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QUEUEING THEORY APPLICATIONS IN IOT NETWORKS: MANAGING HEAVY TRAFFIC IN SMART CITIES

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Abstract

Traffic congestion is a pervasive problem affecting millions worldwide, exacerbated by increasing populations and vehicle numbers across both developed and developing countries. Traditional traffic management systems have proven inadequate in alleviating this issue efficiently. This paper proposes a novel approach integrating an open Jackson Queueing network model with quadratic optimization for dynamic traffic management. The model aims to simulate traffic systems, make data-driven decisions on signal timings based on real-time data inputs, and optimize customer waiting times at junctions. By leveraging these advanced techniques, the proposed autonomous traffic management system seeks to address the challenges posed by growing urban traffic volumes effectively.

Keywords: *traffic congestion, traffic management, Jackson Queueing network, quadratic optimization, autonomous systems*

1. INTRODUCTION

A city is an intricate system, and one of its important linked subsystems is the transportation system. According to research, it is the bedrock of global trade. Besides, it is recognized as one of the critical parts of the savvy city. The quantity of vehicles out and about is ascending couple with the total populace development, and accordingly, traffic bottlenecks are going on more every now and again. Besides the fact that traffic bottlenecks can sit around, yet in certain conditions, it's additionally been seen that unlawful behaves like PDA grabbing at traffic signals happen in enormous urban areas. Nonetheless, it isn't just adversely influencing the ecosystem; it is additionally unfavorably affecting industry effectiveness.

Hence, it is resolved that dynamic traffic control is required. While huge urban areas in numerous wealthy nations utilize midway controlled systems to oversee traffic, most different nations utilize fixed time signals. Traffic management systems have utilized the Internet of Things (IoT) idea.

Apparently, the traffic management systems set up today are as yet incorporated. These sorts of systems can crash in case of a systems administration issue. Less consideration is likewise paid to varieties in traffic stream. Thus, the proposed arrangement involves the thoughts of IoT and man-made consciousness pair to oversee traffic on both neighborhood and incorporated servers. Specialists could likewise profit from the factual portrayal of traffic information with regards to ongoing traffic control and management. Also, it very well may valuable for prepare.

The rise of smart cities relies heavily on the efficient functioning of Internet of Things (IoT) networks, which connect various devices and systems to streamline urban operations and enhance the quality of life for residents. However, the exponential growth of connected devices generates significant data traffic, leading to congestion and delays. Queueing theory provides a robust framework for analyzing and optimizing data transmission in these networks under heavy traffic conditions.

IoT networks in smart cities encompass a wide range of applications, including smart transportation, energy management, environmental monitoring, public safety, and healthcare. These applications generate massive amounts of data that must be transmitted, processed, and acted upon in real-time to maintain system efficiency and reliability.[3]

1.1.Queueing Theory

Queueing theory involves the study of waiting lines or queues, providing tools to model and analyze systems where resources are shared among competing tasks. [4] Key components include:

- Arrival Rate (λ): the speed at which information packets enter the system.

- Service Rate (μ): The rate at which information packets are read, translated, and transmitted.
- Queue Discipline: The order in which data packets are processed (e.g., FIFO, priority-based).

Applying Queueing Theory to IoT Networks

1. Modeling Traffic Flows:
    - Single Queue Models: Used for individual IoT devices or gateways where data packets arrive and are processed in a single queue.
    - Network of Queues: Models the interconnected nature of IoT networks where data packets may traverse multiple nodes, each with its own queue.
2. Performance Metrics:
    - Queue Length: The average quantity of packets waiting in line.
    - Waiting Time: Average amount of time a packet is held in the queue.
    - System Utilization: the percentage of time that packet processing takes on the system.
3. Traffic Management Strategies:
    - Load Balancing: Distributing data packets evenly across multiple processing nodes to prevent any single node from becoming a bottleneck.
    - Priority Queuing: giving vital data packets—like emergency signals—a higher priority in order to guarantee prompt processing.
    - Dynamic Resource Allocation: Adjusting the allocation of processing and communication resources based on real-time traffic conditions.

