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A Review on Performance of Toll Plaza by using Queuing Theory

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ABSTRACT

One of the key problems in the study of any stream of traffic system is the analysis of delay. Delay is a more delicate concept. It may be well defined as the difference between the actual travel time on a given section and some ideal travel time of that section. This raises the question as what is the ideal travel time. In practice, the ideal travel time chosen will depend on the situation. There are two particular travel times that seem best suited as benchmarks for assessment with the actual performance of the system. These are the travel times under free flow conditions and travel time at capacity. Most recent research has found that for highway systems, there is reasonably little difference between these two speeds. The analysis of delay normally focuses on the delay when demand exceeds its capacity. Such delay is known as queuing delay, and may be studied by means of queuing theory. This theory involves the analysis which is known as a queuing system, which is composed of a server, a stream of customers who demand service, and a queue or line of customers waiting to be served.

KEYWORDS: *Length of system, Length of queue, queuing theory, waiting time in queue.*

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INTRODUCTION

Queuing theory is the mathematical study of waiting lines, or the act of joining a line which are called as queues. In queueing theory, a model is constructed so that queue lengths and waiting times can be predicted. The rate of arrival of traffic is always high near an urban city. Since vehicles are arriving in very huge numbers that directly infers that service time will also increase and hence people have to wait for a long time in the queues. The most significant issue in the operational efficiency of a toll plaza is its queue length. The length of queue on a toll plaza is directly proportionate to the waiting time, service time and the arrival pattern of the vehicles. Longer waiting times in the queues results in losses such as fuel wastage, increases pollution and wastage of time which often results in frustration of the travelers. Highway toll plazas constitute a unique type of transportation system that requires distinct investigation when trying to identify their operation and their interaction with other roadway components. On the one hand, these facilities are one of the most effective means of collecting user fees for roadways. The object of a toll highway should be to minimize average travel time of all drivers on that road. On the other hand, toll plazas badly affect the throughput or capacity of the facilities they serve. The adverse effect of toll plazas is particularly evident during hours when traffic is usually heavy. Thus, highway toll experience long vehicular queues and lengthy delays when demand is near or exceeds processing capacity. Efficient sizing of toll plazas becomes critical in minimizing the space requirements and capital expense of collecting user fees. Operational research is a precise method to evaluate problems and making powerful decision. In operational research, queueing theory is a mathematical technique to minimize the waiting time of a particular queueing system. Whenever, the problem of congestion arises in the course of traffic management, the queueing theory and its application always comes into picture. Toll tax is collected to improve the total capital outlay which comprises the cost of construction, repairs, maintenance, expenses on toll operation and interest on the outlay. The new facility thus constructed should provide reduced travel time and increased level of service. In India most of the highway projects are given on PPP basis, i.e. Public Private Partnership. In this the private organization funds and constructs the facility and recovers the capital from the users in the form of toll tax. This tax is collected for a reasonable period of time after which the facility is surrendered to the public. The queuing phenomenon is very common in multi-line bus-stops and there is no doubt that bus operations at stops affect the road link capacity [11]. When an incident or disaster happened, the most important thing the government sector considered was to raise emergency commodities and set them to affected area or refugee shelter as soon as possible [12]. Waiting period is a global problem that almost everyone has to face, which causes a great waste of time for everyone. It is well known that all these waiting line problems critically restrict the further development [13]. Computer simulation is one of the popular approaches to the design of toll plazas where toll plaza configurations such as

toll collection methods, number of toll booths, and types of vehicles have been studied [14]. The assessment of uninterrupted traffic flow is traditionally based on empirical methods [15]. The issues of traffic management are the process of increased disturbance in the movement of traffic. In India the traffic congestion is rapidly increased due to increasing vehicles on the road which produces many problems [16]. Due to the escalating traffic issues a large number of highways have been built in the recent past which are maintained by tax collection at toll plazas by various operating agencies. Due to smooth and hassle-free driving on highways, the arrival rate of vehicles at toll plazas increases. The arrival rate goes beyond control if the traffic on the highway increases in an uncontrolled manner with the passage of time [17]. The toll plaza on the Kaduna – Zaria highway has been modeled as a queue system by adapting the Makino model [18].

FEATURES OF THE QUEUING SYSTEM

Generally, any queuing arrangement is composed of units, denoted as customers, requiring some kind of service. When a customer arrive at a service facility, join a queue if service is not instantly available, and ultimately leave after receiving the service. A server refers to mechanism that delivers service to the customer. Upon arrival, if a "customer" finds the server busy, then he may form a queue, join it or leave the system without getting any service even after waiting for some time. This therefore permits a number of different possible arrangements such as the following, to describe vehicular traffic flow as a queuing system:

1. The arrival pattern: This is the manner in which arrivals occur, indicted by the inter-arrival time between any two consecutive arrivals. For our stochastic modelling framework, the inter-arrival time may vary and may be described by a specific probability distribution that best describes the arrival pattern observed.
2. The Service Pattern: This is the manner in which the service is rendered and is specified by the time taken to complete a service. Similar to the arrival pattern, distribution of the service time must be specified under stochastic modelling considerations.
3. Arrival Rate (λ): This is the average number of vehicles arriving per unit time.
4. Service Time (μ): This gives the average number of vehicles served per unit time.
5. Server Utilization (ρ): This gives the average utilization of the server.

