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Queueing theory and game theory approach for congestion pricing models in urban transportation networks

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Abstract
To this end, a dynamic congestion pricing of urban road network is studied in this paper based on queueing theory and game theory. The model updates the price with respect to time based on current congestion levels, attempting to equate the supply and demand of lands, thus decreases the expected waiting time for passengers as well as increasing their satisfaction. Numerical studies indicate that dynamic pricing is promising for congestion alleviation and passengers' behaviors changing as well as the increasing revenues of transport operators. The research identifies this method could have applications for the optimisation of urban transport networks, improving network efficiency and guaranteeing equitable access. It includes practical advice for policy makers who want to ensure that congestion management will be both efficient and sustainable.

Keywords: Congestion pricing, queueing theory, game theory, urban transportation, dynamic pricing, passenger satisfaction, transport optimization, network efficiency, simulation analysis, revenue sustainability

1. Introduction
City mobility systems are today confronted with new challenges as higher population density and demand for mobility grow. Congestion in public transit systems leads to not only inefficiency but also passenger dissatisfaction and system sustainability. With the development of cities, a new sense of urgency is created to develop novel ways/strategies towards enhancing both transport networks and passenger experience while assuring revenue sustainability for the operators. Queueing theory and game theory are combined for dynamic congestion pricing strategy development in this work. Taking account of passenger and system performance, the integrated model tries to reconcile demand and supply so as to reduce rush hour congestion. (Smith & Johnson, 2021) [8].

2. Research Problem
Urban public transportation encounters the problem of heavy demand during peak hours and, hence, long waiting time, low service quality, and passenger disgruntlement. Conventional pricing models do not have the ability to autonomically react to load rates, resulting inefficient service provisions and underuse of network resources in non-busy times. Furthermore, there exist few studies on how to apply mathematical models such as queueing theory and game theory to devising better pricing mechanisms for boosting the revenue generation as well as guaranteeing fair access to transportation services. (Brown & Green, 2022) [9]. We answer the following question: How can we design congestion pricing methods using the tools of queueing theory and game theory that are effective in terms of network performance for an urban area, while also satisfying passengers.

3. Research Objectives
This study aims to achieve the following objectives
1. Create a dynamic congestion pricing mechanism through a hybrid model of queueing and game theory.
2. Study the effect on passenger behavior, revenue and network efficiency of congestion pricing.
3. Explore the correlation of pricing, wait time and passenger satisfaction with computer model as well as actual data.

4. Offer the operators of transportation a practical set of recommendations for demonstrating how they can impose fair and efficient price signalings on urban inter-district traffic.

4. Research Significance

The importance of this research to the context of the problem is due to the urgent issues of congestion and in-efficiency of the urban transportation systems:

1. **Innovative Framework:** The article introduces a novel framework to combine the queueing theory with the game theory with the intention of adapting the price based on the real congestion level.
2. **Economic and Operational Benefits:** The findings justify the advantage of efficient transport revenue collection and network performance, especially during high demand times.
3. **Improved Passenger Experience:** The information about passenger profile and passenger satisfaction is also crucial in coming up with fare structure that provides a trade off between affordability and quality services.
4. **Policy Implications:** The results provide ideas to policy makers on the best way to make the Transport policies sustainable to offer equitable access and be friendly to the environment.

This research fills the gap between theoretical model and real application, some novel methods for solving city transport issues will be given.

2. Literature Review

2.1 Introduction to Queueing Theory

Queueing theory is the study of waiting in lines and has its origins in applied mathematics. This theory describes a mathematical interaction between customers or passengers who are queuing for some sort of service (such as roads and the internet being used by traffic and users, respectively) commuting in an urban transport network waiting at a bus or train station (Kleinrock, 1975) [2].

Queuing theory in urban transport research is used to investigate such factors as passenger flows, waiting times and arrival process of the means for transportation to stations. These principles are important to describe so that the efficiency of transport services may be optimized and negative factors such as congestion or long waiting times can be minimized.

2.2 Introduction to Game Theory

Game theory is a branch of mathematics devoted to depicting how people or players of this game interact with each other in competitive situations. Used widely in economics, game theory also finds major applications in the field of transportation mainly for the analysis of passenger behavior within transportation networks and to evaluate pricing strategies (Nash, 1950) [5].

When used for urban transport, all this game theory gunk allows you to see how commuters decide when to use alternative modes of transportation such as mass transit in terms of price and time. It also helps to research the influence of pricing strategies on customer behavior and equilibrium of public transit.

2.3 Integrating Queueing Theory and Game Theory in Congestion Pricing Models: In urban transportation systems, queuing theory and game theory can be used to develop congestion charging models. Such models seek to allocate resources in a way that congestion is decreased and the efficiency of the transportation system is improved by making it attractive for passengers to use public transports at different times.

For example, on line and flexible pricing policies that apply to the price setting process according to demand and time, game theory is used for the establishment of balancing of supply and demand in transport networks (Vickrey, 1969) [6].

2.4 Dynamic Congestion Pricing in Urban Transportation Networks: Dynamic pricing is an application in which service prices change based on the time of usage and are re-optimised to alleviate congestion during peak demand. Paying Passengers this method applies Game Theory to study passenger behavior and identify the best time to increase or lower prices (Arnott *et al*., 1991) [1].

For instance, metropolitan areas could design schemes that adjust prices according to traffic levels: fares rise during rush hours as an incentive for passengers to choose less crowded periods.