Through our investigation, we successfully addressed a complex traffic congestion scenario by proposing a model that conventional static traffic management systems, relying on visual guesses, cannot effectively resolve. Traditional traffic management systems do not rely on systematic data, predictions, or numerical estimations. Consequently, these systems lack autonomy, managing traffic signals with minimal reliable information or assessments.[5]

This research [1] examines the offloading issue in a HetNet utilizing D2D communication, taking into account the network's traffic load. The goal of traffic offloading in this study is to maximize network throughput overall while preserving the stability of system queues. It is demonstrated that the throughput maximization problem is non-convex. As a result, we suggest a heuristic offloading approach that is demonstrated to provide performance that is similar to that of an exhaustive search method. Based on numerical results, the suggested offloading technique performs better than comparable algorithms found in the literature that do not account for the traffic load of the users.

It [2] is important to give a conventional presentation examination strategy to assess QoS in IoT applications. By coordinating a few sorts of queueing models to make queueing networks, queueing network models give a clear displaying climate that can be utilized to portray cooperations between IoT gadgets. Insightful or reenactment models can be used to investigate execution utilizing the produced networks. In this exploration, we propose different kinds of queueing models that depict different QoS situations of IoT associations, including asset compelled gadgets, message drop likelihood, accessibility/legitimacy, and discontinuous portable availability. We duplicate our models with MobileJINQS and show how changing QoS boundaries significantly affects reaction times and message achievement rates.

The [3] (IoT) is a mechanical headway that expands the extent of the Web to remember both living and non-living items for the actual world. A stage that interfaces individuals and PCs is the Web. Things are genuine items viewed as in reality, including, yet not restricted to, vehicles, schools, pets, pulse screens, and different home machines. Researchers have been dealing with making devices, organizations, and conventions that could be utilized to track, screen, and control genuine occasions and items throughout recent many years. For these reasons, sensors, actuators, and Radio Recurrence Distinguishing proof Gadgets (RFID) are the gadgets that are utilized; in this proposal, they are alluded to as Web of Things gadgets. Instances of organizations developed with the guide of these gadgets incorporate machine-to-machine (M2M) organizations, remote sensor and actuator organizations (WSAN), and different organizations. In addition to other things, SCADA, RFID global positioning frameworks, and machine-to-machine (M2M) correspondence. In this review, cooperative burden adjusting across mist hubs is proposed, and the heap is disseminated utilizing the heap adjusting approach.

2. SYSTEM MODEL

2.1.Road Traffic Model

It is best to gain the intuition from real-world examples when applying Jackson queueing networks and optimization theory to solve traffic problems.

Figure 1 shows that there are primarily four routes, with routes 1 and 4 connecting to Roads 2 and 3. Additionally, we can observe that Roads 2 and 3 are independently connected to a few other roads besides Roads 1 and 4, which may have exterior vehicle entry or connect to other roads other than Roads 1 and 4.

Each route within the provided figure below incorporates a activity framework with a particular operation and benefit period. Moreover, cars have the alternative to switch between the a few interfacing roadways. In this way, the number of cars on Road 1 can be separated among Road 2, Road 3, and any other road. All other roads in this network are subject to the same regulation. In other words, in circumstances such as these, one or more car lines must wait for a car that attempts to shift to a different road or destination. We want to limit the sitting tight time for a vehicle in the organization to upgrade these situations.

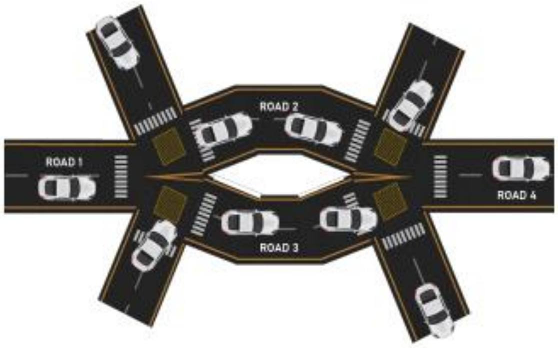

Figure 1: Four-way Traffic Display

2.2.Queueing Network Model

We can think of each route as a queue by applying the understanding shown in figure 2. A queueing network as a whole is formed by the connections between individual queues. In order to minimize the amount of time a client must spend in the network, our primary goal will be to decrease total waiting times within the system. As we recently examined, in the event that queues in an organization are associated with each other, changing to another line might cause holding up times in different queues. The queue line gets longer as a result. Less waiting time can therefore be achieved by decreasing the network's mean customer. In order to determine what has to be done to shorten wait times, we endeavor to streamline for every single line in the Jackson queueing network.

Figure 2 shows how to convert a very basic network of roads into a queueing network, which is a representation of our earlier example. Here, the length of each line (Q1, Q2, Q3, and Q4), the rate of customer arrivals, and the rate of service time are all unique. The arrival rate of Q2, Q3, and Q4 in this queueing organize is managed by the probability of moving to Q4 from both Q2 and Q4, and the arrival rate of Q4 is decided by the entirety of the probabilities of traveling to Q4 from Q1 and the external arrival rate.