NEGATIVE IMPACTS OF TRAFFIC CONGESTION

1. Wasting time of drivers and passengers in blocked traffic affect the economic health of the nations.
2. Wasted fuel increases the air pollution and carbon dioxide emission owing to increased idling, acceleration and braking.
3. Due to blocked traffic, emergency vehicles may delay in reaching to their destination where they are urgently needed.
4. Spillover effect from congested main routes to secondary roads and side street as alternative routes are attempted which affect colony amenity and real estate prices.
5. Delays, which may result in late arrival for employment, meetings and education, resulting in loss of business, disciplinary action or other personal losses.

MEAN PERFORMANCE PARAMETERS

1. Traffic Intensity

The average number of customers being served is the ratio of arrival and service rate. For a stable system the service rate μ should always exceed the arrival rate λ and thus ρ should always be less than one. Therefore, it is also known as utilization factor of the server. This can be represented as

$$\rho = \lambda / \mu$$

2. Average Number of Customer in the System

The average number of customers in the system is equal to the average number of customers in the queue together with those being serviced. It is expressed as

$$Ls = \rho / (1-\rho)$$

3. Average Number of Customer in Queue

It can be viewed as average queue length that is, the average number of customers who are waiting in the queue. It is defined as

$$Lq = Ls - \rho$$

4. Average Time Spent in the System

The average time spent in the system is equal to the total time that a customer spends in a system i.e. waiting time plus the service time. It is given by

$$Ws = Ls / \lambda$$

5. Average Waiting Time in Queue

The average waiting time in queue is the average time a customer waits in queue forgetting service. It is expressed as

$$Wq = Lq / \lambda$$

METHODS OF TOLL COLLECTION

There are three methods of toll collection available. These are: (i) Manual, (ii) Automatic, and (iii) Electronic system.

1. Manual Toll Collection

Manual toll collection is most broadly used collection technique in India. It requires a toll collector or attendant. Based on the vehicle classification, cash toll is received by the collector. The collector, who also dispenses change, may accept and sell scrip, tickets, coupons, making an entry of the vehicle in the system and issuing receipt to the patron. Due to manual intervention, the processing time is highest

2. Automatic Toll Collection

Automatic toll collection is based on the use of Automated Coin Machine (ACM). These accept both coins and tokens issued by the operating agency. Depending on the toll rate, the use of automated coin or token collection instead of manual collection reduces transaction and processing time as well as the operating cost

3. Electronic Toll Collection

Electronic Toll Collection (ETC) is a system that automatically identifies a vehicle equipped with a valid encoded data tag or transponder as it moves through a toll lane or checkpoint. The ETC system then posts a debit or charge to a patron's account, without the patron having to stop to pay the toll. ETC increases the lane throughput because vehicles need not stop to pay the toll.

REVIEW OF LITERATURE

YAN Qiu et al. (2013) made an evaluation of the design requirements when expected traffic flow is in Erlang

distribution and negative exponential distribution respectively. The outcome shows that the exact forecast of vehicle flow arrival is the important guarantee of highway toll station design. On this basis, the paper studied about three capacity extension schemes, valid to toll station with limited space during peak hours, and then infers some design methods used for the queuing model with both the vehicles interarrival times and the tollbooth service times being negative exponential distribution, thus providing an example for further expansion. Scheme A is to add a temporary tollbooth in the place nearby the outermost tollbooth, where there is sufficient area for charge service. Scheme B is to set up two or more tollbooths, which are in series on a toll lane. All the tollbooths can serve for dissimilar vehicles at the same time. Scheme C is to add a tollbooth in the front or rear of the existing tollbooth where there is enough place for charge service. He concluded that vehicle arrival law is an important factor influencing the toll station design, and on the other hand, the system design also has direct effect on the service efficiency of toll station. So, it is necessary to fully investigate the traffic data and accurately predict traffic arrival law.

WU Zhizhou and ZHANG Jianqiao (2011) explained that Container terminal is a closed action structure, including terminal gate which is the out-and-in passage of trucks and containers. The passing capacity of gateway is a main factor of the whole service quality in the terminal. If the arrangement and configuration of the gate system is unreasonable, the congestion caused by trucks waiting and queuing outside the terminal gate becomes quite serious in the rush hours, and thus disturbs the operating efficiency of the container terminal. He presented the optimal arrangement of gate system by using the queuing model and prove that the queuing model can well describe the actual operation of the gate system and the objective function is formulated based on the consideration of the trucks and the server. A case study is presented to verify the efficiency of the proposed method and showed that it is viable to determine the optimal planning of terminal gate system.