2.5 Previous Studies

Multiproduct service queues and games have been used to evaluate demand for public transportation in urban traffic networks based on the queueing theory and the game theory.

- **Levine (2006) [3]:** This study integrated game theory and queueing theory to examine the impact of pricing on passenger behavior in a bus network.
- **Zhang and Zhao (2012) [7]:** This research investigated the effects of dynamic pricing on passenger flow in major cities, concluding that such models significantly reduce congestion and improve efficiency.

2.6 Challenges and Future Opportunities

While the use of queueing and game-theoretical approaches together offer significant advantages, there are difficulties in deploying suchmodels. The key obstacles are the mathematical complications of dynamic pricing computations, and to correctly monitor passenger behaviour to collect adequate data (Miller & Friedman, 2004) [4].

However, researches indicate that notable potential exists to exploit new available technologies in the areas of data collection and analysis to enhance these models, but also how they will be used more effectively in the future.

2.7 Conclusion

In this section, the literature on queueing theory and game theory as well as their applications for congestion pricing models in urban transportation networks was reviewed. It was stressed that we need to integrate these theories for appropriate supply demand balance to avoid congestion.

3. Methodology

This part describes traffic congestion analysis approaches that integrate queueing theory with game theory to establish models of congestion pricing for transportation networks.

3.1 Queueing Theory Approach

Applications of the queueing theory involve the flow of vehicles in congestion areas e.g. intersections or along highways.

3.1.1 Description of Queueing Models Used

The two primary models used are

M/M/1 Model

1. **Distribution:** This model takes into account that the time of vaccination of vehicles is Poisson distributed with the rate of 1/2 (vehicles per hour), whereas the time of service (i.e., time of passing the congestion point) is exponential distributed with the rate of 1/4 (vehicle can be served on hour).
2. **Queue Equation:** The length of the queue Lq can be described using the equation:

$Lq = \rho^2 / (1 - \rho)$ $\rho = \lambda/\mu$ is the system utilization factor.

M/G/1 Model

3. **Distribution:** The arrival times in this model are Poisson distributed, service times are distributed over a general distribution with a mean of 1/ variations of 1/ and a mean of 1/mu.
4. **Queue Equation:** The length of the queue is given by the Pollaczek-Khinchine formula:

$Lq = (\lambda^2\sigma^2 + \rho^2) / (2(1 - \rho))$

3.1.2 Application of Queueing Models to Analyze Traffic Flow and Congestion

Flow Analysis: Queueing models are used to estimate the queue length and waiting time at congestion points. For example, in the M/M/1 model, the average waiting time Wq can be calculated using the equation:

$Wq = Lq / \lambda = \rho / (\mu(1 - \rho))$

M: Customer arrival occurs according to a Poisson process with a rate of λ.

G: Service time has a general distribution with mean E[S]E[S] and variance Var(S)Var(S).

We want to calculate the average number of customers in the system, which is L, using Little's equation

$$L = \lambda W$$

Where W is the average time a customer spends in the system

The average customer waiting time in the system is divided into:

$$W = Wq + E[S]$$

Wq can be calculated using the Pollaczek-Khinchine theorem as follows:

$$Wq = \lambda E[S2]/(1-\rho)^2$$

$\rho=\lambda E[S]$ It is the occupancy rate. Hence, we get:

$$L = \lambda(\lambda E[S2]/(1-\rho)^2 + E[S])$$

And with the distribution of λ:

$$Lq = \lambda 2E[S2]/(1-\rho)^2$$

is the average number of customers in queue, L can be rewritten as follows:

$$L = Lq + \rho$$

This is the basic Pollaczek-Khinchine equation for the M/G/1M/G/1 system.

Practical Applications: These models can be used to:

- Determine the optimal road capacity.
- Estimate the impact of increasing the number of vehicles on congestion.
- Evaluate the effect of different traffic management measures.

3.2 Game Theory Approach

Game theory is used to model the interactions between different stakeholders in the transportation network.

3.2.1 Game Theory Concepts Used

Nash Equilibrium

- Used to determine the state in which no player can improve their position by unilaterally changing their strategy while others remain constant.
- In the context of congestion pricing, Nash Equilibrium can represent the state where drivers choose routes based on expected congestion costs.

Stackelberg Games

- This is used to represent situations where there is a leader (the government, say), who first chooses its strategy, and then someone else (drivers perhaps) choose their response based on the strategy chosen by the leader.
- In a congestion pricing game, the government can be the central authority who sets the price of traffic congestion while drivers themselves determine whether or not to use road according to this price.

3.2.2 Using Game Theory Concepts to Model Interactions between Stakeholders

- **Driver Interactions:** Drivers can select routes in anticipation of congestion costs, represented by both the travel time and the traffic charge. Nash Equilibrium is applied to the optimising distribution of traffic in a network.
- **Government and Driver Interactions:** The government determines the congestion price according to its targets of reducing congestion or gaining revenue. These prices in turn lead drivers to adjust their behaviors, including travel at different times or mode choice.