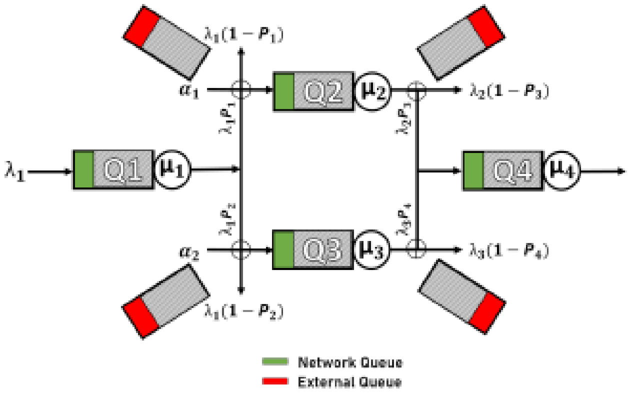

Figure 2: Traffic Model Queue

2.3.Formulation of the Problem

We must familiarize ourselves with the concepts that are used to represent clients in order to control the length of the wait and maximize their service time. In a nutshell, the service rate of each client is represented by μ, which is equal to 1/[average service time], and the arrival rate of consumers in a line is represented by λ, which is equal to 1/[expected inter-arrival time]. The consumer might switch to another queue after receiving service time in one. With a probability of P, the customer can shift to one or more queues. Once more, the external arrival rate of clients in the line is represented by α. Here, we want to maximize the network W's mean waiting time.

Little's formula in the Jackson network is used to get

$$W = \frac{N}{\Lambda}$$

N is the average number of clients in the network in this case.

$$N = \sum_{i=1}^{M} \frac{p_i}{1 - p_i}$$

Here, ρ represents the server's utilization.

$$p_i = \frac{\lambda_i}{\mu_i}$$

With the formula, we can determine the λ.

$$\lambda_i = \propto_i + \sum_{i=1}^{K} \lambda_j P_{ji}$$

where 1 ≤ i ≤ K

Here, P_{ji} shows the likelihood of transferring a consumer from the i queue to the j queue.

By omitting the value of ρ from N yields

$$N = \sum_{i=1}^{M} \frac{\lambda_i}{\mu_i - \lambda_i}$$

Now, using Little's formula with the value of N, we obtain,

$$W = \frac{1}{\Lambda} \sum_{i=1}^{M} \frac{\lambda_i}{\mu_i - \lambda_i}$$

In our model,

W stands for the mean waiting time of the vehicles,

Λ for the rate at which vehicles enter from all external sources

λ for the rate at which vehicles enter a road.

μ = Transport rate switching to another route while the lane is open

A road's susceptibility to traffic congestion increases with the number of vehicles on it. In theory, less traffic congestion will arise from a reduction in W.

3. METHODOLOGY

3.1.System Workflow

Initially, we will optimize a customer's mean waiting time by calculating service time using simulated arrival data. Since real-time arrival data is not being used, the Jackson network will be implemented using an M/M/1 queue. Since genuine street traffic can't work on a shut network, our Jackson network will be open. Then, we'll sort out how much help time should be provided to augment the typical client stand by time in network W. To limit the mean number of shoppers in the network N, we will then, at that point, apply an advancement hypothesis as per our capability. Next, we'll forecast the value of W using the optimum value of N. In the end, we will compare the two results to determine whether they agree and draw a conclusion.

We suggest using the Jackson queueing network as the queueing model, with each queue having the characteristics of an M/M/1 queue. Here, we define the several queueing models required for our research using Kendall's notation. In 1953, Kendall used the A/S/c format to express his notation for the first time.

Here, A represents the arrival time or interval between arrivals in a queue, S represents the customers' service time distribution, and c represents the number of servers providing service to the queue's members.

Later, this notation was expanded to include A/S/c/K/N/D, where k stands for queue capacity or length, N for customers to be served at a node, and D for the queueing discipline or algorithm that serves the customers.