JIAO Peng-peng et al. (2015) analyzed the existing bus scheduling models according to Chinese conditions and the bus route scheduling problem is studied using the theory of stochastic service system (queuing theory). A mathematical model is recognized to achieve the bus route scheduling with travel demand as the essential data and with bus corporation benefits and traveler fulfilment as the objective functions. The process of objective function creation is described, the passenger satisfaction function is presented, and the algorithm of each component of constraints is designed. Finally, a case study is presented on the basis of data from the national mathematical modeling. The model is solved using Mat lab software. Results show that the model has advantages in solving the bus scheduling problem.

Martin Anokye et al. (2013) stated that traffic crowding is a growing problem in many urban areas as it rises travel time, air pollution, carbon dioxide (CO2) emissions and fuel use. They model the vehicular traffic flow and discover how vehicular traffic could be minimized using queuing theory in order to decrease the delays on roads in the Kumasi city of Ghana. Traffic intersection in the city of Ghana is currently operating with one service channel each from the various routes to the intersection. The results showed that traffic intensity, $\rho<1$ for all sessions, a condition that proposes a perfect traffic system. Accordingly, smooth flow of traffic was shown since the server at each channel was able to serve more than the cars in waiting queue when servers resume work. Again, it was found that heavy traffic occurs in the evening. Finally, the government of Ghana could introduce a public transport system so that people do not travel with private cars to their places of work to reduce congestion on the roads, which in turn boosts productivity.

S. Vijay Prasad et al. (2018) studied multi server queuing model and investigate the performance of toll plaza which is situated at Khalghat, Agra-Bombay road (on NH 3). The outcomes of the investigation presented that average queue length, waiting time of vehicle at toll plaza. In particular, he presents the optimal number of toll booths to reduce the queue length and waiting time of vehicles.

Cheng Wang (2017) presented an enhanced model base on M/M/1 queue theory to design the toll plaza by considering different ways of charging in the actual toll service system (human-staffed, automated and electronic toll collection), and the Non-dominated Sorting Genetic Algorithm II (NSGA-II) is used to optimize the design of lane number and charging mode layout and summarized that future work is to study about the prevention of accident, the traffic flow from the tollbooths to the lanes of travel and the total building cost of a toll plaza.

Sachin Antil (2017) stated that a person driving to Delhi daily through the toll plazas can save upto Rs.30000 per annum including toll and the fuel costs during the wait at the toll. He proposed a model to reduce the waiting time for the drivers by analyzing the vehicle arrival pattern at a highway toll plaza in Delhi with applications of queuing theory.

Shuguo Yang and Xiaoyan Yang (2014) analyzed the traffic flow situations of an intersection in certain urban areas by the methods of queuing theory and statistical experiment and sets up an equivalent mathematical model and compares it with the actual values. The result shows that queuing theory is applied in the study of intersection traffic flow and it can provide references for the other similar designs. Queuing theory consists of three parts which consists of input process, queuing rules and service agencies.

Sangavi G V et al. (2017) emphasized that Due to continuously growing road traffic, the road capacity has to be increased to accommodate different configuration vehicular dimensions. Toll roads need huge financing to construct a safe, effective and durable road network. Toll financing is one of the techniques in which revenue collected from the road users for the service provided by them. This in turn results in development in queues at specific junction where the toll booths are established. Long queue could lead to increase in travel time which is disadvantage to the road user. Hence toll should be designed and planned in such a way that minimum time would be wasted in the queuing area. The toll booths are planned on the basis of queuing area. Queuing theory involves parameters such as arrival time, number of lanes, service time, waiting time and merging area.

Yinghong LI and Qiyuan PENG (2007) made analysis on railway section and gave a queuing model which estimates

the average time that the train spends in the queuing system and the maximal carrying capacity. Moreover, they explore the model deeply and developed the relationship between the section occupation rate and the average queue length.

CONCLUSION

From the above discussions we can conclude that toll tax is a fee which is used for the use of a newly built facility to recover the total capital outlay. The private organization builds, operates and then transfers the facility after a projected period of time. The Electronic Toll Collection (ETC) system is the most effective method of toll collection with least delays. But due to its high installation cost, it's not that prevalent in India. We can find the optimum number of tollbooths by applying queueing theory to determine the delays in both queueing and merging areas. The optimum number of tollbooths should minimize the overall delay time. Toll prices are set in such a way that they attract maximum number of users and the agency should be able to recover the cost within specified period of time. As an important field in traffic control science, the research in design of toll plazas has increasingly attracted attention of scholars and society. A good design of toll plaza needs to meet a lot of conditions, such as high safety coefficient, high throughput and low-cost level [19]. Operational research is a scientific approach to analyze problems and making powerful decision. In operational research, queueing theory is a mathematical technique to minimize the waiting time of a particular queueing system. Whenever, the problem of congestion arises in the course of traffic management, the queueing theory and its application always comes into picture [20]. The effective parking space was one of the major quantitative indicators which was analyzed in detail and an optimization model was made with the help of queuing theory [21]. So queuing theory should be well utilized when there is a problem of queuing to determine the waiting times and queue lengths.

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