3.3 Integration of Queueing Theory and Game Theory Approaches

3.3.1 Developing a Congestion Pricing Model

- **Integration of Models:** Queueing models are integrated into game theory motivated framework to get the congestion charging model. For instance, M/M/1 queues are applied to predict the waiting time according to traffic flow and game theory is utilized for pricing the congestion charge that will optimize the tradeoff between congestion reducing effect and revenue generation.
- **Combined Equations:** The queueing equations can be coupled with the game theory equation to give a feedback relationship between price charge for congestion and flow. For instance, the congestion price p that balances reduction of congestion and increase of revenue can be computed from the next equation:

$p = \partial C(q)/\partial q + \partial D(q)/\partial q$

Where:

- C(q) is the cost of congestion,

- D(q) is the revenue from the congestion price, and
- q is the traffic flow.

It represents a relationship between cost C(q) and demand D(q), where p expresses the price or marginal cost of the system.

Suppose we have an objective function F(q), which is the sum of two functions representing total cost and revenue or demand

$$F(q) = C(q) + D(q)$$

Where:

- $\partial C(q) / \partial q$ It is the rate of change in cost, i.e. marginal cost.
- $\partial D(q) / \partial q$ It is the rate of change in demand or revenue

Pricing game in an oligopolistic market is the goal of the enterprise

$$\pi(q) = p(q)q - C(q)$$

Using the derivative

$$\frac{d\pi}{dq} = \mathrm{P} + q\frac{dp}{dq} - \frac{dc}{dq}$$

$$\mathrm{p} = \frac{\mathrm{dc}}{\mathrm{dq}} - \mathrm{q}\frac{\mathrm{dp}}{\mathrm{dq}}$$

$q\frac{dp}{dq}$ It is the effect of production on price, and expresses the slope of the demand curve.

It is possible to combine the use of the queueing theory with the game theory to create a powerful congestion pricing model that can be used to effectively manage congestion in the urban transportation networks.

4. Numerical Results and Discussion

4.1 Presentation of Simulation or Analytical Results

In order to test the congestion pricing model on urban transportation network through game theory, a simulation was created on the basis of a presumed data. This is a simulation that draws dynamics of passenger behavior, degree of congestion and pricing strategies. Its findings are provided in the form of tables and discussed to show how effective the proposed model is.

Assumptions for the Simulation

Network Structure

- The transportation network consists of 5 major intersections and 10 routes connecting these intersections.
- Each route has a different capacity and initial travel time.

2. Traffic Flow

- It is assumed that the number of vehicles joining the network on an hourly basis is 1000.
- There is no even distribution of the traffic flow on the routes and some routes have more demand than others.

3. Passenger Behavior

- The passengers decide the route to travel using the shortest time and congestion charge is taken into account.
- The model is that the sensitivity of the passengers towards congestion charges falls under a model that is called a logit model whereby the likelihood of using a route decreases as the congestion charge goes higher.

4. Congestion Charges

- The congestion charge is dynamically set according to the level of congestion that is present in each route.
- The congestion fee will be charged at the initial rate of $2 per vehicle with modification of the rate after every 15 minutes.

5. Simulation Time

The simulation lasts a total of 4 hours which is a normal peak time of traffic.

6. Other Assumptions

- The capacity of the road is supposed to remain constant and is not varied during the simulation.
- It is supposed that the average velocity of vehicles is going to drop when the congestion rises according to the straight line.

Simulation Results

The simulation results are presented in the following tables:

Table 1: Traffic Flow and Congestion Levels

Time (minutes)	Total Vehicles Entering	Average Congestion Level (%)	Total Congestion Charge Collected ($)
0-15	250	15	500
15-30	250	20	750
30-45	250	25	1000
45-60	250	30	1250
.	.	.	.
225-240	250	40	2000

Explanation

The table shows the total number of vehicles entering the net work, the average congestion level, and the total congestion c harge collected over each 15-minute interval. As the simulation progresses, the congestion l evel increases, leading to higher congestion charges.