In case a queueing model, like M/M/1, is characterized utilizing as it were the primary three documentations, at that point extra symbols will stand in for $K = \infty$, $N = \infty$, and D as the queueing calculation FIFO. The foremost essential line show of them all is M/M/1. Vehicle entries in our activity framework happen autonomously of one another, and entry times are persistent instead of discrete. The M/M/1 demonstrate employments harm dispersion and treats entry time as persistent. In real life, our activity system's benefit time is arbitrary and doesn't follow to any set plan. This demonstrate is primarily utilized for recreating information to evaluate the result of the benefit rate since the M/M/1 line has an exponential dissemination for benefit time. Jackson systems, which are systems with a few lines, can be either open or closed, and exchanging beginning with one associated queue then onto the following requires a likelihood after being served from the primary queue. When clients have the plausibility to take off the arrange and outside entry rates, which come within the frame of Poisson conveyance, can enter the organize, it is said to be an open organize; something else, it is as it were considered a closed organize. The FIFO calculation is another benefit teach utilized by Jackson Arrange. Since each line in the system contains a unique benefit time, there may be varieties within the quality of benefit given. Our recommended show optimizes benefit time utilizing real-time entry information in arrange to abbreviate the hold up times for the transporters that have been in line.

3.2.Approximation of Optimization

We are going to apply optimization theory in order to reduce the average number of customers in the network wherever possible.

$$N = \sum_{i=1}^{M} \frac{\lambda_i}{\mu_i - \lambda_i}$$

$$= \sum_{i=1}^{M} \frac{\lambda_i(\mu_i + \lambda_i)}{(\mu_i - \lambda_i)(\mu_i + \lambda_i)}$$

$$= \sum_{i=1}^{M} \frac{\lambda_i \mu_i + \lambda^2}{\mu^2{}_i - \lambda^2{}_i}$$

$$= \sum_{i=1}^{M} \frac{\lambda_i \mu_i + \lambda^2{}_i + \lambda^2{}_i}{\mu^2{}_i}$$

$$= \sum_{i=1}^{M} \frac{2\lambda_i^2 + \lambda_i \mu_i}{\mu^2{}_i}$$

$$= \sum_{i=1}^{M} 2\lambda^2 \mu^{-2} + \lambda \mu^{-1}$$

Let's now go over the quadratic optimization standard form.

$$\text{minimize x}\frac{1}{2} x^T P x + q^T x$$

$$subject\ to\ Gx \preceq h$$

$$Ax = b$$

$Gx \preceq h$ represents the elementwise inequality over the vectors Gx and h, where x^T is the transpose of x. Convexity is present in the function above if P is positive-semidefinite.

4. RESULTS FROM SIMULATION AND EXPERIMENTATION

Table 1: Default Simulation Conditions

Simulation Conditions		Value
Arrival rate (λ)	λ1	0.56
	λ2	0.36
	λ3	0.33
	λ4	0.47
Service rate (μ)	μ1	0.91
	μ2	0.61
	μ3	0.61
	μ4	0.81
External arrival rate (α)	α1	0.14
	α2	0.16

Table 3 above illustrates four distinct arrival and service rates based on our system model. According to our model, λ2 and λ3 depend on λ1, while λ1 is independent. Furthermore, the external arrival rates, α1 and α2, respectively, similarly affect λ2 and λ3. Finally, our model also shows that λ4 is dependent on λ2 and λ3. The fees for services and external arrivals, however, are separate.

We have used a code-based simulation environment to put our equation for our problem scope into practice. To track changes in a co-related variable whereas holding the other related factors steady, we have relegated one of the factors a indicated range of values. The procedure has been iterated for numerous sets of variables in order to illustrate and examine the correlation. To compare the outcomes obtained from simulating our defined equation with those from quadratic programming optimization under our specified conditions and associated constraints, we also simulated the results using quadratic programming.

4.1.Response to Other Variable Change Waiting Time

Based on the experimental data, we will visualize and consider how waiting time relates to the other variables in our model in the part that follows. This will help us understand how waiting time changes and how those changes affect other associated variables.

4.2.Change in Service Rate and Waiting Time

Figure 3 shows the variations in Waiting Time (represented by Y-axis) for each queue as a function of variations in Service Rate (represented by X-axis) as distinct curve lines. Values λ1 and λ2 were taken into consideration and held constant at 0.56, 0.36, 0.33, and 0.47, respectively. Value λ4 was taken into consideration and held constant at 0.47.

Furthermore, it was determined that the exterior arrival rate for Queue 2 was 0.14, while the external arrival rate for Queue 3 was 0.16.

It is evident when we hold other factors constant, such as arrival rate and external arrival rate, that waiting times decrease as service rates increase within a certain range of values. This graph, which is based on our simulation, demonstrates that the average waiting time of the vehicles in each queue, for all queues, reduces as the pace at which vehicles are served and depart increases. The shorter the wait time for vehicles remaining on a road, the faster the vehicles are served on each road and depart.

