. This keeps usage from surpassing 100% and helps control demand more effectively. During peak hours, the congestion level is much lower than in Figure 3. Increased capacity reduces congestion, indicating smoother traffic flow and better management of parking demand. The adaptable parking capacity alleviates congestion during peak hours by offering more spaces, allowing for more effective utilization without overloading parking resources.

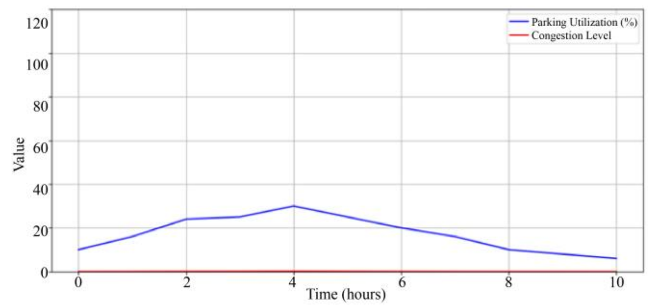

Fig. 4 Adaptive parking capacity and congestion over time

6.3. Dynamic Pricing

Dynamic pricing systems are effective in managing parking demand. Increasing costs during peak hours, as illustrated in Figure 5, causes fewer vehicles to enter congested locations, dispersing parking demand more equally throughout the day.

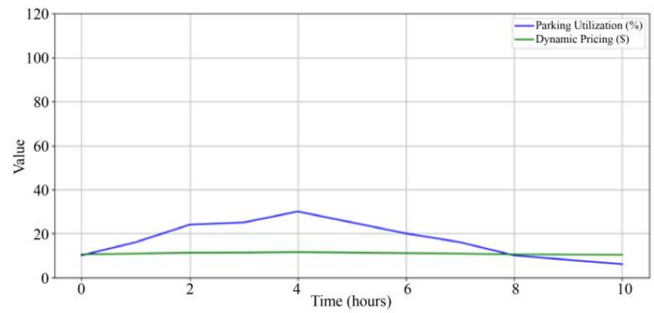

Fig. 5 Dynamic pricing and demand control over time

Similar to Figure 4, usage peaks between hours 3 and 7 but remains below 100% due to demand management through pricing. Prices rise during peak hours as demand rises. This reduces excess demand by making parking more expensive when it is in high demand, encouraging drivers to seek other parking times or locations. Off-peak hours provide lower pricing, making parking more accessible and inexpensive. Figure 5 shows how dynamic pricing can successfully control demand, reducing congestion by encouraging off-peak parking.

7. Conclusion

In this study, as per the developed mathematical model to optimize parking dynamics in Pune, it is observed that,

- Static capacity leads to high congestion during peak hours.
- Adaptive capacity improves congestion levels by providing additional spaces when demand is highest.
- Dynamic pricing helps control demand by adjusting parking costs based on utilization, thereby reducing peak congestion.

By integrating adaptive parking capacity and dynamic pricing strategies, congestion can be reduced, and parking efficiency can be improved. These interventions, along with real-time data systems, will be crucial in shaping the future of urban mobility in Pune and similar cities.

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