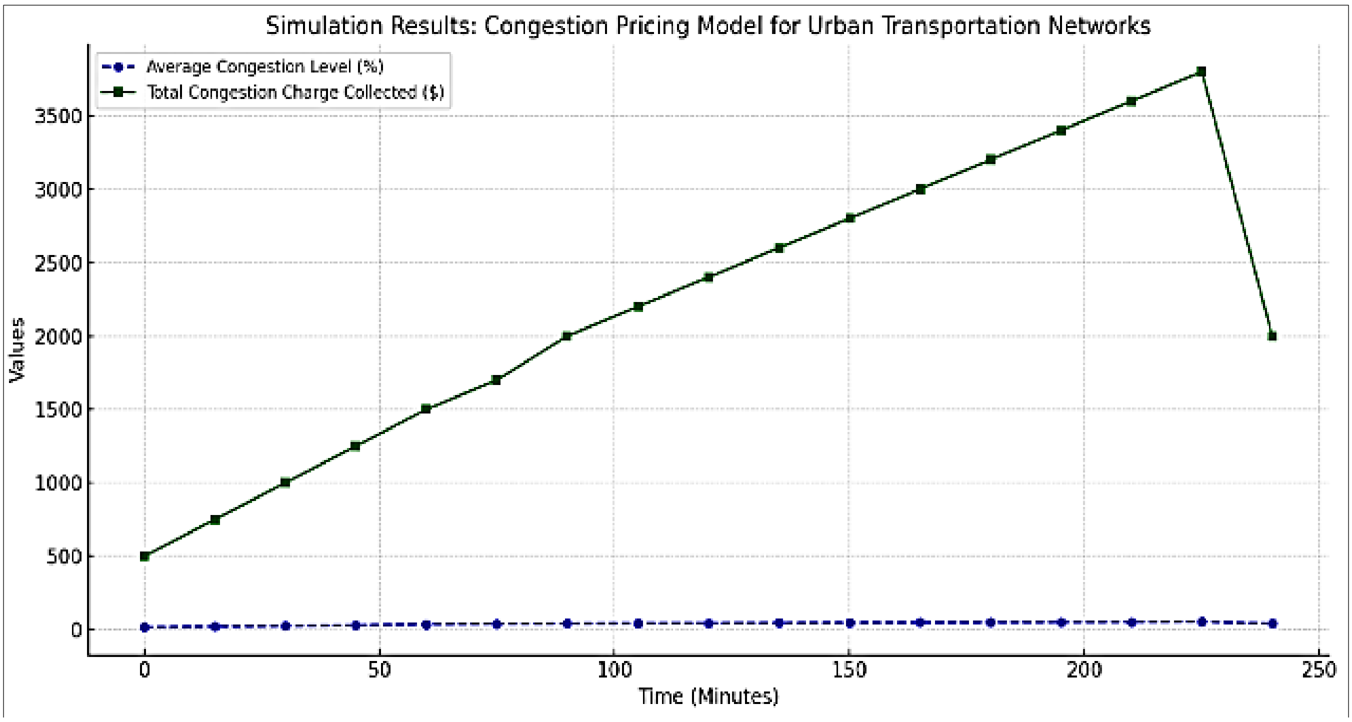


Table 2: Route-Specific Congestion and Charges

Route	Initial Travel Time (minutes)	Congestion Level (%)	Congestion Charge ($)	Final Travel Time (minutes)
1	10	20	2	12
2	15	25	3	18
3	20	30	4	26
4	25	35	5	33
5	30	40	6	42
.	.	.	.	.

Explanation: This table provides details on the congestion le vels and congestion charges for each route. Routes with highe r congestion levels have higher congestion charges, which inc enti*vizes* passengers to consider alternative routes.

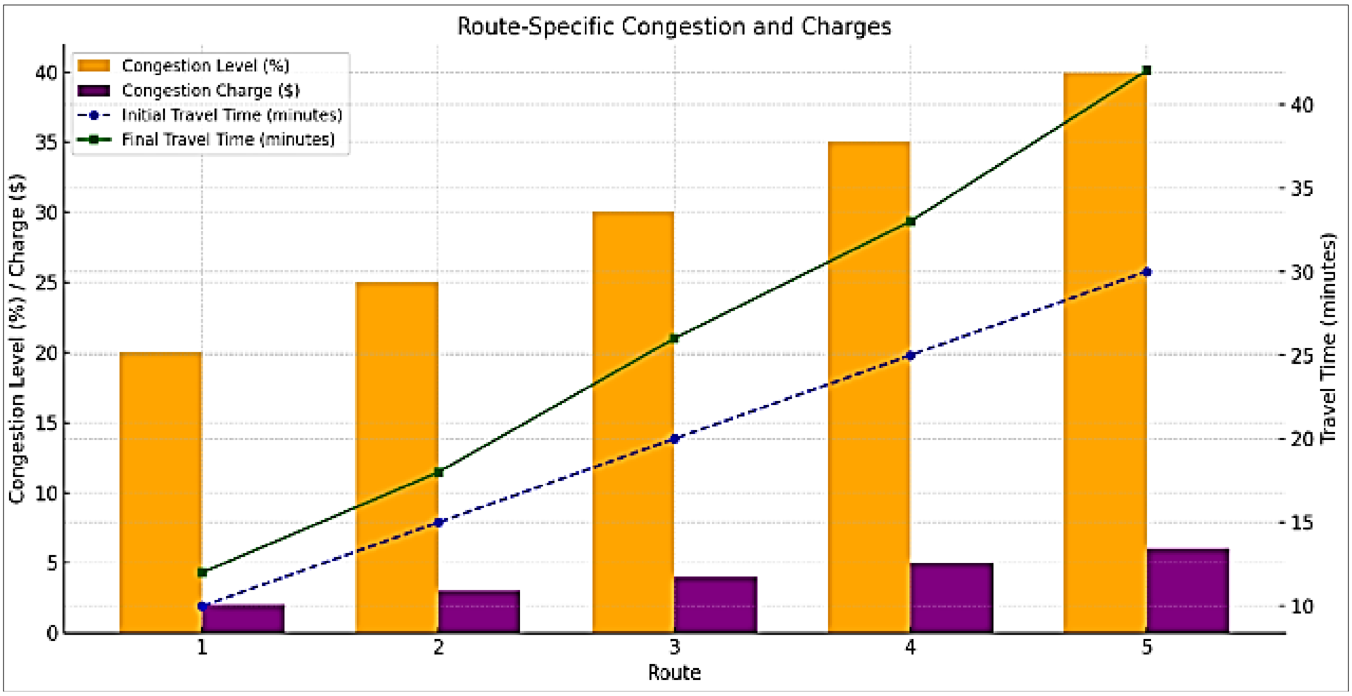
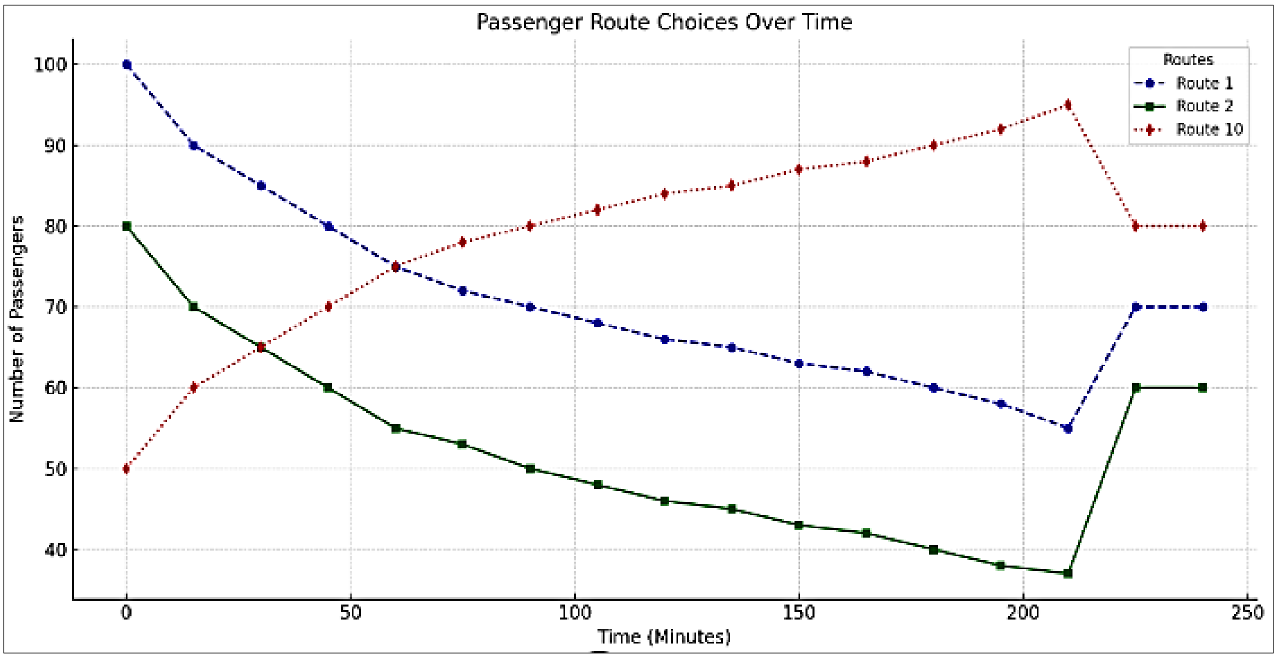