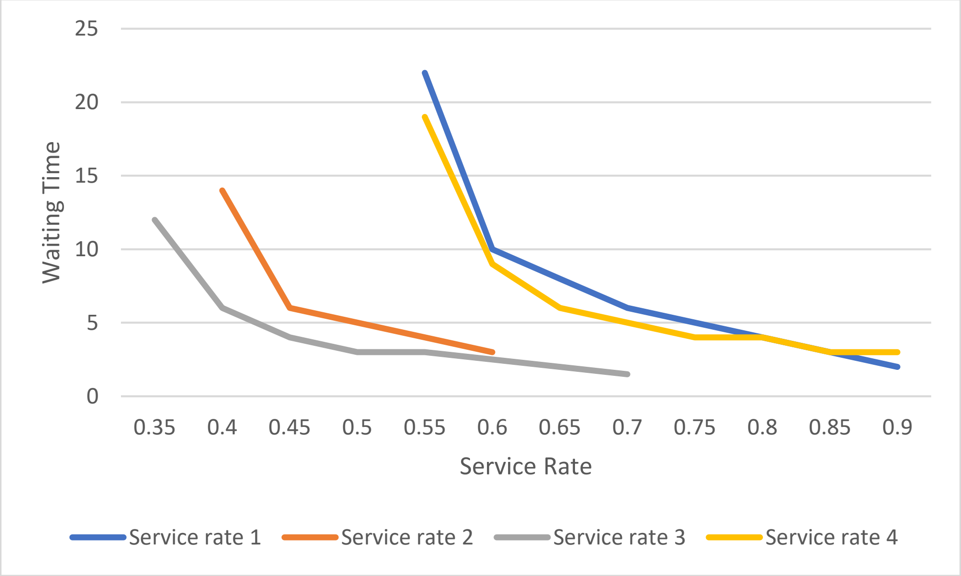

Figure 3: Waiting time vs Service Rate in each Queue

4.3.Arrival rate changes waiting time

Figure 4 shows the variations in Arrival Rate (represented in X-axis) and Waiting Time (shown in Y-axis) for each queue as distinct curve lines.

Values of µ1 and ε2 were taken into consideration and held constant at 0.91, 0.61, and 0.81, respectively. Values of ε3 and ε4 were also taken into consideration and held constant at 0.61 and 0.61.

Within a given range of values, it is obvious that increasing the arrival rate increases waiting time, while other elements, such as the service rate and external arrival rate, remain constant.

Our simulation yielded this graph, which shows that the average waiting time of the cars grows as the rate of joining the queue does. Higher waiting times for vehicles on each road will result from faster vehicles arriving on each one.

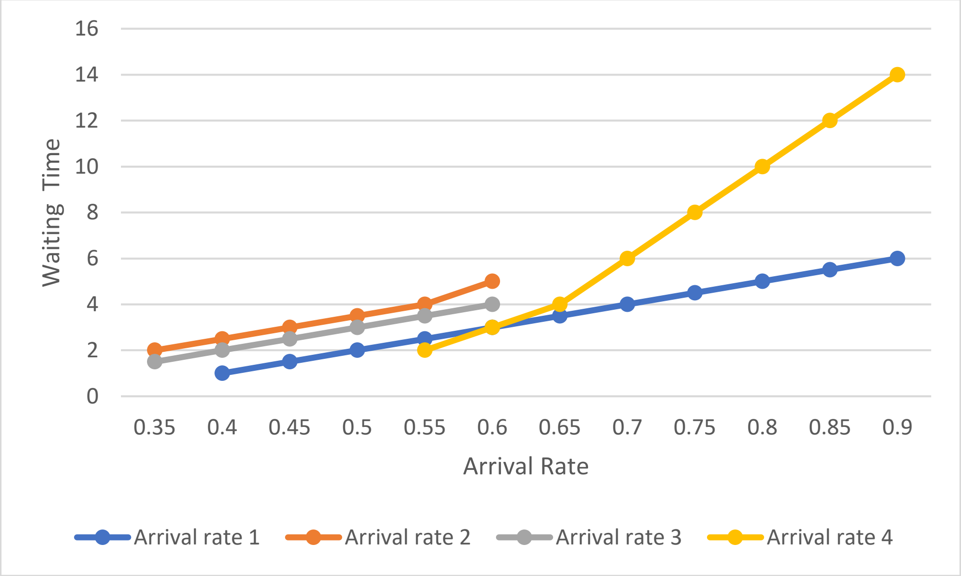

Figure 4: Graphical representation of Waiting time vs Arrival Rate

4.4.Waiting Time Changes with External Arrival Rate

Figure 5 shows how each queue's waiting time (represented by a different curve line) fluctuates in response to variations in the external arrival rate (represented by an X-axis).