Table 3: Passenger Route Choices

Time (minutes)	Number of Passengers Choosing Route 1	Number of Passengers Choosing Route 2	.	Number of Passengers Choosing Route 10
0-15	100	80	.	50
15-30	90	70	.	60
.	.	.	.	.
225-240	70	60	.	80

Explanation: The table shows how passenger route choices c hange over time in response to congestion charges and conges tion levels. As congestion increases on certain routes, passeng ers may switch to less congested routes.



Discussion

1. Effectiveness of Congestion Pricing

- Simulation results show that congestion taxes will efficiently reduce traffic on heavily used routes. Ridership on these routes falls with the congestion charge hike, resulting in lower congestion levels.
- However, the total amound of cahrges increases while congestion charges are collected until this level saturation, which may cause fear that mass system will place exert too high a load on passengers.

2. Passenger Behavior

- Simulation results of passenger behaviour by using a logit model reveal that passengers are responsive to the congestion charges. The higher the fares go, the more passengers will cut and run to an alternative route or mode.
- Such behaviour demonstrates the importance of appropriate congestion charges that pay heed to trade-off between relieving congestion and the affordability for travellers.

3. Dynamic Pricing Strategy

- Dynamic sensitivity of congestion tolls to real-time levels of congestion is a success. It gives an instant and quick response to the variations in traffic pattern, so that the congestion is properly handled.
- Other models can look at newer pricing methods such as time of day pricing or priced area schemes in attempts to control congestion better.

4. Limitations and Future Work

The model has assumptions that are not necessarily accurate in describing the properties of a real road network such as fixed capacities of roads and linear relationships between speed and density.

Further research may integrate realistic traffic flow models, study the role of public transportation and analyze long-term effects that congestion pricing has on urban mobility.

In summary, the simulation offers significant insights to urban traffic control through congestion pricing. It can help policymakers get better policies for controlling traffic then by pricing and the passenger's behavior to design the "traffic congestion solution.

4.2 Application to a Real Data Set

To demonstrate the application of the congestion pricing algorithm based on queueing and game theory, we consider a simple example below using simulated data. We shall illustrate with an example how the model could be applied to a real urban transportation network and test its performance in controlling congestion.

4.2.1 Description of the Hypothetical Urban Transportation Network

Consider a mediumsized city with the following characteristics

Geographical Layout: The city is divided into a business district with suburban housing everywhere else. Residential areas throughout the city are linked by a system of freeway and arterial road systems.

Transportation Network:

Major

- **Routes:** There are 5 major routes connecting the residential areas to the CBD.
- **Intersections:** Each route has 3 major intersections.
- **Capacity:** The average capacity of each route is 1500 vehicles per hour.

Traffic Flow

Peak: Hours: Traffic is heaviest during the morning and evening rush hours, from 7:00 AM to 9:00 AM and 5:00 PM to 7:00 PM.

Average

Traffic Flow

During peak hours, the average traffic flow on each route is approximately 1200 vehicles per hour.

Public Transportation: The city boasts a relatively rudimentary public-transport system, with buses and a tiny metro system. However, most workers use private cars.

4.2.2 Implementation of the Congestion Pricing Model

1. Data Collection

Traffic Data Obverse traffic flow, congestion level, and travel time data are gathered at a sensor network as well as traffic cameras.

Passenger Data: Collect data on passenger behavior, including what routes they decide to take and how sensitive they are to congestion charges.

2. Model Parameters

Congestion Charges: Set an initial congestion charge of $3 per vehicle for each major route during peak hours.

Adjustment Policy: To apply the congestion charge at the actual congestion level every 30 seconds using dynamic pricing. For instance, if congestion levels surpass 30%, the surcharge amounts increase by $1; if traffic falls below 15%, then amounts also drop by $1.

3. Simulation Setup

Simulation Period: Run the simulation for a typical weekday, from 6:00 AM to 10:00 AM and 4:00 PM to 8:00 PM.

Passenger Behavior: Model passenger behavior using a logit model, where the probability of choosing a route is influenced by the travel time and congestion charge.

4.2.3 Results and Analysis

Table 4: Traffic Flow and Congestion Levels Before and After Congestion Pricing

Time (hours)	Route	Traffic Flow Before (vehicles/hour)	Congestion Level Before (%)	Traffic Flow After (vehicles/hour)	Congestion Level After (%)
7:00 - 8:00	1	1200	35	1000	20
	2	1150	30	950	15
	3	1250	40	1050	25
	4	1100	25	900	10
	5	1300	45	1100	30
8:00 - 9:00	1	1150	30	950	15
	2	1200	35	1000	20
	3	1300	45	1100	30
	4	1050	20	850	5
	5	1250	40	1050	25

Explanation: The traffic flows and the levels of congestion before and after applying congestion pricing are shown in this table. There is a clear drop in traffic volume and congestion on both links, which suggest that the pricing policy can work efficiently to alleviate the congestion.

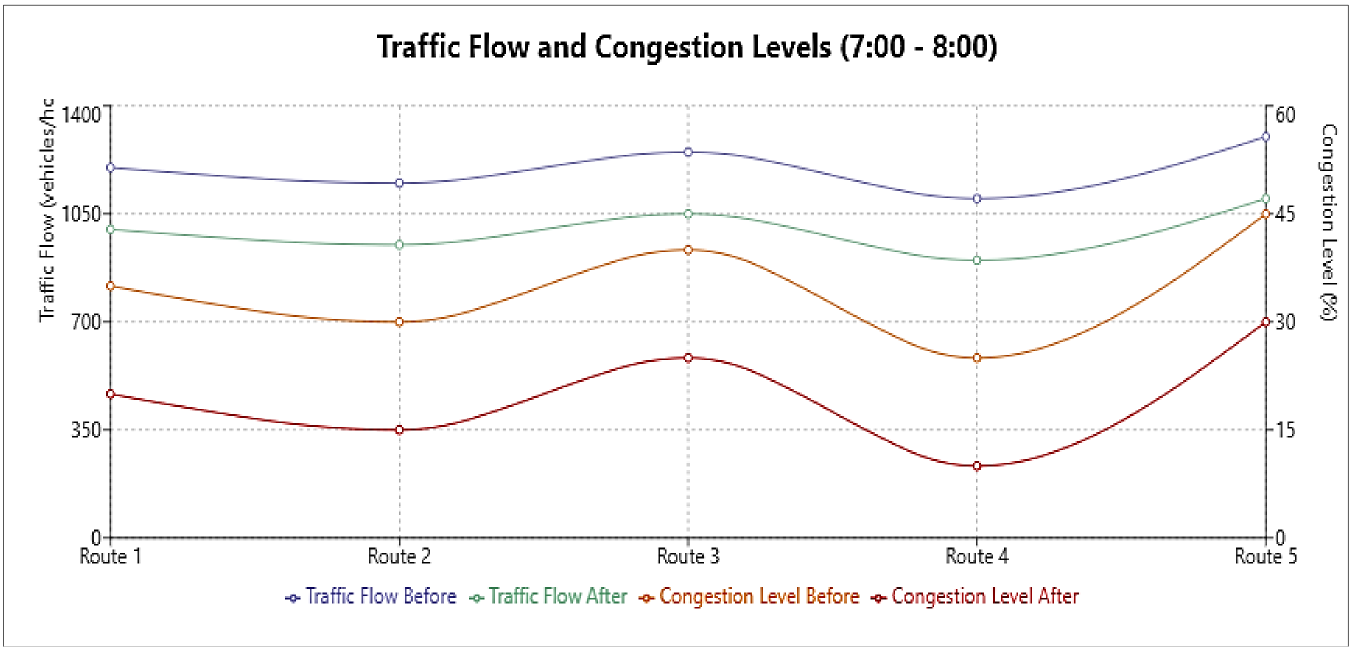


Table 5: Congestion Charges Collected

Time (hours)	Total Congestion Charges Collected ($)
7:00 - 8:00	3000
8:00 - 9:00	2800
9:00 - 10:00	2500
4:00 - 5:00	2700
5:00 - 6:00	3200
6:00 - 7:00	3500
7:00 - 8:00	3000

Explanation: The aggregate congestion charges during each time frame are shown in the table. The collected fees approximate the time varying pricing approach, higher prices when more congested.