The simulation-derived graph indicates that when the number of vehicles entering the second and third queues from outside the network increases, the average waiting season of the vehicles in each queue increases proportionately, with next to no exceptions for any queue. There will be longer wait times for cars on each course as more vehicles arrive in the road network from outside the network.

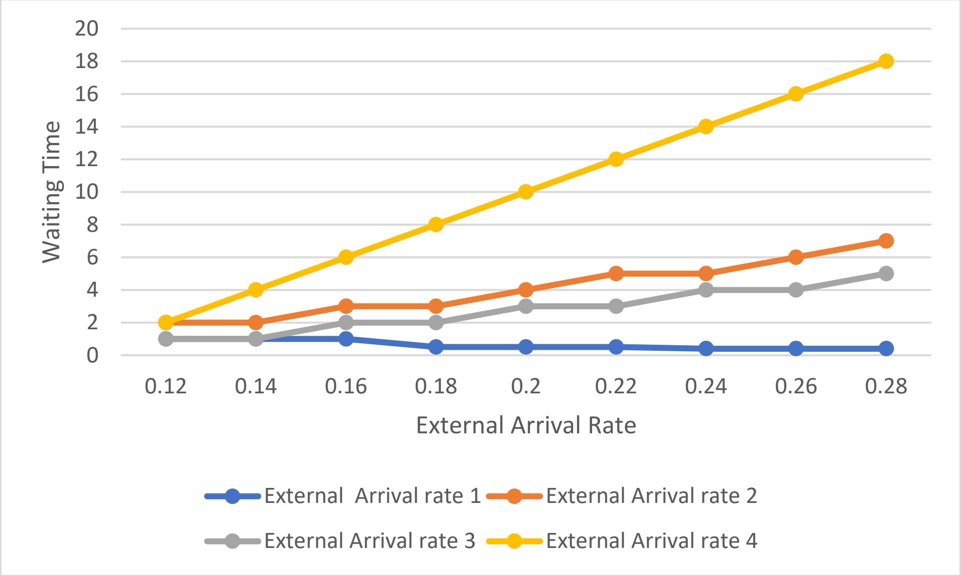

Figure 5: Graphical representation of Waiting time vs External Arrival Rate

4.5.Server Use in Response to Other Variables

Utilization of Servers serves as an pointer of the thickness of vehicles that are involving each line, which in turn shows the degree to which each server is involved and utilized. As a result of the queueing theory, we are ready to discover that a line is considered unstable when the value of the utilization of the server, signified by the image ρ, is essentially more than 1. In other words, it's clear that the line is going to be congested because the arrival rate is greater than the benefit rate for that particular queue. Following this, we will develop an understanding of the changes and impacts in server utilization in relation to changes in related factors by visualizing and reflecting upon the correlation of server utilization with various model parameters based on test results.

5. CONCLUSION

Traffic congestion has been a significant obstacle to the lives of millions, in the event that not billions, of individuals. The industrialized countries, on the other hand, are not excessively far away from being required to deal with this issue because it is also becoming more prevalent in these countries. Moving ahead is the only real option without confronting this challenge because the number of individuals living in the world as well as the number of vehicles on the road are both growing at an alarming rate. Taking effective action to address this issue is the only viable solution to this predicament that can be implemented. When it comes to finding a solution to this issue, the conventional hard-coded traffic control and signaling system has been shown to be both ineffectual and useless. Using an open Jackson Queuing network, our suggested model will establish a connection between a traffic system and a traffic network. The decisions regarding the traffic signals will be decided on the basis of data that we will arbitrarily propose to our model on a particular range. The data will at that point be prepared by our suggested model, which can utilize the equations that we have made based on our research, and quadratic optimization will be utilized to advance the amount of time that customers got to wait. In conclusion, the demonstrate that has been given is centered on the usage of an independent and cleverly activity administration framework. This framework will viably diminish and upgrade the sum of time went through holding up at activity crossing points and signals in arrange to address the trouble of this ceaselessly extending deterrent all over the world.

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