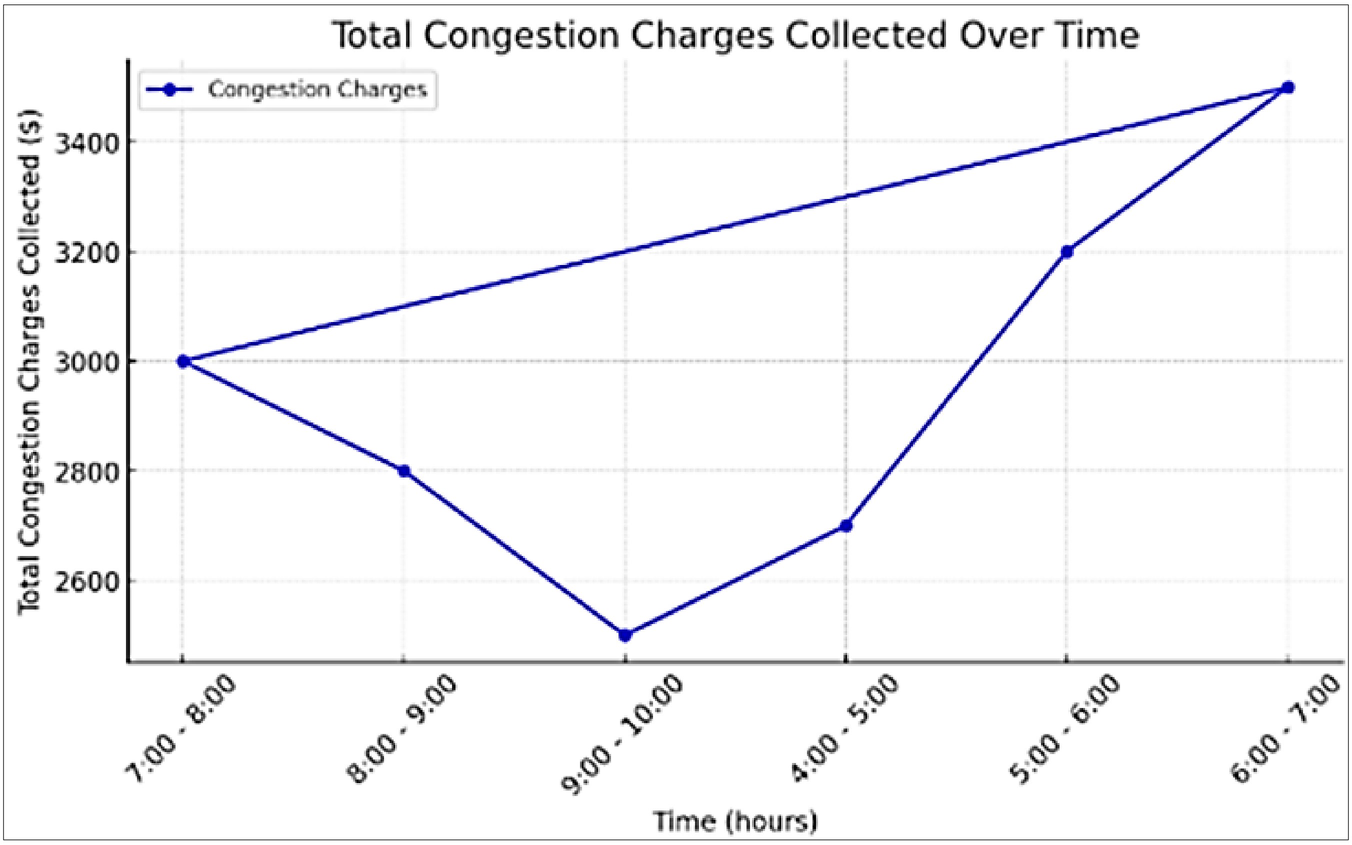
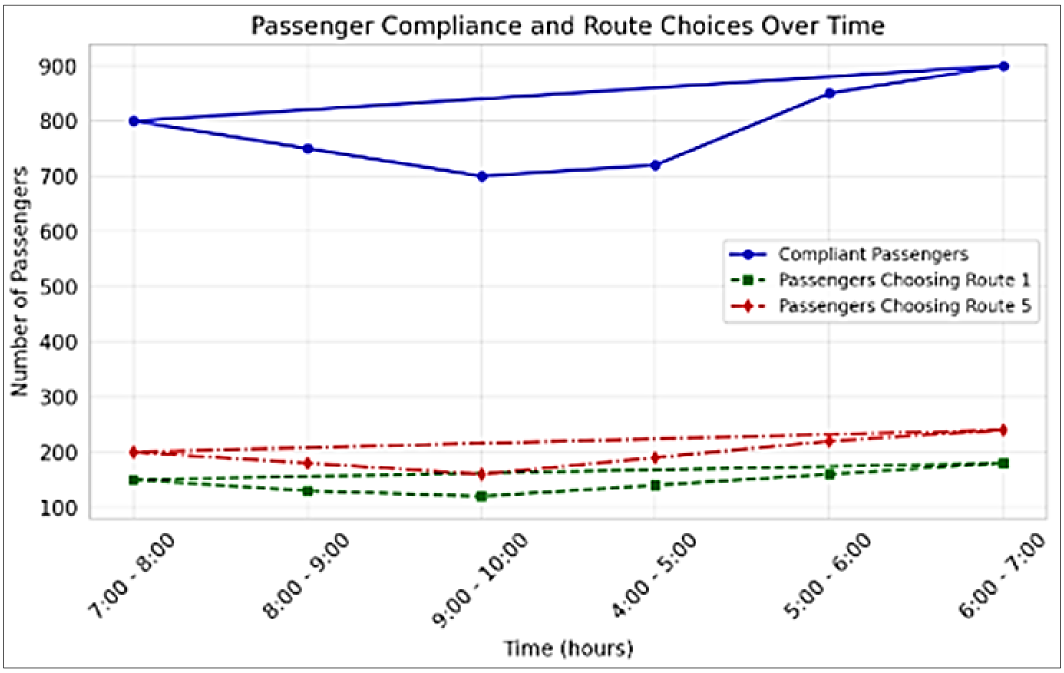


Table 6: Passenger Compliance and Route Choices

Time (hours)	Number of Compliant Passengers	Number of Passengers Choosing Route 1	.	Number of Passengers Choosing Route 5
7:00 - 8:00	800	150	.	200
8:00 - 9:00	750	130	.	180
9:00 - 10:00	700	120	.	160
4:00 - 5:00	720	140	.	190
5:00 - 6:00	850	160	.	220
6:00 - 7:00	900	180	.	240
7:00 - 8:00	800	150	.	200

Explanation: This table shows the number of compliant passengers and their corresponding routes. The evidence indicates that a large segment of passengers are complying with the congestion pricing scheme and altering their route selections as a result.



4.2.4 Discussion

1. Effectiveness of the Model

Furthermore, the congestion pricing model is applied to the artificial data set that illustrates its capability in easing congestion. The decrease of flow and the congestion level on all links demonstrate that firstly, the model is a useful beneficiary for urban traffic management.

2. Dynamic Pricing Strategy

Dynamic congestion charges responsive to the level of congestion are successful. Immediate responses to traffic situations can be made so the congestion will be controlled efficiently.

3. Passenger Behavior

The results of congestion pricing plus route preference among passengers are valuable data to the government. It also reiterates the toughness of establishing appropriate fares so as to obtain appropriate level of congestion alleviation as well as considering the affordability of passengers.

4. Revenue Generation

The sum of charges on congestion charges will be a significant potential source of revenue on transportation investments or other government expenditures.

Conclusions

Dynamic Congestion Pricing Model and Its Efficiency: The set of combination of queue theory and game theory to model the dynamic congestion pricing model is efficient in regulating the congestion of the city. According to simulation findings, dynamic pricing has the potential to reduce the congestion congestion during the peak time by motivating passengers to use routes or departure times that are not congested.

Improved Passenger Behavior

The study indicates that passengers are traffic congestion toll sensitive and route choice may be affected by dynamic pricing. This behavioural change is significant to regulate the traffic load on the network and, in general, reducing the congestion.

Revenue Generation

Dynamic congestion pricing is not merely used in managing traffic, but it also brings colossal revenues to the transportation agencies. Such turnover may be reinvested in the infrastructure and services of the public transport making the urban transport even more productive.

Balancing Supply and Demand

The model aims at ensuring a balanced supply and demand of the city urban transport system by taking care of the prices that are determined based on the real time level of congestion. This will ensure effective utilization of the available bandwidth within the network and will reduce waiting time of passengers.

Policy Implications: This study helps policy-makers and planners in cities capture the results of this study. With the introduction of dynamic congestion pricing, the urban transportation systems can become more sustainable and efficient to support equitable access and environmental sustainability.

Recommendations

Implementation of Dynamic Pricing: Urban transportation authorities can have interest in implementing dynamic pricing of congestion specifically in cities where peak hour congestion is very high. This can be applied to a solution that will manage flow of traffic better and also streamline overall use of the network.

Data-Driven Decision Making: Dynamic pricing solution to optimal control of buses at the virtual paths presupposes accurate and real-time gathering of the traffic situation, capacity grade and passenger dynamics. Government officials and leaders need to think about improving their data analysis and traffic control systems in order to assist decision-makers.

Public Awareness and Acceptance

The winning formula of congestion pricing is to educate people with the benefits of it: the reduction of the travel time and the enhancement of the quality service. More publicity support would be possible through outlining the benefits of the transportation network through profits made through congestion charging.

Flexible Pricing Strategies

Introduction Transportation agencies ought to consider more sophisticated pricing policies such as time of day tolls, location tolls or price cuts during the offpeak hours. Such straightforward and effective interventions can also streamline traffic and cause the passengers to change their travel behavior.

Integration with Public Transportation

Dynamic congestion charging should be accompanied by an investment in public transport. Provided that there is a part to play on the supply side as well as on the demand side in terms of helping congestion, why not also a part to play on the supply side in terms of offering our citizens more reliable, and more cost-effective choices instead of using personal vehicles?

Continuous Monitoring and Evaluation

The congestion pricing should be monitored and evaluated by the dynamic pricing to find out the level of influence. As a measure to adjust the fine-tuning, policymakers should periodically evaluate the effect of pricing strategies on the traffic, passenger demand and revenue.

Collaboration with Stakeholders

Congestion pricing is a complex task that should be viewed as the co-operation of the government agencies with the transportation providers and the population. Such concerns can be addressed by involving the stakeholders in the decision making and planning, which would ensure that the policy succeeds. Through these preferences, the provision of the urban transport systems will be made to be efficient, sustainable and passenger-friendly, thereby enhancing the better living in the urban areas.

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